SALT WATER INTRUSION OF COASTAL AQUIFERS IN THE UNITED STATES

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SUMMARY

The paper describes the occurrence of salt water intrusion, originating from connate or oceanic sources, in coastal aquifers of the United States. The present status of intrusion in the twenty-three coastal states is reviewed. Mention is made of areas, cause-and-effect, remedial measures, and future possibilities of intrusion. Advances in knowledge of intrusion and current research are reported. An understanding of the hydrodynamics of the phenomenon is developing. Particularly significant is progress in analysis of the formation and maintenance of the interfacial transition zone.

RÉSUMÉ

L’article décrit les situations dans les aquifères littoraux des États-Unis, où se présente l’intrusion souterraine d’eaux salées, littorales ou maritimes. Les conditions actuelles d’intrusion en vingt-trois États bordant les océans sont rapportées et les régions, les raisons, les effets, les procédés de remède et la probabilité d’intrusion future sont passés en revue. Comptes est rendu du progrès dans la connaissance du phénomène d’intrusion et la recherche courante. La compréhension, de l’aspect hydrodynamique s’accroît. Le progrès dans l’analyse de la formation et du maintien de la zone transitoire de séparation a été d’une importance particulière.

1. INTRODUCTION

The intrusion of saline waters into coastal aquifers is presently occurring at many locations along all of the United States coasts. The problem has become increasingly serious in recent years as demands for water from underground sources have expanded. It is the purpose of this paper to summarize the status of intrusion in the United States and to review recent advances in the knowledge as well as to indicate research in progress.

Saline water is that water generally considered unsuitable for human consumption or for irrigation because of its high content of dissolved solids. The U. S. Public Health Service standard for drinking water permits a maximum of 250 ppm chloride and 1000 ppm dissolved solids. Irrigation limits exceed these values, but salt tolerances vary with crops and other agricultural factors. Rather than restricting intrusion to a prescribed salt content, it will here be defined as the occurrence of a salinity which markedly exceeds that normally found in a given aquifer at a specified depth.

In coastal aquifers salt water originates from two primary sources—connate water and sea water. Connate water is water remaining in a rock formation from the time of deposition. Often the water has been considerably modified from its original composition. Increased salinities may result from solution of rock minerals, or saline invasions by shifting sea levels. Decreased salinities can result from dilution and incomplete flushing by meteoric water. Salinities of connate water vary from a minor fraction of that of sea water to several times that of sea water. It is not uncommon in layered sedimentary formations to find large variations in salt content from one stratum to another, presumably resulting from differences in circulation which are affected by stratigraphy and permeability. Sea water most often occurs in aquifers by entrance through submarine outcrops. Surface sources, which may be important locally, include leakage downward around wells, tidal waves, hurricane-blown sea spray, and tidal marshes. Special conditions may provide opportunities
for intrusion, including sea level canals and regulation of streamflow such that sea water may advance upstream in estuaries.

Intrusion is the increase of salinity in an aquifer resulting from acts of man. The most common cause is localized overpumping of wells penetrating coastal aquifers. If saline connate waters exist below the pumped aquifer, the reduction in pressure can cause an upward migration of poor quality water. For aquifers exposed to the sea, pumping can reduce the normal seaward ground water flow to an extent that the hydraulic gradient is reversed, causing a lateral advance of sea water inland. In permeable oceanic islands underlain by sea water, excessive pumping from basal fresh ground water can produce upward coning of sea water to wells.

2. OCCURRENCE OF INTRUSION IN THE UNITED STATES

A survey was made of the occurrence of salt water intrusion of coastal aquifers in the United States as of 1959. Information was obtained from a review of published material and from responses to a questionnaire sent to district offices of the U.S. Geological Survey and to state water resources agencies in all coastal states. Significant publications relating to intrusion are listed in references at the end of the paper; these supplement those in Todd (15).

Fig. 1 — Location of salt water intrusion of coastal aquifers in the United States.

One result of the study is the map shown as Fig. 1, which indicates the locations of known intrusion. Locations of probable future intrusion were omitted, so that each dot on the map shows a location where increases of salinity with time have been observed. No distinction has been made as to the source of the saline water; in many areas the source is known, in others not.

The state most seriously affected by intrusion is Florida, followed by California, Texas, and New York. The situation in Florida is produced by a combination of circumstances all favoring intrusion. The state is entirely a lowland, being a part
of the Coastal Plain occupying the southeastern margin of the United States (10, 19). Almost the entire state is underlain by saline artesian waters in permeable limestone aquifers. Add to these the lengthy coastal line and the desire for people to live near the pleasant coastal beaches. Intrusion is a natural consequence.

Little direct effort is being made to control intrusion, except by a well recharge program at Los Angeles, California. In most instances the only feasible way to handle intrusion is to understand the field situation, monitor key wells continually, and recommend a pattern and magnitude of ground water pumping which will not induce further intrusion. In many instances intrusion has necessitated abandonment of wells. This is an unintentional, but also an uneconomical, method of controlling the problem.

The following paragraphs contain a brief summary of the salt water intrusion situation in each of the 23 coastal states.

Alabama: The only instance of intrusion is that at Mobile in an alluvial unconfined aquifer. The development of closely spaced wells for air conditioning and industrial uses, combined with heavy withdrawals in 1941 during construction of a tunnel, created a cone of depression which caused entrance of saline Mobile River water. Since 1941 about 20 wells have been abandoned or deepened to tap less saline waters. Well samples show that chloride concentrations increased from 1941 to 1945, but have gradually decreased since then as pumping rates have been curtailed.

Alaska: Anchorage is the only major coastal city using ground water in large quantities. Indications are that continual pumping in the area will reduce ground water levels to sea level; hence future intrusion is a possibility.

California: The lengthy coastline of California combined with the concentration of population centers along the coast have produced several localities of intrusion. As of 1957 sea water intrusion was a critical water quality problem in nine coastal ground water basins (6). Almost all were confined aquifers with salinity increases resulting from lateral movement of sea water as a result of overpumping. Continued pumping at present rates will permit further encroachment into these basins. In addition, 71 other coastal ground water basins are areas of suspected intrusion where chlorides exceed 100 ppm. In Santa Clara Valley leakage of saline waters through abandoned and defective wells is believed to have caused contamination of a lower confined aquifer.

The most serious intrusion area exists in the West Coast Basin of Los Angeles County. In 1904 flowing wells existed in the area, but increased pumping as the metropolitan area grew produced the first intrusion in 1912. Today, static water levels have declined to 90 feet below sea level, and chlorides exceeding 100 ppm extend along a 14-mile coastal front and for an average of 2 miles inland. An experimental project to control intrusion in the area was undertaken in 1952 with the drilling of nine 12-inch wells at 500-foot intervals along a line parallel to and 2000 feet inland of the coast. The wells were recharged with treated Colorado River water containing 5-10 ppm chlorine. It was found that a total recharge of 4.5 cfs in the 4000-foot reach was sufficient to maintain a pressure ridge of the necessary minimum elevation. The recharge line has continued in operation since 1953. The well line intersected the wedge of intruded sea water so that recharging caused an increase followed by a decrease in chloride content as the saline wave moved inland.

Connecticut: Intrusion is reported at New Haven and Bridgeport, with occurrences mostly in unconsolidated stratified glacial-drift sand and gravel deposits. Intrusion extends inland for a maximum distance of 3000 feet. Salt water has caused
abandonment of some industrial wells with replacement water supplies coming from increased purchases of municipal supplies. Studies are underway in the New Haven area.

**Delaware:** Localized salt water contamination has occurred at six locations, including New Castle, Slaughter Beach, Lewes, Rehoboth Beach, and Fenwick Island. Intrusion occurs in unconfined Coastal Plain sediments with the salt residuals dating from the Pleistocene epoch. The area involved is not large and probably can be confined to a strip a mile wide or less along the coast. Intrusion has resulted in abandonment of several municipal wells, requiring location of new ones further inland. Efforts to abate increases in salinity by reduction of pumping have been made at three well fields. A serious potential danger exists near the Chesapeake and Delaware Canal. The canal crosses the outcrop of an extensive fresh water aquifer. Enlargement of the canal together with progressive industrialization of the area could result in migration of sea water down dip to this aquifer.

**Florida:** Intrusion is occurring in 28 specific locations along the coast of Florida (1). Limestone aquifers cover most of the state, while connate or residual salt waters underlie the entire state. The chief cause of intrusion is excessive pumping of ground water in the heavily populated coastal areas; however, other causes include excessive drainage of inland areas, lack of protective works in tidewater channels, improper well locations, and leakage through wells. The intruded areas result from saline contamination by lateral movement of sea water or by coning of salt water from below; in some areas it is not known which is the source of salinity.

To date some 18 municipal water supplies have been adversely affected. The first intrusion occurred at Tampa in 1924. Three municipal well fields in the Miami area have been affected since 1925. In most instances the remedy has been the construction of new well fields with reduction or abandonment of old fields.

In the Miami area intrusion has long been a serious problem (2). The intrusion first resulted from construction of interior drainage canals which lowered the water table both inland and along the coast. Subsequently, enlargement of the Miami Canal permitted invasion of saline water by tidal action for a distance of 10 miles upstream during a drought in 1939. In this and other canals in the area, salt water has entered the aquifers and formed fingers extending inland adjoining the canals. Intrusion was halted by installation of control dams. The salt-fresh water front has been stabilized since 1946.

Over the past 25 to 30 years salting of municipal well fields has been one of the foremost water problems in the State. Municipalities large enough to finance large water supply projects have solved the problem by building pipelines and relocating well fields up to 40 miles away from the coast. In some cases smaller towns have joined together or arranged to be served by a larger city. Smaller communities, unable to finance long pipelines, are faced with problems of using water in excess of 250 ppm chloride or using marginal supplies. In places restrictions on water use prevent growth of communities.

**Georgia:** At present no intrusion has been reported along the coast. Studies of possible future contamination are underway in the Savannah area, where the cone of depression has extended northeastward to a point where the confined limestone aquifer outcrops on the ocean floor.

**Hawaii:** As the Hawaii Islands consist of largely permeable volcanic rocks, sea water underlies all of the islands with basal fresh-water lenses superposed. Pumping during this century on Oahu has lowered the water table 10-15 feet and produced
a marked rise in the sea water interface in accordance with the Ghyben-Herzberg relation. Encroachment of salt water is continuing in the Honolulu area but has not advanced to a serious stage. Increased salinities have also been noted at locations on Maui. Much of the fresh water development on the Islands is by horizontal wells which skim off the upper fresh waters and give a minimum disturbance of deeper saline waters.

**Louisiana:** The coastal plain aquifers show no evidence of hydraulic connection with the Gulf of Mexico (§). Connate waters, however, have migrated up dip, resulting in contamination of ground water supplies in cities of Lake Charles and New Orleans. It is estimated that the northward movement of water in these aquifers is slow — the order of 10 to 50 feet per year. Contamination in the two metropolitan areas is aggravated by the upward movement of saline water in the piezometric cones created by concentrated pumping. Sea water intrusion is occurring in the areas adjoining the lower portions of Vermilion and Atchafalaya Rivers. During dry years sea water migrates upstream by tidal action. At the same times wells recharged by the rivers are pumped for rice irrigation in the area. Intrusion resulted in 1951 from this combination of circumstances, and it is expected to recur in the future.

**Maine:** No intrusion is reported along the coast. In general, there is little industry having wells situated along the coast and few coastal towns withdraw public water supplies from wells.

**Maryland:** The principal locations of encroachment are in the Baltimore, Aberdeen, and Christfield-Westover areas. High chloride contents have been encountered in a few domestic jetted wells in the Solomons Island area of Calvert County; however, contamination is local and believed to result from downward movement of brackish water along the outside of casings in wells near the shore line.

Salt water contamination exists in the Baltimore area from entrance of saline water through outcrops of confined aquifers in the Patapsco River estuary and from leakage of salty water from shallow formations down abandoned or faulty wells into deeper fresh water aquifers. The latter cause is the most serious difficulty. As shallow wells are abandoned in favor of better quality water in deeper aquifers a large pressure gradient develops toward the lower strata. Salt water is forced down operating wells when casings are perforated by corrosion or when external casing seals are broken. There is evidence of leakage in every large group of wells in the area. Contamination is worse where abandoned wells are most numerous; many of these were left unsealed and have become permanent sources of leakage.

**Massachusetts:** Salt-water encroachment is not significant along the coast. Three localized instances of intrusion are reported. At Provincetown a group of shallow wells in unconsolidated deposits 300 feet from the sea became saline from heavy pumping. The wells were abandoned and new ones constructed farther inland. The town of Scituate has a well tapping an unconfined aquifer located 500 feet from a salt marsh. Heavy pumping produces a rise in the chloride content of the water; the difficulty is overcome by reducing pumping to a rate which does not increase the salinity. At Somerset water from a shallow well 200 feet from a tidal stream becomes salty when unusually high tides bring sea water near the well. The well is only pumped when quality is satisfactory, replacement water is pumped or purchased elsewhere.

**Mississippi:** Although connate waters underlie the entire coastal plain of the state, intrusion is occurring only to an insignificant extent (§). At Moss Point salt water is pumped from a localized gravel formation at a depth of 155 feet. This is
attributed to a connection to the Pascagoula River estuary. Recent increases in pumping and reductions of ground water levels to sea level suggest that intrusion may soon develop in the Pascagoula and Biloxi areas.

New Hampshire: Minor encroachment of salt water in recent years has been noted along the coast and along the lower reaches of Piscataqua River, primarily as a result of heavier pumping of wells.

New Jersey: Salt water contamination has reached some of the municipal wells of Atlantic City. Abandonment of wells and replacement by new ones has been necessary. The rapidity of the increase in salinity suggests, after investigation, that salt water enters the confined aquifer through openings in the overlying clay beneath the salt marshes and through openings in stream bottoms in the area. Heads in deeper aquifers are below sea level, suggesting that more intrusion can be expected in the future.

Intrusion was noticed in the Sayreville-Parlin area after construction in 1929 of a nearby canal which provided direct access of salt water into a confined aquifer heavily pumped for industrial supplies. Test wells showed salinity advancing at a rate of about 900 feet per year. Salt water has appeared at Newark because of excessive pumping and exposure of the aquifer by dredging of ship channels in the Passaic River. Encroachment is occurring around the Raritan Bay area and along the southeast coast between Atlantic City and Cape May. Localized increases in salinity are reported at industrial sites bordering the Delaware River below Camden.

A proposed sea level canal across central New Jersey from the Delaware River would introduce saline water into the Raritan-Magothy aquifer which would have detrimental effects on public water supplies of Perth Amboy and Dumural.

New York: Intrusion is concentrated in the coastal plain sediments of Long Island as a result of overpumping (1). In Brooklyn, at the western end of the island, serious contamination has resulted in shallow and deep aquifers. The seriousness of the situation led to passage of a water conservation law in 1933 which required that ground water pumped for industrial cooling purposes be returned to the aquifer from where it was taken. Municipal water sources from underground were entirely abandoned by 1947 to be replaced by upstate surface water supplies. Since then the cone of depression occupying the area has filled so that today gradients are now seaward in most localities. The salt water is presumed to be moving seaward although no appraisal of recent data has been made.

Along the southern coast in the western third of the island, intrusion is occurring in three different formations. Chloride contents are increasing slowly; the advance of salinity probably is less than 100 feet per year (4). This area is now being studied. Intrusion is also occurring along the northern coast in this part of the island. Some localized contamination of shallow wells is known to be occurring in northeastern Long Island, principally from seasonal pumping of wells adjacent to salt-water marshes for supplemental irrigation.

North Carolina: Intrusion is occurring in 6 metropolitan areas along the North Carolina coast. Points up to one mile inland have been affected. A total of 15 domestic and municipal wells have been abandoned in favor of supplies from deeper and more inland uncontaminated aquifers. Abandoned wells have been located in areas adjacent to tidal estuaries; overpumping has resulted in interception of saline water. Chloride monitor wells have been established on Bodie and Hatteras Islands to provide a basis for adjusting pumping rates of the limited ground water supplies available.
Oregon: Development of permeable alluvial deposits along the Oregon coast is only now getting underway; therefore, no intrusion has been reported. Precautions against inducing movement of sea water or connate water in tertiary rocks toward wells are being taken in the form of selective pumpage and recharging with diverted surface water.

Rhode Island: Small instances of intrusion have been reported in unconfined aquifers in the Providence area and at Warren. Four industrial wells have been abandoned at Providence with alternative water coming from municipal surface water supplies. Intrusion is regarded as a serious potential problem if development of ground water resources is increased in the future.

South Carolina: Extensive intrusion is reported in the rural areas of Beaufort and Parris Island at the southern extremity of South Carolina. Salinity is attributed to entrance of sea water as a result of pumping in the flat coastal plain containing large areas of salt marshes. Heavy pumping in the Savannah area may be aggravating the problem. Contamination has led to abandonment of 25 or more wells supplying a military base and domestic needs. Replacement wells have been located further inland. Efforts to limit intrusion have included dispersing new well fields and reducing pumping rates. Studies of intrusion are in progress in the general area affected. Less critical encroachment exists in the Charleston and Georgetown areas.

Texas: Intrusion is occurring in the Galveston, Texas City, Houston, and the Beaumont-Port Arthur areas of Texas. Salt water remains in the confined Coastal Plain sediments, with salinities increasing down dip toward the Gulf. The lateral migration of salt water up dip in fresh-water formations is producing the intrusion along the Texas coast. Galveston found it necessary to obtain its water supply from wells on the mainland, but tests indicate that even these wells are being contaminated and so the city has drilled new wells further inland. Texas City industries are meeting a similar problem by shifting from wells to the Brazos River for their water supplies. The pumping cone around Houston is drawing saline water up dip. The movement is slow; at present increases in salinity have been observed only in deep test wells. In the Beaumont-Port Arthur area intrusion has occurred to such an extent that pumpage has been reduced to 5 per cent of its former value.

Virginia: Limited intrusion has resulted from underlying connate waters. At one location in Warwick County wells tapping confined aquifers were overpumped during a drought. Chloride contents increased, either from migration of water up dip or from upward movement from greater depths. A group of 5 shallow coastal wells used for air conditioning in Newport News became brackish and their use was discontinued. Similarly, 18 shallow wells supplying the town of Cape Charles were abandoned in favor of deeper inland wells.

Washington: Most water supplies for populated portions of the coast come from surface sources; hence intrusion is not occurring at present. As part of a continuing program of evaluating the ground water resources of the State, attention is being given to potential intrusion areas. The Washington Ground Water Code provides authority for preventing salt water contamination by controlling permits for new wells and well specifications.
3. ADVANCES IN KNOWLEDGE OF INTRUSION

The inadequacy of the Ghyben-Herzberg principle for describing the geometry of coastal intrusion is now generally recognized. Studies in recent years have concentrated on the flow patterns of the fresh and salt waters, on the structure of the interface, and on the effects of external influences such as tides, pumping, and recharge.

Through the efforts of several investigators a clear picture is emerging of the hydrodynamic equilibrium involved. One concept now well established is that salt water disperses upward into the interfacial transition zone as a result of fluctuations produced by external influences and is then transported seaward by the fresh water flow. This induces a slow landward flow in the salt water body to maintain the hydrodynamic equilibrium. In 1927 Nomitsu (17, Ref. 28) with two of his students first postulated this circulation system. Much later, in 1951, Senio (17, Ref. 29) analyzed field data of Toyohara (17, Ref. 90) and suggested the same flow pattern. More recently Carrier (1) in an analytic treatment of the problem stated that the recirculation system is the only acceptable flow distribution. Shortly afterward Cooper (9) suggested the same circulation based on a study of field data from Hawaii and Florida. Interestingly enough, each of these four investigators apparently recognized this flow pattern independently as none refers to the work of any of the others. It would be appropriate, and convenient, to recognize this salt water flow system as the Nomitsu circulation.

Recent contributions on dispersion in porous media make it clear that this process of miscible fluid displacement accounts for the existence of the transition zone whereas diffusion alone cannot. The early work of Kitagawa, summarized in his paper of 1939 (9), outlined many of the concepts of dispersion known today. The rinsing hypothesis of Wentworth (27, Ref. 44) for formation of the transition zone was another way of describing the effect of dispersion. The first comprehensive analytic treatment of the transition zone for two-dimensional flow has been carried out by Carrier (1).

Beginning with a modification of Wentworth's hypothesis, he derives an equation for the salt distribution of the transition zone. The result is expressed as functions of a time and spatially varying velocity field and an effective diffusivity (actually dispersion). Interpretation in terms of actual aquifers remains to be done.

The thickness of the transition zone depends upon four variables: an unsteady fresh water flow field, the tidal pattern, permeability, and dispersion. As the relations among these parameters are established, it seems reasonable to expect that the wide range of transition zone thicknesses found in different coastal aquifers can be shown to be special cases of a general solution.

4. CURRENT RESEARCH IN THE UNITED STATES

Recent recognition of the magnitude of salt water intrusion in the United States, together with the realization that the problem will enlarge in the future, has stimulated research efforts. Studies are being conducted by the U. S. Geological Survey, by state and local agencies, and by universities. Both laboratory and field investigations are underway. The major programs are briefly noted in the following paragraphs.

The encroachment problem on Long Island is being studied by N. J. Lusczynski of the U. S. Geological Survey. Analytic studies concern the hydraulic conditions of the fresh, transition, and salt water zones in the Long Island environment. Field data from observation wells enable analyses to be checked and provide a basis for recommending water management practices.

A field investigation of intrusion in the Savannah area of Georgia and South Carolina is being conducted by H. B. Counts of the U. S. Geological Survey. Test wells have been installed to collect lithologic and water quality data.

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The major experimental effort to control intrusion is being continued by the Los Angeles County Flood Control District on the west coast of Los Angeles County, California. A barrier in the form of a continuous pressure ridge was created by injecting chlorinated imported water into the affected aquifer through a line of recharge wells parallel to the coast. The pressure ridge has been successfully maintained since 1953. Engineering and geologic studies are now being conducted to determine the feasibility of extending the barrier to protect the entire 11-mile coastal boundary of the basin.

The fresh-salt water distribution in the Hawaiian Islands is being examined by the U. S. Geological Survey. Field data are being collected to assist in evaluating the dynamics of the Ghyben-Herzberg system. The study will attempt to determine the relation of fresh water storage to island geology, rainfall, head, tidal fluctuations, leakage, and draft. Companion papers describe some findings of this research program.

The most comprehensive research program of intrusion by the U. S. Geological Survey is that being conducted in southern Florida under the direction of H. H. Cooper, Jr. The investigation is concerned with the dynamics of intrusion, the structure of the transition zone, and the effects of external forces such as tides. One phase of the study is concerned with the collection of valuable field data near Miami, Florida, from a group of specially constructed wells which enable point measurements of head and salinity to be made through a vertical cross-section of aquifer normal to the coast. A second phase covers theoretical studies of tidal action and dispersion on the formation and maintenance of the transition zone. The third phase, being studied by A. I. Johnson in Denver, Colorado, consists of laboratory model studies to confirm and extend results obtained from the field and analytic portions of the investigation. A companion paper describes this research program.

An analytic study of steady two-dimensional fresh and salt water flows in confined aquifers is being conducted by H. R. Henry of Michigan State University. Equations for the location of the interface and for boundary velocities for several boundary conditions assuming immiscibility have been derived (9). The work is being extended to include effects of dispersion and tidal action.

A research program on salt water intrusion is being carried out in the Hydraulic Laboratory of the University of California, Berkeley. One phase, involving a new analytic treatment of the simultaneous flows of two fluids, has been developed by G. de Josselin de Jong (8). The method consists of replacing the two different fluids by one hypothetical fluid and introducing vortices along the interface where the change in fluid properties occurs. The magnitude of vorticity is chosen such that the specific discharges in the hypothetical fluid are everywhere identical to the specific discharges in the actual fluids. The flow in the hypothetical fluid can be determined by potential theory from the transformed boundary conditions and from singularities at the vorticity points. The result is valid for any point in the entire field irrespective of the fluid present. A corollary of the vortex theory enables two-fluid flow problems to be studied in electric analogy models. Verification tests in electric analogy and viscous fluids models are being completed. A second phase, being studied by J. Bear, concerns the hydrodynamics of the transition zone. Analytic expressions taking into account dispersion, tidal action, and seasonal influences on aquifers are being developed for two-dimensional aquifer conditions. Model verifications will complete the study. The third phase of the program is an analytic study of the hydraulics of fresh and salt water flows particularly as they apply to the shape of the interface under coastal aquifer conditions.

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