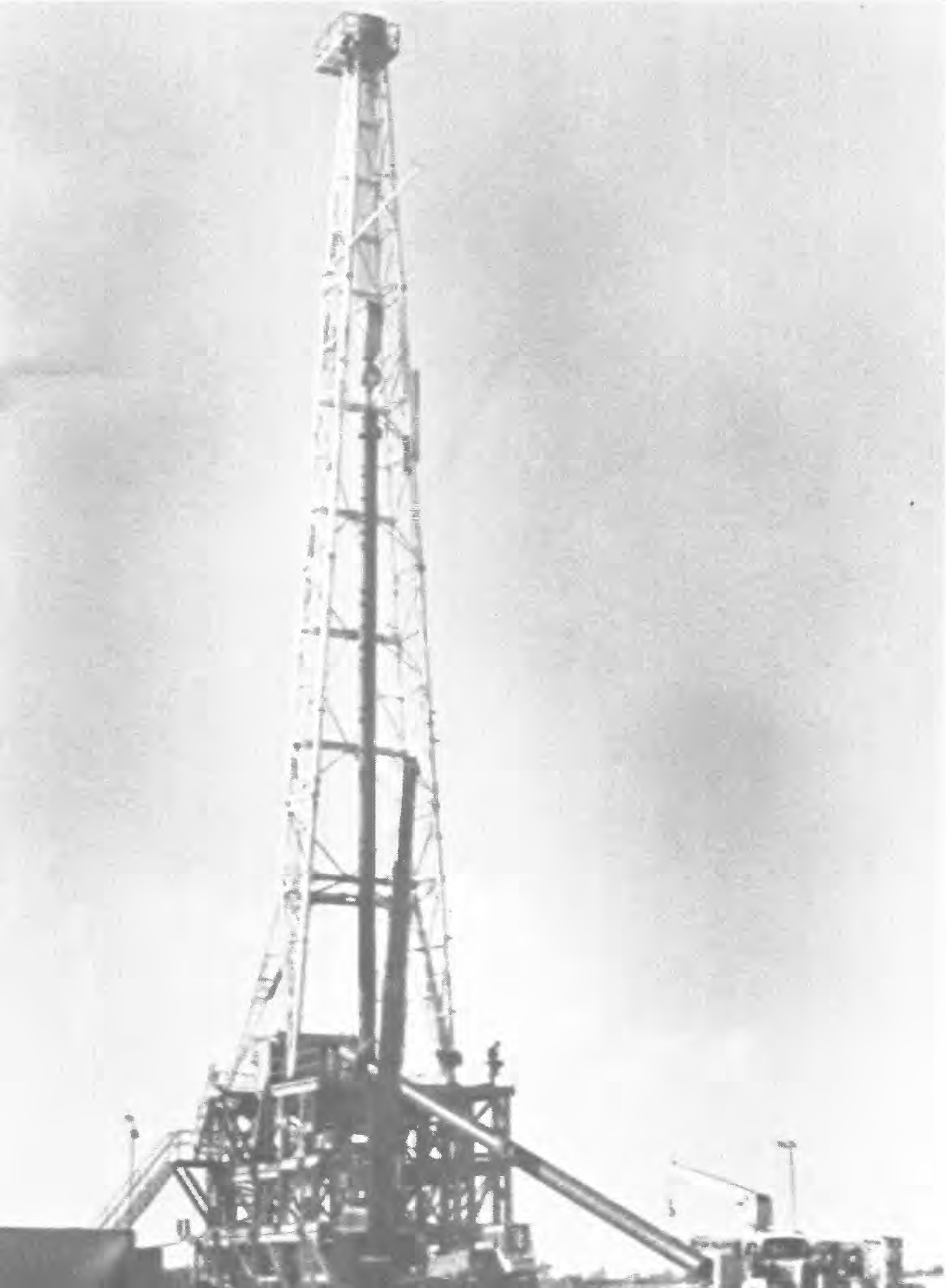
Subsurface Injection of Liquid Waste With Emphasis on Injection Practices in Florida



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Subsurface Injection of Liquid Waste With Emphasis on Injection Practices in Florida

By JOHN J. HICKEY and JOHN VECCHIOLI

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FOREWORD

As described herein, subsurface injection of liquid wastes has been practiced in the United States for more than 50 years. Early use was for the return to the subsurface of oilfield brines brought to the surface during petroleum production. Application to other liquid wastes began during the 1930's but did not achieve a significant status until the introduction of comprehensive Federal water pollution control laws and regulations in the 1960's and early 1970's.

My involvement with industrial and municipal wastewater injection technology began 20 years ago at the time interest in the method was strongly growing. I was convinced, at that time, that full use of the available oil-industry technology with appropriate modifications for the special problems involved would result in an environmentally safe practice that was well suited to some wastewaters. While never promoting subsurface injection, I attempted to provide technical information in an understandable form to other professionals, to administrators, and to the public so that appropriate regulatory judgments could be made at all political levels and so that wastewater injection, when practiced, would use the best available technology.

The evidence from practice available today supports my original beliefs about the environmental safety of wastewater injection, as pointed out by J.H. Lehr in his article "The Word Is Out on Underground Injection and It's Not All Bad," published in the July-August 1984 issue of "Ground Water." Moreover, a rather comprehensive and sophisticated regulatory program has evolved under the Safe Drinking Water Act and the attendant Underground Injection Control Program that incorporates the necessary technical provisions for safe injection practice. Critics continue to question the methodology itself and the effectiveness of regulation, but evidence strongly supports continuation of its use in appropriate circumstances and with proper system design, construction, and operation.

This publication is a fine contribution to the continuing documentation of injection practice. It ably summarizes the geology and hydrology and historic aspects of wastewater injection in Florida and provides a general background for those not already familiar with the technology.

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October 1984

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By John J. Hickey *and* John Vecchioli

Abstract

Subsurface injection of liquid waste is used as a disposal method in many parts of the country. It is used particularly when other methods for managing liquid waste are either not possible or too costly. Interest in subsurface injection as a waste-disposal method stems partly from recognition that surface disposal of liquid waste may establish a potential for degrading freshwater resources. Where hydrogeologic conditions are suitable and where surface disposal may cause contamination, subsurface injection is considered an attractive alternative for waste disposal. Decisions to use subsurface injection need to be made with care because, where hydrogeologic conditions are not suitable for injection, the risk to water resources, particularly ground water, could be great. Selection of subsurface injection as a waste-disposal method requires thoughtful deliberation and, in some instances, extensive data collection and analyses.

Subsurface injection is a geological method of waste disposal. Therefore, many State and local governmental officials and environmentally concerned citizens who make decisions about waste-disposal alternatives may know little about it. This report serves as an elementary guide to subsurface injection and presents subsurface injection practices in Florida as an example of how one State is managing injection.

INTRODUCTION

Subsurface injection of liquid waste is used as a disposal method in many parts of the country. It is used particularly when other methods for managing liquid are either not possible or too costly. The petroleum industry, since the 1930's, has used subsurface injection to dispose of brine wastewater that is produced with oil and gas. More recently, chemical and manufacturing industries have begun to dispose of liquid wastes into the subsurface in a number of States. In Florida, several municipalities have adopted subsurface injection for disposal of effluent from sewage-treatment plants because stringent water-quality regulations make surface disposal costly.

Interest in subsurface injection as a waste-disposal method stems partly from recognition that surface disposal of liquid waste may establish a potential for degrading freshwater resources. Where hydrogeologic conditions are suitable and where surface disposal may cause contamination, subsurface injection is considered a viable alternative for waste disposal.

Decisions to use subsurface injection are made carefully because, where hydrogeologic conditions are not suitable for injection, the risk to water resources, particularly ground water, could be great. Selection of subsurface injection as a waste-disposal method requires thoughtful deliberation and, in some instances, extensive data collection and analyses.

Subsurface injection is a geological method of waste disposal. Therefore, many State and local governmental officials and environmentally concerned citizens who make decisions about waste-disposal alternatives may know little about the method. This report serves as an elementary guide to subsurface injection and presents subsurface injection practices in Florida as an example of how one State is managing injection. The first half of the report describes hydrogeologic factors, classification and distribution of injection wells, and regulation of injection. The second half of the report describes experience with subsurface injection in Florida, where it has been widely practiced for many years. Support for this report was provided by the Information Transfer Program of the U.S. Geological Survey, Water Resources Division.

SUBSURFACE INJECTION FUNDAMENTALS

Subsurface injection is the forcing of liquid through a well into underground rock openings that generally are filled with water. Sometimes the weight of the liquid column in a well provides sufficient force for injection. In this application, the well is called a gravity injection well (fig. 1). Commonly, another force is added to the weight of the liquid to cause injection. Pumps add this force by increasing the pressure on the liquid until its pressure, at the point of injection, exceeds the pressure of the water in the underground rock openings. Where a pump is employed, the well is called a pressure injection well (fig. 1).

An injection well is a cylindrical conduit extending from land surface into underground rock openings. Most of

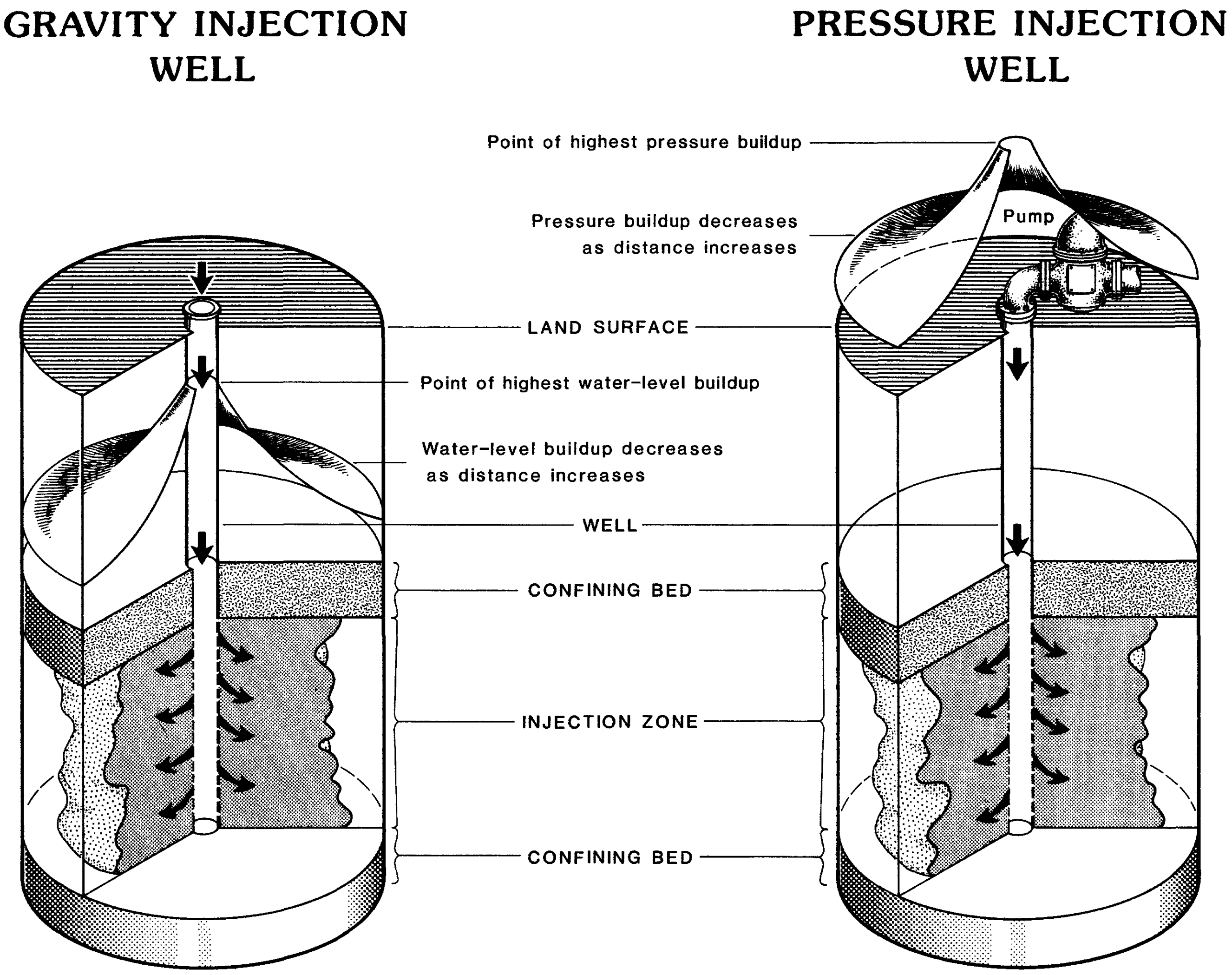

Figure 1. Gravity and pressure injection wells.

an injection well generally is lined with a casing to prevent the collapse of the conduit and to restrict outflow of the liquid to the desired injection depths. Wells that are constructed in unconsolidated sand and gravel strata commonly are equipped with a perforated casing or a screen attached to the end of the casing to emplace the injected liquid at the chosen depths. Wells constructed in consolidated rock, such as limestone, typically have an interval of unlined borehole below the casing for the same purpose. Two or more concentric casings, each having a surrounding cement grout sheath, commonly are installed through the shallow strata to facilitate drilling and to provide maximum protection of fresh ground-water resources.

Underground rock openings are called pores; the volume of pore space in a unit volume of rock is called porosity and is expressed as a percentage. Generally, a rock contains both isolated and connected pores (fig. 2). Only the connected pores can accept, store, and transmit injected liquid away from a well. Pressure buildup that results from injection increases porosity by expanding the receiving rocks. Additional storage space is also created by compression of the native water by the increased pressure.

In some hydrogeologic terranes, most available space for storage of waste would be related solely to expansion of rock and compression of native water. This is likely when the aquifer chosen for injection is well confined vertically and laterally. In other hydrogeologic terranes, particularly those that place little restriction on lateral flow, the greatest amount of storage space for injected liquid waste would be provided in the long term by displacement of the native water. This displacement could be an important constraint on use of subsurface injection because, in aquifers chosen for waste disposal, native water generally is saline. When saline water is displaced it could discharge into or mix with freshwater. The possibility of movement of native water at distances from the injection point is an important consideration when mak-

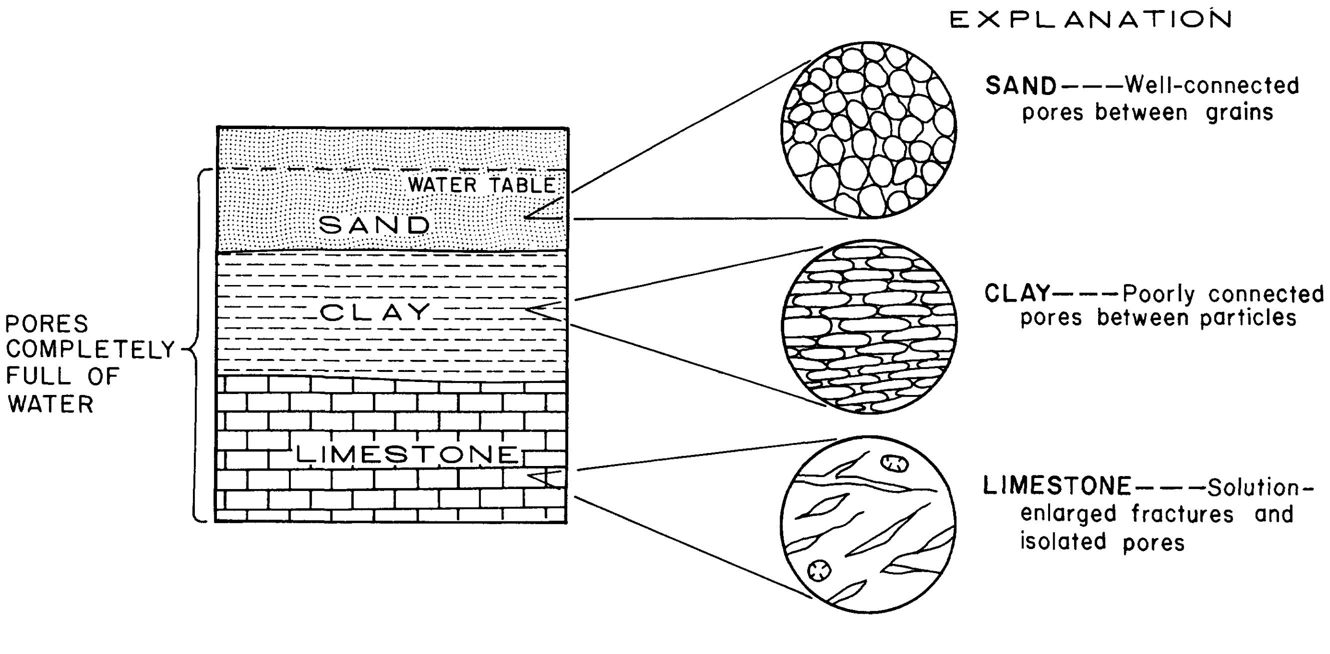

Figure 2. Common types of underground rock openings.

ing decisions about whether or not to use subsurface injection.

Injection Well Construction

A typical injection well is constructed of several components. The number and type of these components depend on the chemical nature of the liquid waste and the degree of consolidation of the host rock. A well used for injection of treated sewage into a consolidated formation has at least three components: (1) wellhead, (2) casing(s), and (3) cement sheath(s). In contrast, a well used for injection of industrial waste into an unconsolidated formation has at least eight components: (1) wellhead, (2) casing(s), (3) cement sheath(s), (4) noncorrodible injection tubing, (5) annular fluid between casing and tubing, (6) packer at end of tubing, (7) well screen, and (8) gravel pack (fig. 3). Items 7 and 8 may be replaced by an open hole in consolidated rock. To minimize corrosion and to ensure long-term structural integrity, the material used for each component must be matched to all other components, to the liquid waste, and to the native formation water. Most injection wells have multiple casings, cement sheaths, and injection tubing (fig. 3). The multiple casings are a pipe within a pipe within a pipe, each separated from the others by cement sheaths. The injection tubing, the smallest diameter pipe, commonly is separated from the innermost casing by an annulus that is filled with a corrosion-inhibiting liquid. All components of an injection well are chosen as needed for structural integrity of the well and for protection of underground sources of drinking water.

Hydrogeologic Requirements for Injection

For subsurface injection to succeed as a disposal method within the constraints of Federal and State requirements, the injection site and the surrounding region should possess a number of hydrogeologic characteristics, as follows:

- The injection zone's geometry and hydraulic characteristics allow liquid waste to be injected at a pressure lower than that which would cause fracturing of the rocks;
- The injection zone is regionally extensive so that liquid waste can be stored with minimal, if any, impact on underground sources of drinking water;
- The injection zone is underlain and overlain by confining beds that retard upward and downward movement of native water and liquid waste;
- The injection zone and confining beds have mappable and geologically simple shapes that are not complicated by folds or crossed by hydraulically open faults.
- The injection zone contains native water that has dissolved-solids concentration equal to or greater than 10,000 mg/L (milligrams per liter). Injection of waste into an aquifer containing water having a dissolved-solids concentration of less than 10,000 mg/L is sometimes allowable, providing that the waste is highly treated or the aquifer is exempted following procedures spelled out in Federal or State regulations;
- Liquid waste chemistry is sufficiently compatible with the chemical composition of the rocks and native water to prevent or limit reactions that damage well components

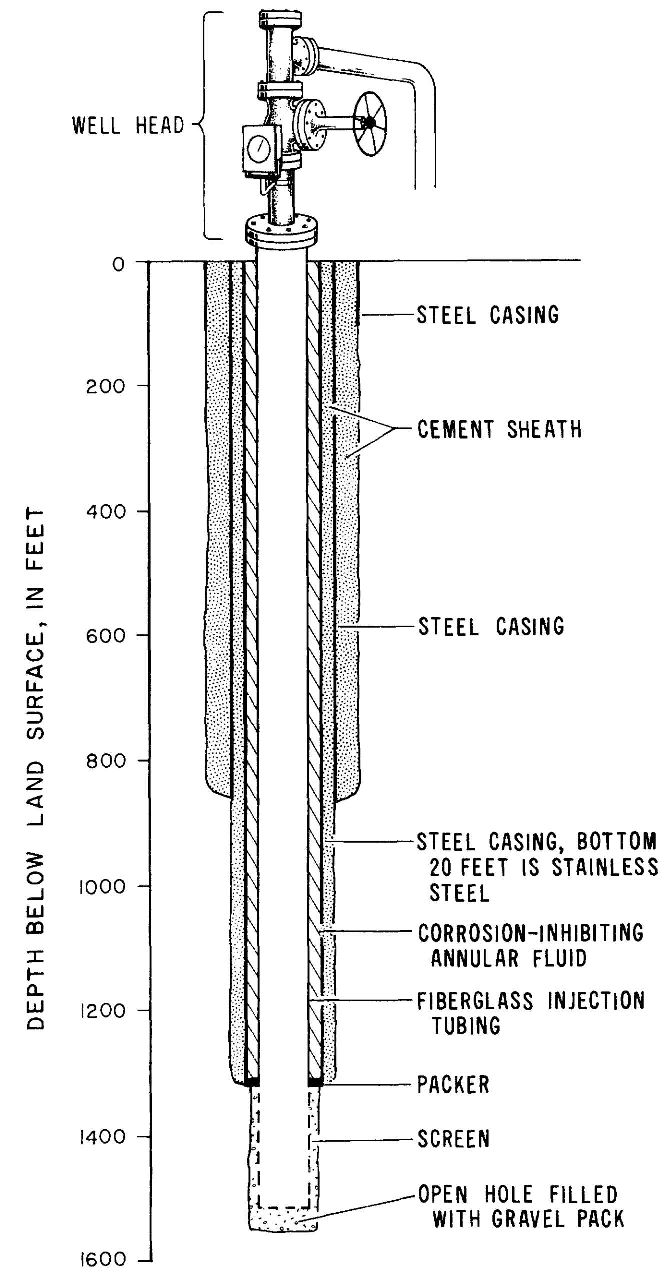

Figure 3. Typical well designed for injection of corrosive waste into an unconsolidated formation.

by corrosion, plug the injection zone, weaken the structural integrity of the rocks, or create toxic substances.

- Mineral and petroleum resources are absent from the injection zone so as not to constrain their development; and
- The injection zone and confining beds are not penetrated by improperly abandoned wells or test holes that could provide pathways to underground sources of drinking water or to mineral and petroleum resources.

The possible consequences of subsurface injection at a site that lacks some of these hydrogeologic characteristics are shown in figure 4.

Assessment of the regional and local hydrogeology of a proposed injection site is needed to evaluate the site's suitability for subsurface injection. A regional assessment by the prospective injector is a preliminary step. If the regional assessment reveals that injection may be feasible, a local assessment in the immediate vicinity of the proposed injection site is performed.

Regional Hydrogeologic Assessment

A regional assessment provides an overview of the hydrogeologic characteristics of the proposed site and the surrounding region. It typically makes use of available information, including information from other geographic areas that have rock types similar to those found at the proposed site. Figure 5 shows a hydrogeologist studying a geologic map as part of an effort to determine the regional extent of a potential injection zone.

A regional assessment commonly consists of the following:

- Preliminary identification of potential injection zones and confining beds and their probable lateral extent;
- Probable presence or absence of complicating folds or faults at the proposed injection site and in the region;
- Probable areal and vertical distribution of dissolved-solids concentrations of native water in the rocks;
- Location of known underground sources of drinking water;
- Location of known mineral and petroleum resources;
- Location of abandoned wells and test holes in the region surrounding the proposed injection site; and
- Qualitative evaluation of the probable regional impact of subsurface injection.

Local Hydrogeologic Assessment

A local assessment is an evaluation of the impact of injection in the vicinity of a proposed injection site. Data from drilling and hydrologic testing at the site are used to evaluate the specific hydrogeologic characteristics of the site. A well-drilling rig in the process of boring a hole at a proposed injection site is shown in figure 6. Examples of some of the lithologic, geophysical, and hydraulic data that are commonly collected in a drilled borehole are shown in figure 7.

A local hydrogeological assessment commonly consists of the following:

- Delineation and description of the injection zone, confining beds, and underground sources of drinking water;

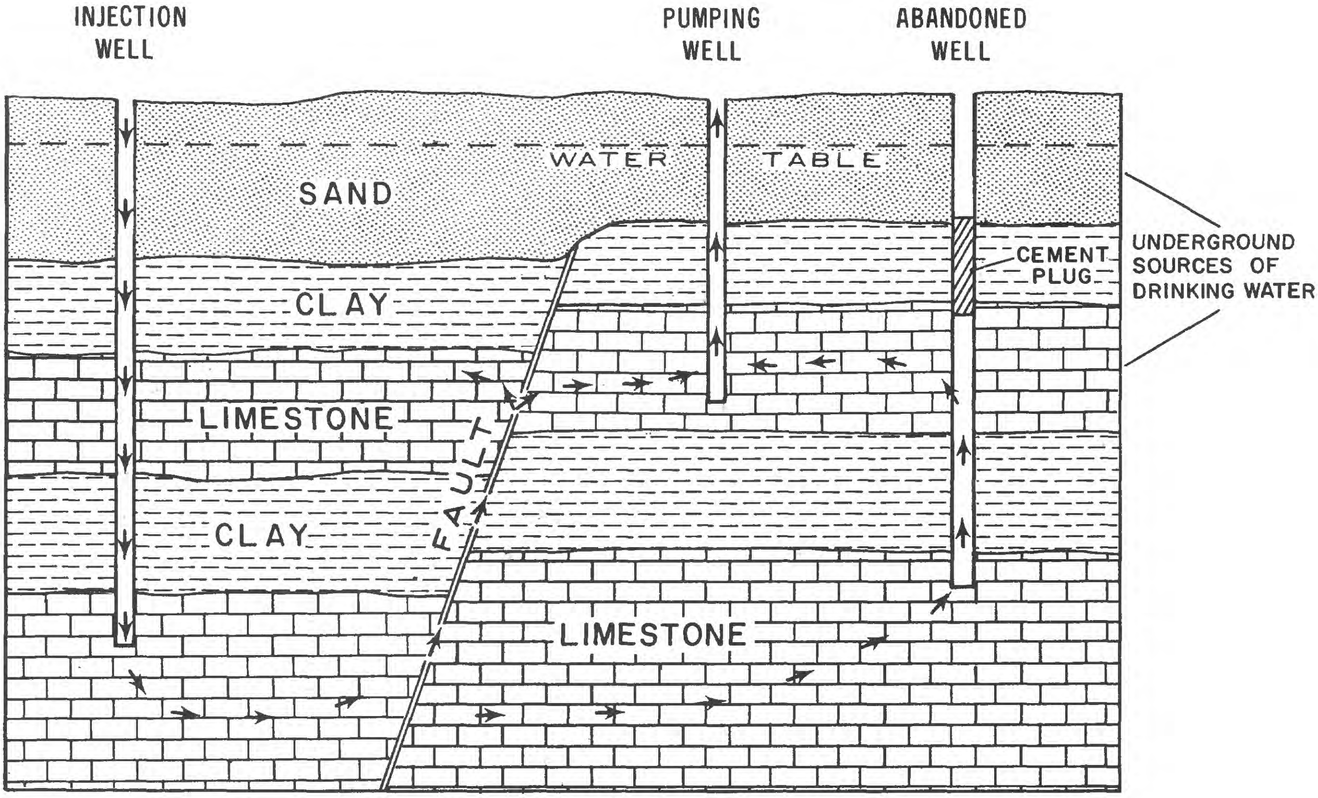

Figure 4. Possible consequences of subsurface injection at a site not having the necessary hydrogeologic characteristics.

Figure 5. Hydrogeologist studying a geologic map as one step in assessing the regional extent of a potential injection zone.

- •Determination of chemical compatibility of the liquid waste with rocks and native water in the injection zone;
- •Determination of the hydraulic characteristics of the injection zone and confining beds;
- •Demonstration of the injection zone's capability to accept liquid waste at the desired rate;
- •Estimation of pressure and water-quality changes likely to occur because of long-term injection; and
- •Specification of a monitoring program for long-term observation of the impact of injection on the subsurface.

Monitoring

Monitoring of subsurface injection of liquid waste generally consists of measuring and recording the effects of injection at the injection well and the surrounding observation wells. Injection rate, wellhead pressure, annulus pressure (if pertinent), and waste properties are monitored at an injection well. Pressure and water properties are monitored at observation wells at various distances from the injection well.

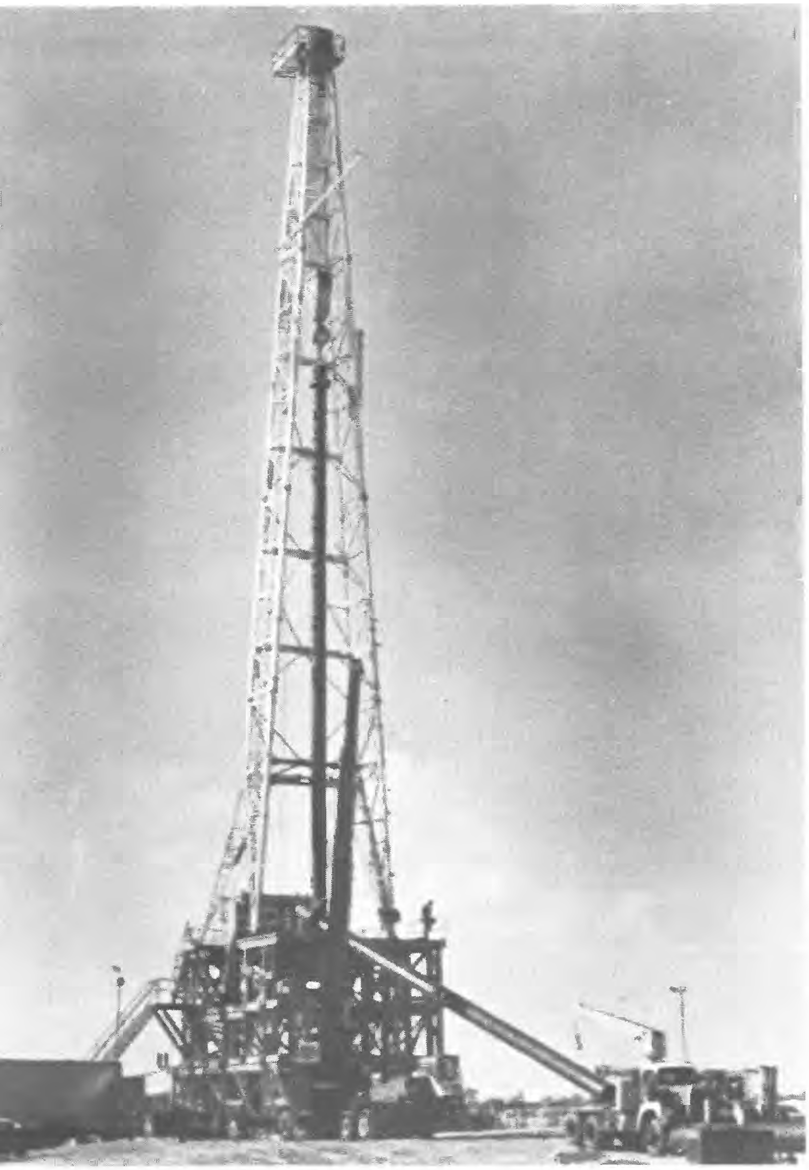

Figure 6. Drilling rig at a proposed injection site. Photograph courtesy of Vincent P. Amy, Geraghty and Miller, Inc.

These data can be used to assess the injection well's performance and the environmental impact of subsurface injection. Common surface features of the wellhead component of an injection well are shown in figure 8.

On the basis of their distance from an injection well, observation wells can be classifed as onsite, satellite, or regional (Vecchioli, 1979). Onsite wells are generally within tens of feet from an injection well and are used to monitor vertical migration of waste or displaced saline formation water. Satellite wells monitor the injection zone at distances of hundreds to several thousands of feet from an injection well and are used to monitor: (1) hydraulic response of the aquifer to individual injection systems, (2) position and direction of movement of waste, and (3) alterations in the chemical and physical quality of the waste. Regional wells monitor the injection zone at distances of miles from an injection well and are used to record the effects of injection wells on the ground-water flow system, such as on the position of distant saltwater-freshwater interfaces. Figure 9 is a schematic diagram of observation wells installed at several distances from an injection well to measure hydraulic and chemical changes.

Migration of injected waste from the point of injection involves flow of native water that commonly has a density different from the waste. Under these variable-density circumstances, pressure is the appropriate physical quantity to measure to determine flow directions. In addition to the pressure data, chemical concentration of water from observation wells is used to assess the impact of injection on underground sources of drinking water.

Monitoring requirements vary depending on the class of injection well; in some instances, they also can vary from State to State for the same class of well. (Classification of injection wells is discussed in the following section.) For example, Florida regulations allow for requiring observation wells in the vicinity of a class I injection well, whereas Texas regulations have no such allowance. Both States require that operation of a class I injection well be monitored.

SUBSURFACE INJECTION IN THE UNITED STATES

The first large-scale use of subsurface injection for the disposal of liquid wastes in the United States was by the petroleum industry in the 1930's. Brine produced with oil was injected back into the subsurface instead of discharged onto the land surface. Since the 1930's, the petroleum industry has added injection wells for secondary and enhanced recovery of oil to an increasing number of brine-disposal wells.

In contrast to the half-century-old practice in the petroleum industry, injection wells for disposal of industrial and municipal wastes have been employed mainly within the last few decades. However, once begun, their use grew rapidly.

The five classes of injection wells defined by the U.S. Environmental Protection Agency (EPA) are given in table 1. Class I wells are used for disposal of industrial or municipal waste beneath a formation that contains, within one-quarter mile, an underground source of drinking water. Class II wells are used by the petroleum industry. Class III wells are used during the process of extracting minerals or energy from the subsurface. Class IV wells are used for disposal of hazardous or radioactive wastes into or above a formation that contains, within one-quarter mile, an underground source of drinking water. Class V wells are those wells not included in the other classes.

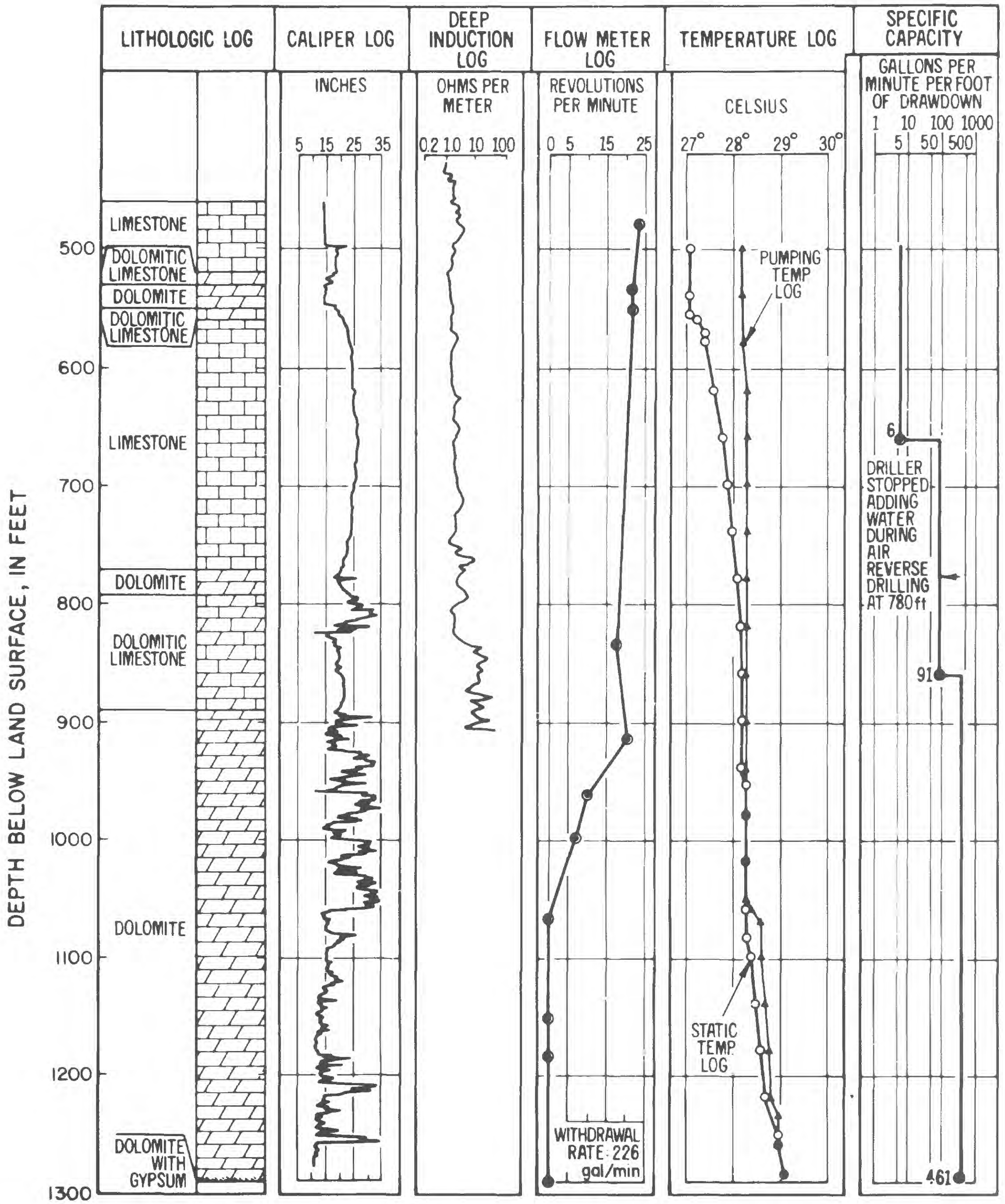

Figure 7. Examples of lithologic, geophysical, and hydraulic data that are collected in a drilled hole. (From Hickey and Barr, 1979, p. 16.)

Figure 8. Surface features of an injection well.

The EPA maintains a record of the number of injection wells by class in each State based on information reported to EPA by the States. A "Condensed Summary Report" from the EPA's Federal Underground Injection Control Reporting System, June 21, 1983, is given in table 2. At that time, Texas had the most class I, class II, and class III injection wells; New York, the most class IV injection wells; and Massachusetts, the most class V injection wells.

There were more than 222,000 injection wells in the United States in 1983 (table 2). Class II wells, used by the petroleum industry, made up more than 60 percent of these wells. The distribution of recorded injection wells throughout the country is shown by state in figure 10 and by class in figure 11.

Federal regulation of subsurface injection has evolved over the last two decades. Increased disposal of industrial and municipal wastewaters by subsurface injection during the 1960's prompted the Federal Water Quality Administration (FWQA) to issue a Federal policy statement on wastewater injection. The policy stated that subsurface injection should be used as a waste-disposal method only as a last alternative—and then only with great caution and for a limited period of time. In 1973, after creation of the EPA (in 1970) and absorption of the FWQA, EPA issued a policy statement on subsurface emplacement of fluids by well injection that was similar to the FWQA policy. In the EPA policy, subsurface injection was also viewed as a temporary practice until new technology to treat the waste became available.

In response to the general concern with ensuring the safety of drinking water in the United States, Congress in 1974 enacted the Safe Drinking Water Act, Public Law 93-523. Protection of underground sources of drinking water from damage by subsurface injection of liquids was dealt with in detail in part C of the Act. In 1977, part C was amended by Public Law 95-190. Through the Safe Drinking Water Act, Congress assigned responsibility for developing regulations for underground injection control to the EPA. These regulations were published in the Federal Register on May 19 and June 24, 1980, and were amended and republished in the Federal Register on April 1, 1983. The regulations allow a State to accept primary enforcement responsibility for an underground injection control program providing that the State's program contains regulations at least as stringent as the Federal regulations. By mid-1983, 13 states (table 3) had accepted primary enforcement responsibility for some or all of the five classes of injection wells. Identification of States with enforcement responsibility will be made during 1984. EPA is required by the Safe Drinking Water Act to propose, promulgate, and enforce an underground injection control

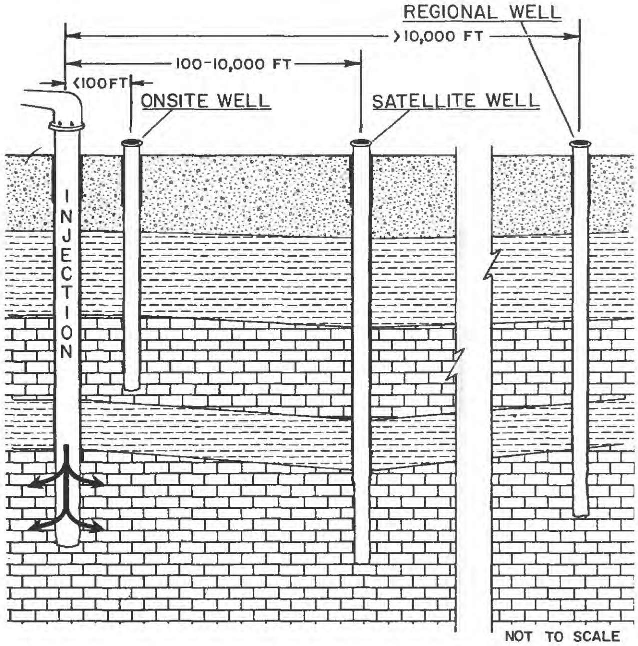

Figure 9. Observation wells around an injection well. (Modified from Vecchioli, 1981.

Table 1. Classification of injection wells
[Source: U.S. Environmental Protection Agency, 1980b, p. 42502–42503]

Class I	1. Wells used by generators of hazardous wastes or owners or operators of hazardous waste management facilities to inject hazardous waste, other than class IV wells. 2. Other industrial and municipal disposal wells which inject fluids beneath the lowermost formation containing, within one-quarter mile of the well bore, an underground source of drinking water.
Class II	Wells which inject fluids: 1. Which are brought to the surface in connection with conventional oil or natural gas production; 2. For enhanced recovery of oil or natural gas; and 3. For storage of hydrocarbons which are liquid at standard temperature and pressure.
Class III	Wells which inject for extraction of minerals or energy, including: 1. Mining of sulfur by the Frasch process; 2. Solution mining of minerals; *Note.*—Solution mining of minerals includes sodium chloride, potash, phosphate, copper, uranium, and any other mineral which can be mined by this process. 3. In situ combustion of fossil fuel; and *Note.*—Fossil fuels include coal, tar sands, oil shale, and any other fossil fuel which can be mined by this process. 4. Recovery of geothermal energy to produce electric power. *Note.*—Class III wells include the recovery of geothermal energy to produce electric power, but do not include wells used in heating or aquaculture, which fall under class V.
Class IV	Wells used by generators of hazardous wastes or of radioactive wastes, by owners or operators of hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to dispose of hazardous wastes or radioactive wastes into or above a formation which within one-quarter mile of the well contains an underground source of drinking water.
Class V	Injection wells not included in classes I, II, III, or IV. *Note.*—Class V wells include: 1. Air conditioning return flow wells used to return to the supply aquifer the water used for heating or cooling in a heat pump; 2. Cesspools or other devices that receive wastes, which have an open bottom and sometimes have perforated sides. The Underground Injection Control (UIC) requirements do not apply to single family residential cesspools; 3. Cooling water return flow wells used to inject water previously used for cooling; 4. Drainage wells used to drain surface fluid, primarily storm runoff, into a subsurface formation; 5. Dry wells used for the injection of wastes into a subsurface formation; 6. Recharge wells used to replenish the water in an aquifer; 7. Saltwater intrusion barrier wells used to inject water into a freshwater aquifer to prevent the intrusion of saltwater into the freshwater; 8. Sand backfill wells used to inject a mixture of water and sand, mill tailings, or other solids into mined-out portions of subsurface mines; 9. Septic system wells used: To inject the waste or effluent from a multiple dwelling, business establishment, community, or regional business establishment septic tank; or For a multiple dwelling, community, or regional cesspool. The UIC requirements do not apply to single family residential waste disposal systems; 10. Subsidence control wells (not used for the purpose of oil or natural gas production) used to inject fluids into a non-oil- or non-gas-producing zone to reduce or eliminate subsidence associated with the overdraft of freshwater; 11. Wells used for the storage of hydrocarbons which are gases at standard temperature and pressure; 12. Geothermal wells used in heating and aquaculture; and 13. Nuclear disposal wells.

Table 2. National distribution of injection wells
[Source: U.S. Environmental Protection Agency Federal Underground Injection Control Reporting System, June 21, 1983]

Region	State	All wells	Class I wells	Class II wells	Class III wells	Class IV wells	Class V wells
01	Connecticut	173	9	--	--	7	157
	Massachusetts	18,252	--	--	--	--	18,252
	Maine	18	--	--	--	--	18
	New Hampshire	27	--	--	--	--	27
	Rhode Island	42	--	--	--	--	42
	Vermont	1	--	--	--	--	1
02	New Jersey	1,327	--	--	--	--	1,327
	New York	6,348	11	3,853	149	184	2,151
03	Delaware	3	--	--	--	--	3
	Maryland	968	--	--	--	3	965
	Pennsylvania	8,760	5	4,607	--	31	4,117
	Virginia	1,676	--	1	--	3	1,672
	West Virginia	2,034	7	319	17	--	1,691
04	Alabama	169	8	152	9	--	--
	Florida[1]	7,075	52	80	3	3	6,937
	Georgia	4	--	--	--	--	4
	Kentucky	4,642	--	4,357	--	--	285
	Mississippi	1,348	7	1,223	--	--	118
	North Carolina	33	3	--	--	3	27
	South Carolina	63	--	--	--	30	33
	Tennessee	57	--	13	--	11	33
05	Illinois	18,503	10	18,493	--	--	--
	Indiana	3,669	76	3,565	--	--	28
	Michigan	4,207	97	1,275	110	--	2,725
	Minnesota	19	--	--	--	--	19
	Ohio	6,417	--	3,601	2	--	2,814
06	Arkansas	871	23	808	--	--	40
	Louisiana	4,544	80	4,249	215	--	--
	Oklahoma	11,291	13	11,278	--	--	--
	Texas	65,470	129	41,859	23,124	--	358
	Indian lands within the region	3,300	--	3,300	--	--	--
07	Iowa	14	--	--	--	--	14
	Kansas	16,298	57	15,175	394	--	672
	Missouri	223	--	223	--	--	--
	Nebraska	1,983	--	1,983	--	--	--
08	Colorado	1,069	1	1,001	59	2	6
	Montana	1,448	--	1,447	--	--	1
	North Dakota	434	1	429	4	--	--
	South Dakota	8	--	8	--	--	--
	Utah	541	--	504	30	--	7
	Wyoming	4,924	--	4,016	898	--	10
09	Arizona	509	--	3	484	5	17
	California	13,844	--	13,844	--	--	--
	Guam	136	--	--	--	--	136
	Indian lands within the region	519	--	518	--	--	1
10	Alaska	164	--	160	--	1	3
	Idaho	581	--	--	--	1	580
	Oregon	712	--	--	--	--	712
	Washington	5,640	1	--	--	10	5,629
	Total	220,358	590	142,344	25,498	294	51,632

[1]Number of wells in Florida adjusted to reflect a more recent Florida Department of Environmental Regulation inventory of injection wells.

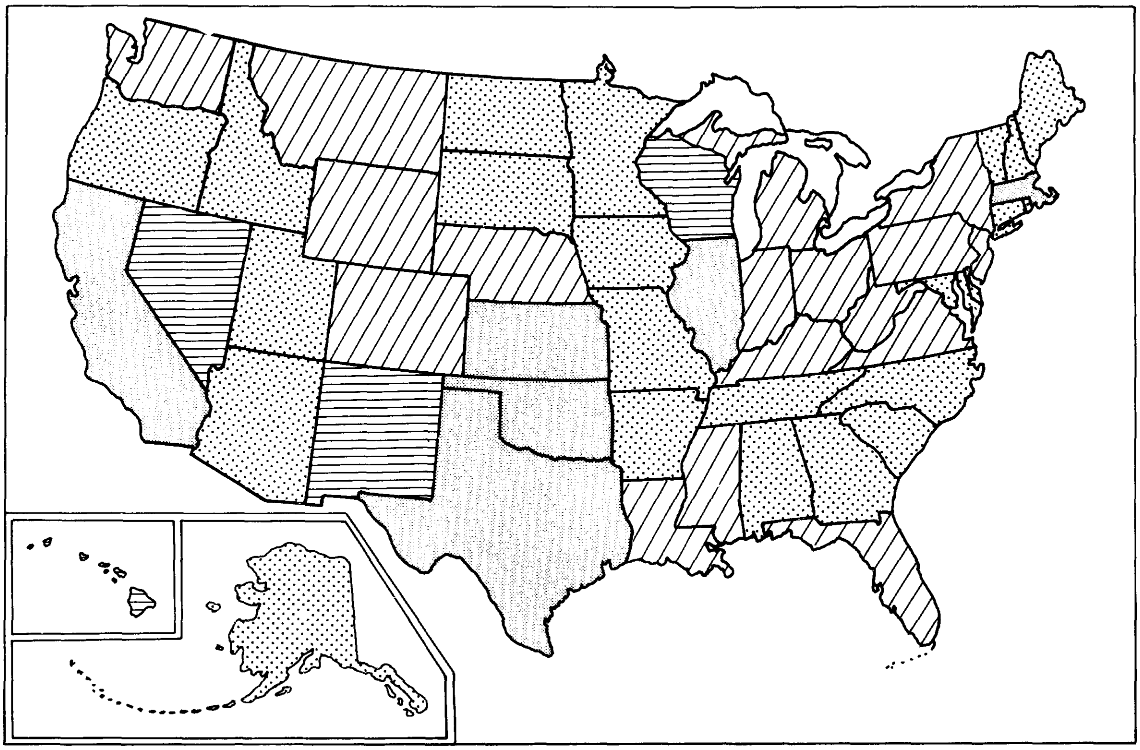

Figure 10. Distribution of injection wells in the United States. (Source: U.S. Environmental Protection Agency Federal Underground Injection Control Reporting System, June 21, 1983.)

program for all injection wells within those States that do not accept primary enforcement responsibility.

SUBSURFACE INJECTION IN FLORIDA

Subsurface injection has been practiced in Florida for about 80 years. Its history ranges from early uncontrolled use of gravity injection wells for disposal of various types of waste to present-day State-regulated use of all classes of injection wells. Selected highlights of the practice of subsurface injection in Florida are discussed in the following sections.

History

Subsurface injection in Florida started in earnest when a gravity injection well was drilled in 1904 to accept drain water from a flooded area in the city of Orlando. Flooding had occurred when a sinkhole that had been draining stormwater became plugged. Soon after that well was constructed, gravity wells were installed throughout central and south Florida for surface-water drainage and for disposal of municipal sewage and industrial waste. Gravity wells were generally terminated in freshwater aquifers at depths ranging from about 100 to 1,000 ft below land surface. Permitting of specific injection wells by the State Board of Health began in the late 1930's. Currently, surface-water drainage wells are one of several types of class V injection wells permitted.

In the early 1940's, oil was discovered in south Florida, and in the late 1960's, in north Florida. Saltwater is produced with oil pumped from both parts of the State. Subsurface injection of the saltwater was reported by the Florida Department of Natural Resources (FDNR) in 1966 to have started as soon as oil production began. In south Florida, saltwater is injected under pressure in class

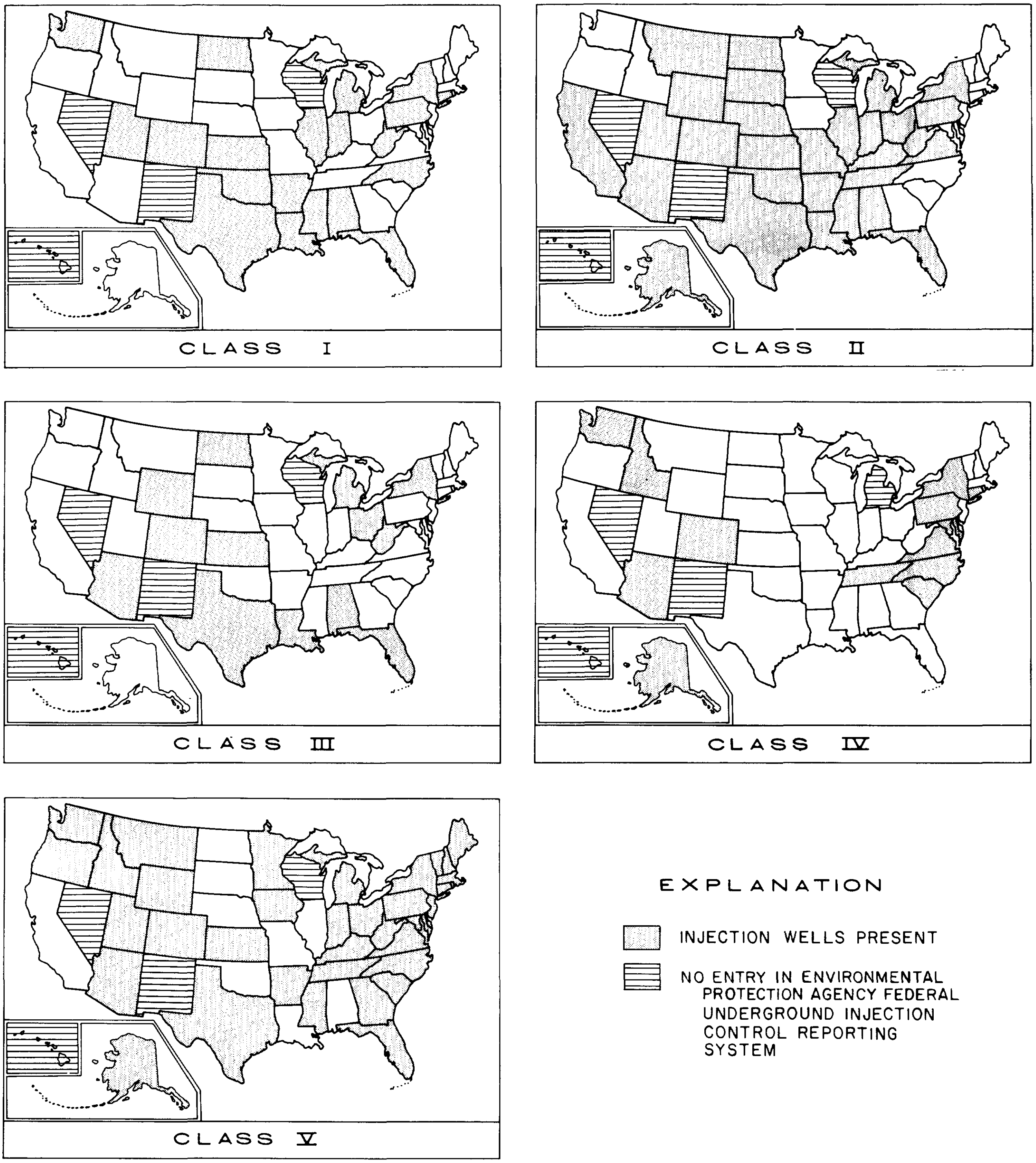

Figure 11. Distribution of injection wells in the United States, by class. (Source: U.S. Environmental Protection Agency Federal Underground Injection Control Reporting System, June 21, 1983.)

Table 3. States that had accepted primary enforcement responsibility for an underground injection control program as of mid-1983

[Philip Tate, Special Assistant, Office of Drinking Water, U.S. Environmental Protection Agency, Washington, D.C., oral commun., 1983]

State	Class of well in State Underground Injection Control Program				
	I	II	III	IV	V
Alabama		X			
Arkansas	X		X	X	X
California		X			
Florida	X		X	X	X
Louisiana	X	X	X	X	X
Massachusetts	X	X	X	X	X
Nebraska		X			
New Hampshire	X	X	X	X	X
New Mexico		X			
Oklahoma	X	X	X	X	X
Texas	X	X	X	X	X
Utah	X	X	X	X	X
Wyoming		X			

II wells to depths ranging from about 2,000 to 4,000 ft below land surface. In north Florida, saltwater is injected to depths ranging from about 6,000 to 10,000 ft. In both parts of the State, saltwater is injected into zones that are above the oil-producing horizons. In addition to saltwater injection, class II wells are used to emplace various fluids in oil-bearing zones to improve oil recovery. Pressure injection wells have been in operation for this purpose since the late 1960's.

The first use of a pressure well for subsurface injection of treated sewage into saline water in Florida occurred in 1959 in Broward County in south Florida. This injection well was constructed to a depth of about 1,200 ft at a subdivision waste-treatment plant. A second injection well was constructed at the site in 1970, and both were operated until 1975.

Construction of the Broward County well marked a major change in the practice of subsurface injection in Florida. Prior to 1959, most injection wells depended on gravity to force waste liquids into receiving zones. Therefore, injection wells were located only in central and south Florida, where ground-water levels in aquifers were generally below land surface. With the advent of the Broward County well, it became apparent that liquid waste could be injected under pressure throughout the State wherever hydrogeologic and water-quality conditions were appropriate.

The first use of a pressure well for subsurface injection of industrial waste into saline water occurred in 1963 in northwest Florida. This class I well was constructed to a depth of about 1,800 ft at a nylon manufacturing plant in Escambia County. A second class I well was constructed at this site in 1965 to a depth of about 1,700 ft, and a third well was constructed in 1982 to a similar depth.

One of the most permeable rock masses in the world underlies south Florida, and in 1971 it was first used as a receiving zone for treated sewage. A class I injection well, open to this zone, was constructed to a depth of about 3,000 ft at a waste-treatment plant in Dade County. Oil industry drillers had previously identified this rock mass at other places in south Florida and called it the "boulder zone." Since 1971, most class I wells in south Florida have used this permeable zone.

The first pressure wells for subsurface injection of municipal sewage into saline water in west-central Florida started operation in 1979. These class I wells are in the city of St. Petersburg and were constructed to depths ranging from about 900 to 1,100 ft. Spray irrigation is the city's principal means of disposal of the sewage effluent. The injection wells are used only for effluent that remains after spray irrigation demands are met.

A tabulation of injection wells in Florida was completed in 1981 by the Florida Department of Environmental Regulation (FDER). Results of the tabulation were published (Florida Department of Environmental Regulation, 1982) in a document submitted to the EPA as part of Florida's application for primary enforcement responsibility for subsurface injection. The 1981 tabulation reported 52 class I injection wells, 80 class II injection wells, 3 class III injection wells, 3 class IV injection wells, and 6,931 class V injection wells. About 50 percent of the class V wells were used with air-conditioning systems.

Nine of the 67 counties in Florida had class I injection wells in 1981 (fig. 12). The number of class I wells had grown from 1 in 1959 to 7 in 1972 and to 52 in 1981. Most growth in the 1970's was in Dade, Broward, and Palm Beach Counties in south Florida and in Pinellas County in west-central Florida. Records of injection rates for class I wells are generally available from FDER.

Five counties in Florida had class II injection wells in 1981 (fig. 12). The number of class II wells has grown since the late 1960's, mainly in Escambia and Santa Rosa Counties in northwest Florida. Records of injection rates for class II wells also are generally available from FDNR.

Only one county had class III injection wells in 1981. St. Johns County in northeast Florida had three class III wells that were being used for experimental slurry mining of phosphate ore.

Three counties, Broward, Dade, and Pinellas, had class IV injection wells in 1981. The wells are no longer in operation, but had been used for disposal of electroplating waste.

Forty-two counties in Florida had class V injection wells in 1981 (fig. 13). Twenty-three of these counties had wells that were used for draining surface water or for draining ground water from the surficial aquifer in

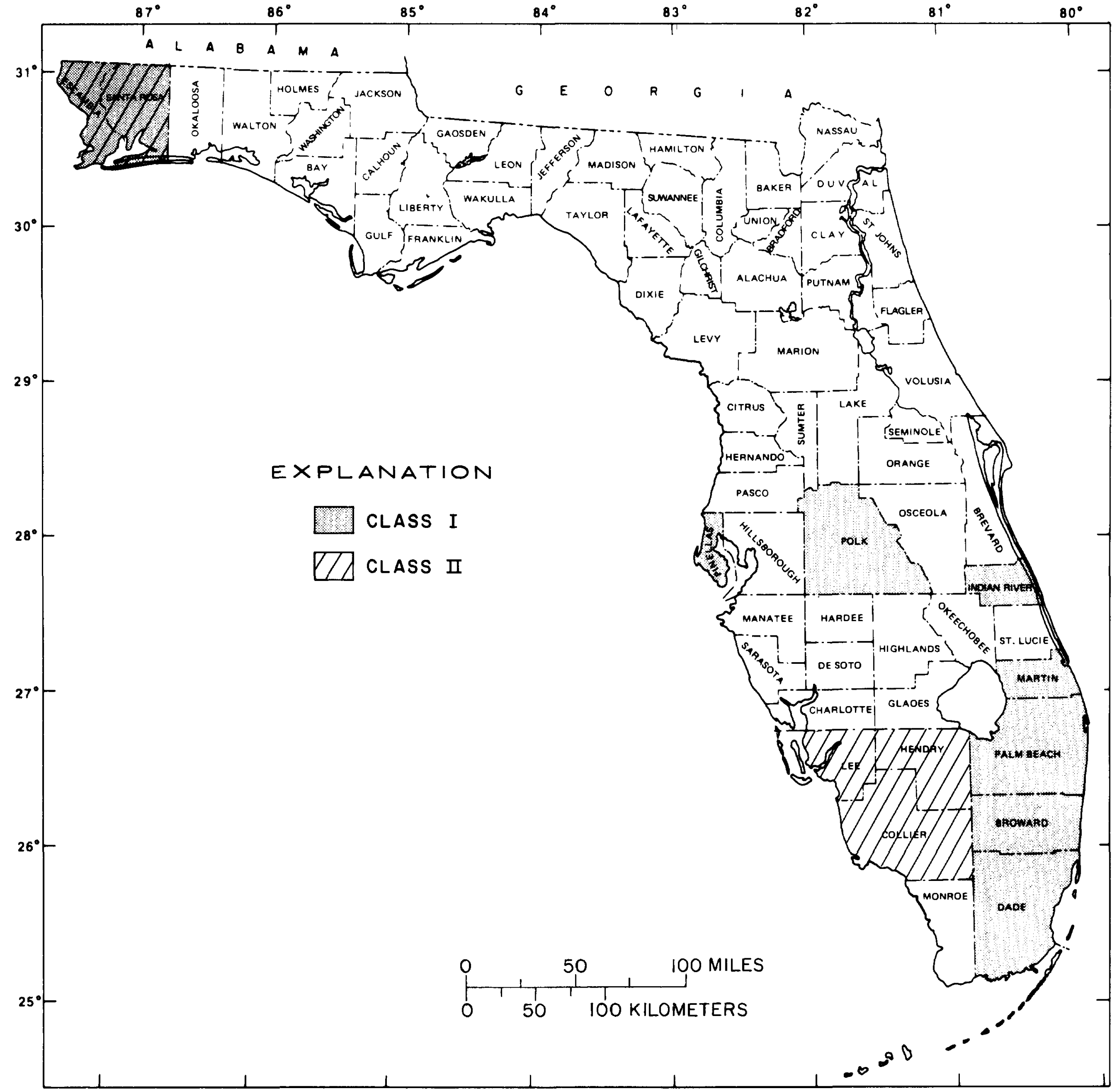

Figure 12. Florida counties having class I or class II injection wells in 1981.

phosphate mining districts. Records of injection rates for class V wells are generally unavailable.

Regulation

In 1913, the Florida Legislature enacted a law that required State permission before surface water or sewage could be drained into underground water through a cavity, sink, or driven or drilled well. The State Board of Health (now called the Division of Health) was designated the permitting agency. The first well permit, for gravity drainage of storm runoff, was issued on April 2, 1937, to the city of Orlando's Superintendent of Public Works.

The State formally adopted administrative rules in the early 1970's to regulate the drilling and use of drainage wells. These regulations resulted from enactment of the Florida Air and Water Pollution Control Act of 1967. In this law, as amended in the early 1970's, the

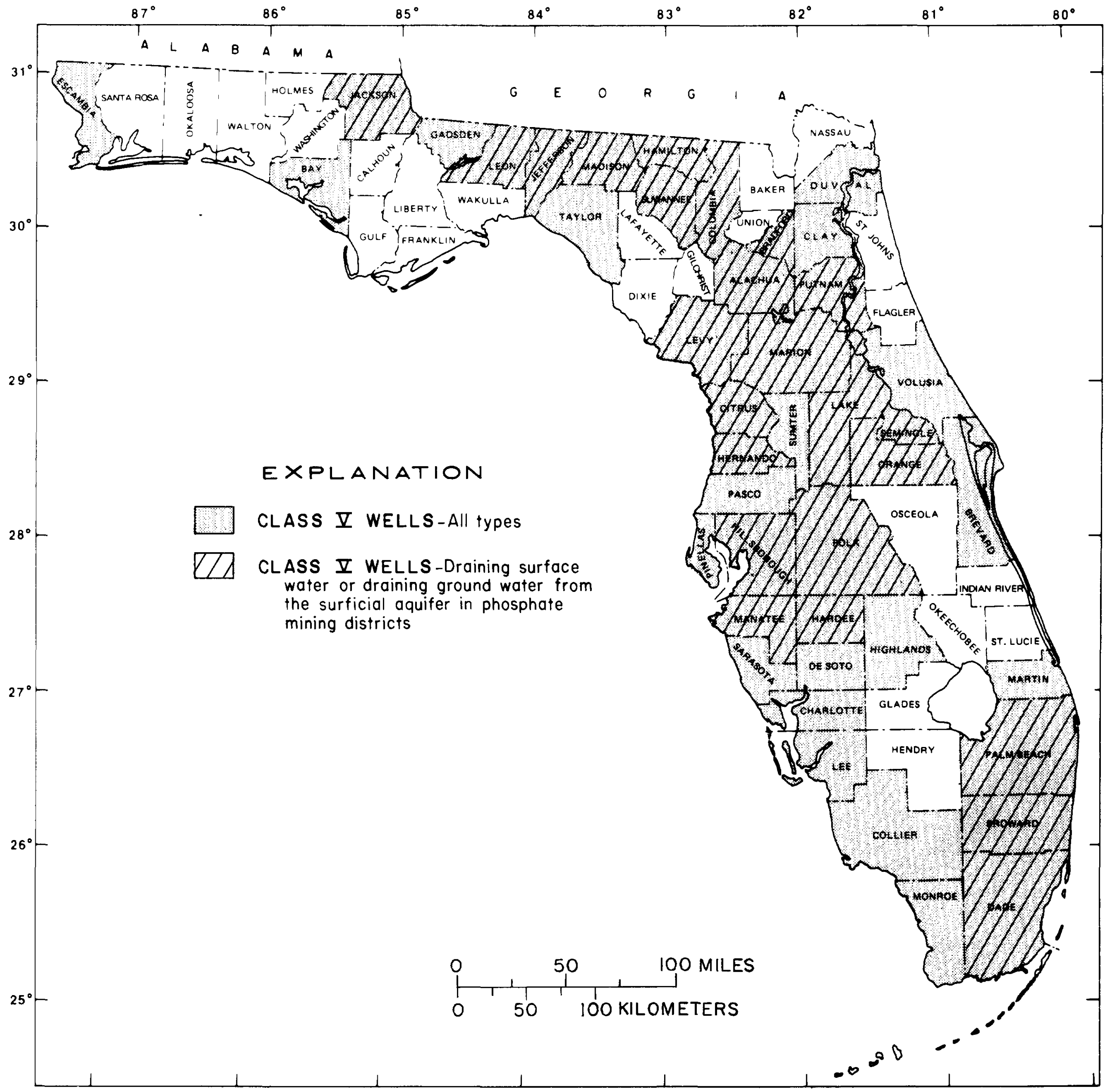

Figure 13. Florida counties having class V injection wells in 1981.

Florida Department of Environmental Regulation was charged with governing the use of drainage wells.

Florida adopted additional and more inclusive administrative rules for underground injection control in 1982. these rules covered class I, III, IV, and V wells and were similar to those formulated by the EPA in 1980. Adoption of the rules was part of the process of Florida's acceptance of primary enforcement responsibility from the EPA. The rules adopted in 1982 govern construction and mechanical integrity of injection and monitor wells, amount and types of hydrogeologic information needed to assess probable impact of injection on underground sources of drinking water, type and frequency of operating and monitoring data and procedures for reporting these data to FDER, and procedures for plugging and abandoning injection and monitor wells.

The process of developing formal rules to control underground injection in Florida began in 1980 by formation of a statewide advisory panel composed of governmental and nongovernmental representatives.

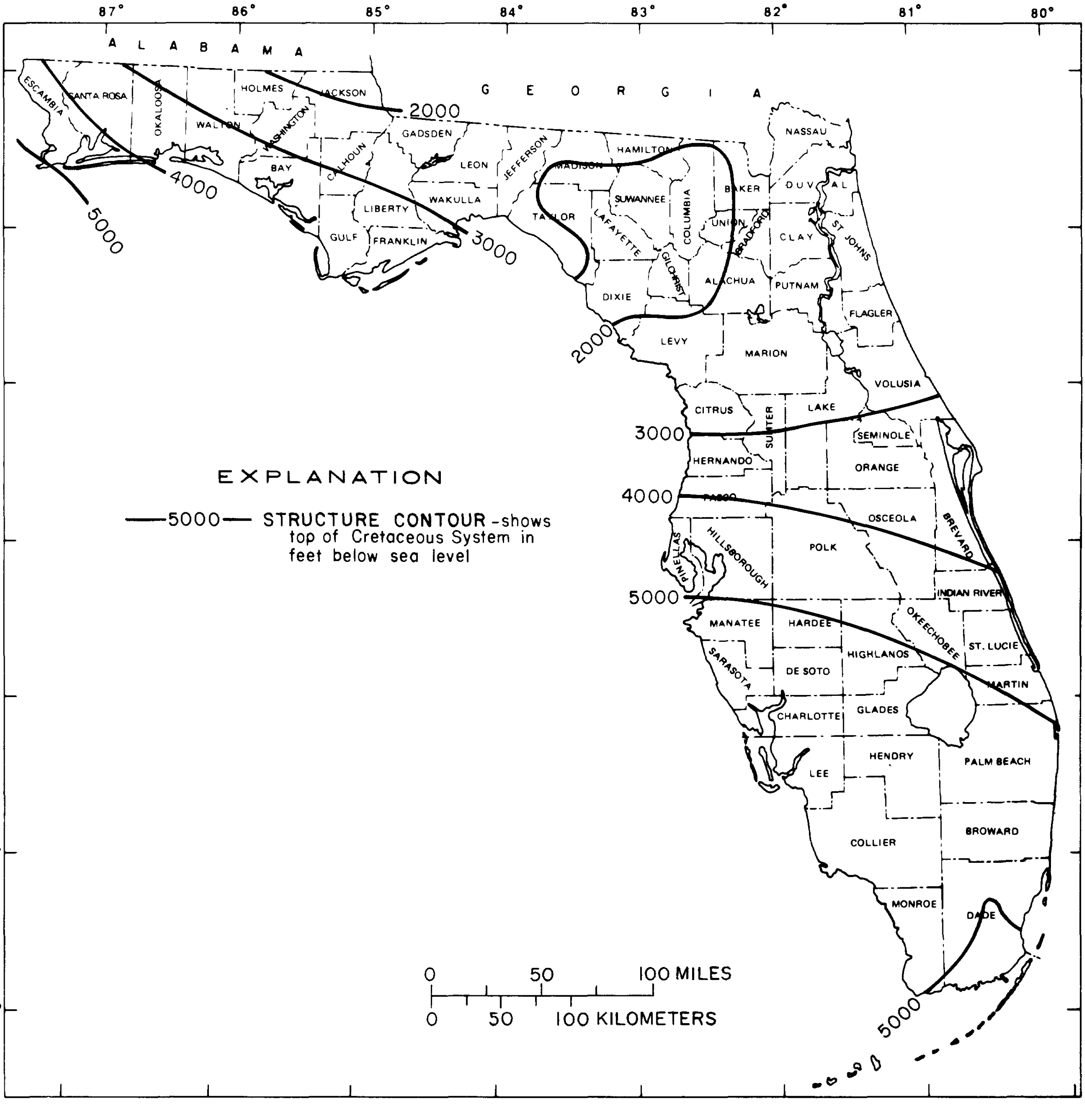

Figure 14. Altitude of top of Cretaceous System in Florida. (Modified from Puri and Vernon, 1964, p. 5, fig. 3.)

Members of the panel were recognized experts in the technology of subsurface injection and hydrogeology of Florida and were drawn from the well-construction industry, consulting engineering and hydrogeologic firms, water management districts, the U.S. Geological Survey, the University of Florida, the EPA, the FDNR, and the FDER. After the advisory panel finished a draft of the rules in 1981 (having participated in one workshop and two public hearings), the FDER guided the draft rules through the State rule-making process. Rules controlling underground injection became effective as chapter 17-28 of the Florida Administrative Code on April 1, 1982, and were amended almost immediately, on August 30, 1982. This was about 45 years after the first injection-well permit was issued and about 78 years after construction of the first documented injection well in Orlando, Fla.

A number of refinements to the EPA rules were made and incorporated into the Florida rules to adapt them to the hydrogeologic framework of Florida. For example, Federal rules allow class IV wells but Florida rules ban them. Federal rules deferred consideration of class V wells to a future date, whereas Florida rules allow class V wells but require a permit for construction and operation. Probably the most important refinement was the requirement to have a Technical Advisory Committee review and comment on class I and class III injection-well applications. Members of the committee are drawn from the water management districts, the EPA, the Survey, and the FDER.

Hydrogeology of Injection Sites

Florida is the emerged part of the Floridan Plateau, a prominent projection of the North American Continent. The Floridan Plateau is underlain by a thick sequence of Cretaceous System to Quaternary System sediments lying upon basement rock. The altitude of the top of the Cretaceous System, shown in figure 14, ranges throughout the State from about 2,000 to 5,000 ft below sea level. With the exception of class II wells used by the oil industry, subsurface injection of liquid waste in Florida is generally into rocks that lie above the Cretaceous System.

Generalized lithology of the rocks overlying the Cretaceous System is shown in table 4. Dolomite and limestone predominate, and in some units these carbonate rocks are associated with either clastic sediments or anhydrite and gypsum. The Miocene to Holocene Series contain the clastic sediments in addition to carbonate rocks; the Paleocene to middle Eocene Series contain varying amounts of anhydrite and gypsum in addition to carbonate rocks.

For regional ground-water studies, the sedimentary rocks underlying Florida are generally arranged into four major hydrogeologic units. From top to bottom, the hydrogeologic units are (1) surficial aquifer, (2) intermediate aquifer or, if these rocks have no water-supply

Table 4. Sedimentary rocks underlying Florida
[Modified from Stringfield, 1966]

Erathem	System	Series		Generalized lithology
Cenozoic	Quaternary	Holocene and Pleistocene		Sand, clay, and limestone.
1.6 million years before present	Tertiary	Pliocene		Sand, clay, and phosphate.
		Miocene		Sand, clay, and limestone.
		Oligocene		Limestone.
		Eocene	Upper	Limestone.
			Middle[1]	Dolomite and limestone.
			Middle[1], Lower[1]	Dolomite and limestone with intergranular anhydrite and gypsum present in some areas.
66.4 million years before present		Paleocene[1]		Dolomite and limestone with beds of anhydrite.
Mesozoic	Cretaceous	Undifferentiated for this report.		

[1]In northwest Florida, sand and clay are present instead of dolomite and limestone.

potential, intermediate confining unit, (3) Floridan aquifer system, and (4) sub-Floridan confining unit. The surficial aquifer is composed of rocks that include all or part of the Pliocene to Holocene Series. The intermediate aquifer or intermediate confining unit is composed of rocks that include all or part of the Miocene to Pliocene Series. The Floridan aquifer system is the principal source of freshwater throughout Florida and is composed of rocks that include all or part of the Paleocene to Miocene Series. The sub-Floridan confining unit throughout most of Florida is composed of rocks that contain Paleocene anhydrite beds. In northwest Florida, the sub-Floridan confining bed is composed of rocks that contain Paleocene to middle Eocene clay beds.

The deeper parts of the Floridan aquifer system in southeast Florida contain saline water similar in composition to seawater. Saline water also occurs in the lower part of the Floridan aquifer system in the northwest part of the State and along most of the State's coastline. These saline parts of the Floridan aquifer system are considered candidate reservoirs for subsurface injection of liquid waste where other hydrogeologic characteristics are suitable.

In southeast Florida—Dade, Broward, and Palm Beach Counties—a lower Eocene dolomite whose top ranges in depth from about 2,500 to 3,000 ft below sea level serves as that region's injection zone. This zone, in the lowermost part of the Floridan aquifer system, is very transmissive and accepts liquid waste with very little pressure buildup. Saline water that has dissolved-solids concentrations similar to seawater occurs in the injection interval. Overlying this interval is about 500 to 1,000 ft of limestone and dolomite considered to have a permeability sufficiently low to retard vertical migration of injected waste. Water that has less than 10,000 mg/L of dissolved solids is generally found above these beds. Freshwater in southeast Florida is obtained from the surficial aquifer that extends to depths not exceeding 200 ft below sea level. A generalized hydrogeologic column for an injection site in Dade County is shown in figure 15.

In central Florida—Polk County—a lower Paleocene dolomite lying well below the Floridan aquifer system serves as the injection zone for the disposal of waste hydrochloric acid. The top of the injection zone is about 4,000 ft below sea level and the base corresponds approximately to the top of the Cretaceous System at about 4,400 ft below sea level. This injection zone has a relatively low transmissivity (Hickey and Wilson, 1982) in comparison with injection zones in the Floridan aquifer system. At the site, the Floridan aquifer contains freshwater throughout and, therefore, could not be used for injection. Saline water that has a dissolved-solids concentration about four times greater than seawater occurs in the injection interval. The injection interval is overlain by about 800 ft of alternating dolomite and anhydrite beds that have very low permeability. These beds make up the sub-Floridan confining unit and significantly restrict vertical migration of waste. Freshwater supplies are generally obtained in the vicinity of the injection site from depths of less than about 1,200 ft below sea level. A generalized hydrogeologic column for the injection site in Polk County is shown in figure 15.

In west-central Florida—Pinellas County—a middle Eocene dolomite whose top ranges from about 700 to 800 ft below sea level in the Floridan aquifer system serves as the injection zone for the disposal of treated sewage. This injection zone has a high transmissivity and generally accepts treated sewage with very little pressure buildup (Hickey, 1982). Saline water that has a dissolved-solids concentration similar to seawater occurs in the injection zone. Overlying this zone is about 400 ft of limestone of moderately low permeability that retards vertical migration of injected water. Even though water that has a dissolved-solids concentration of less than 10,000 mg/L occurs above these low-permeability beds, freshwater supplies for drinking purposes are not obtained in the vicinity of the injection sites in Pinellas County. Most of the county's water supply is imported from outside the county. A generalized hydrogeologic column for the injection site in Pinellas County is shown in figure 15.

In northwest Florida—Escambia and Santa Rosa Counties—an upper Eocene limestone whose top ranges from about 1,200 to 1,400 ft below sea level within the Floridan aquifer system serves as the injection zone for disposal of liquid industrial waste. In Escambia County, an acidic organic waste that results from the manufacture of nylon and other products is injected. In Santa Rosa County, an organic waste that results from the manufacture of acrylic fibers is injected. The injection zones at both sites have a relatively low transmissivity compared with injection zones in Pinellas and Dade Counties (Vecchioli, 1981). Saline water that has a dissolved-solids concentration of about two-fifths that of seawater occurs in the injection zone. Overlying this zone is about 200 ft of clay that has an extremely low permeability and greatly retards upward migration of injected waste. Freshwater supplies in Escambia and Santa Rosa Counties are obtained from the surficial aquifer which extends to depths of less than 300 ft below sea level. A generalized hydrogeologic column for the injection site in Santa Rosa County is shown in figure 15.

Effects of Injection

Generally, the potential effects of subsurface injection of wastes in Florida are: (1) pressure or water-level changes in the injection zone and overlying permeable

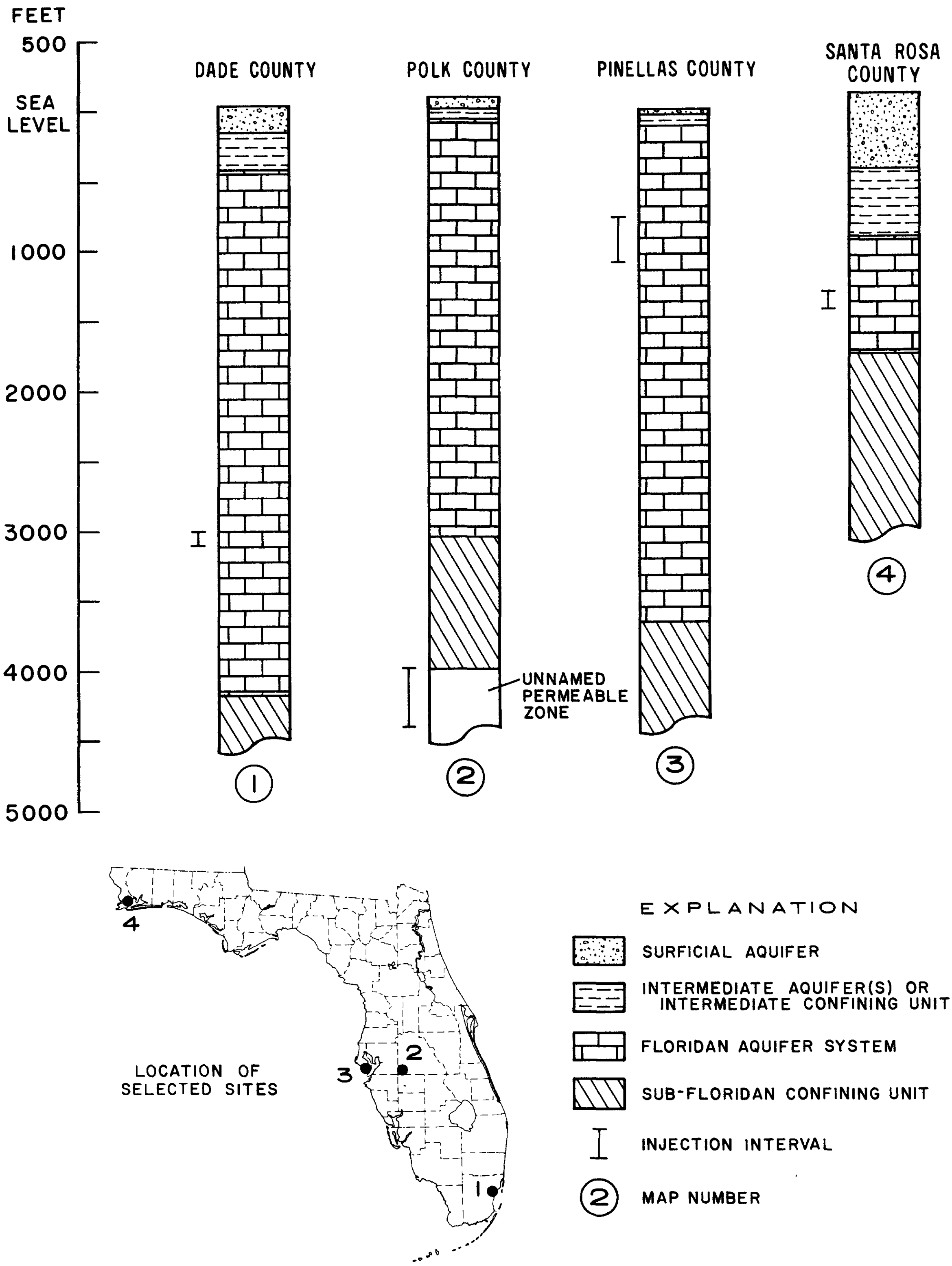

Figure 15. Generalized hydrogeologic columns for selected injection sites in Florida.

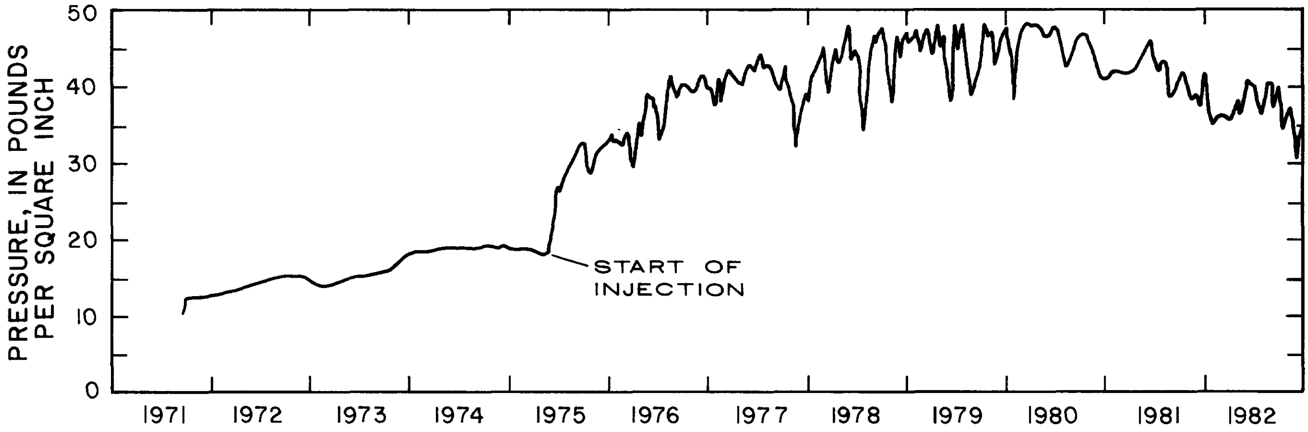

Figure 16. Pressure measured at land surface in an observation well 1,050 feet from the Santa Rosa County injection well. (Modified from Hull and Martin, 1982, p. 16.)

strata, (2) water-quality changes in the injection zone and overlying permeable strata, and (3) dissolution of the host rock. Class I wells are the most rigorously monitored, and, therefore, most information on the effects of injection deals with them. Examples of some effects caused by class I wells are described below.

Pressure Changes

As liquid waste is injected underground, pressure is increased in the injection zone depending on the rate of injection and the hydraulic properties of the injection zone. The pressure increase is greatest at the point of injection and diminishes radially from that point. Because injection rates and hydraulic properties of the host rocks vary widely, changes in pressure vary, as illustrated by the following two contrasting examples.

Injection of industrial liquid waste began in Santa Rosa County in mid-1975. Since then, the injection rate has been reported to vary little from a mean of about 0.8 Mgal/d. The ability of the injection zone to transmit water at this site is low compared with most other injection sites in Florida. The zone's low transmissivity—1,500 ft^2/d—is reflected by the substantial pressure increase from the start of injection (fig. 16) in an observation well 1,050 ft from the injection well.

In Pinellas County at St. Petersburg, treated sewage is injected into rocks that have a much higher transmissivity—1,000,000 ft^2/d—than at the Santa Rosa site. Even though the injection rate was more than four times greater, averaging about 3.5 Mgal/d during a yearlong test, pressure buildup (fig. 17) at a closer distance in a St. Petersburg observation well was just a fraction of that observed at the Santa Rosa County site.

Water-Quality Changes

Water-quality changes caused by class I injection wells involve mixing of the injected water with formation water and alteration of the injected waste as it resides in the subsurface. The following discussion illustrates examples of each.

The degree of mixing between injected waste and formation water can be monitored by observing changes in chloride concentration of water from nearby observation wells. For example, figure 18 shows chloride concentrations in water from three observation wells. Well B6 is 35 ft, and wells B2 and B3 are 733 ft, from a treated-sewage injection well in St. Petersburg. Wells B6 and B3 are open to the upper part of the injection zone; well B2

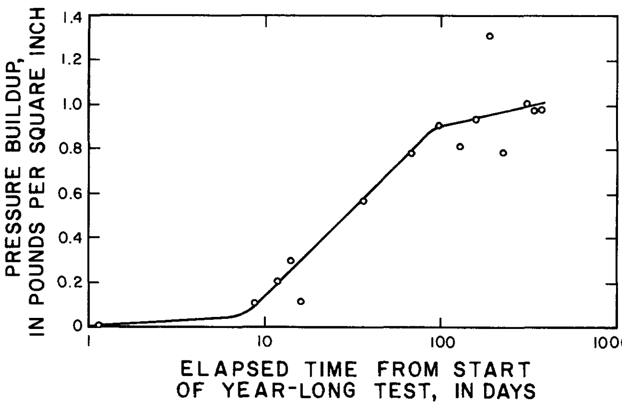

Figure 17. Pressure buildup in an observation well 733 feet from a St. Petersburg injection well. (Modified from Hickey, 1984, p. 53.)

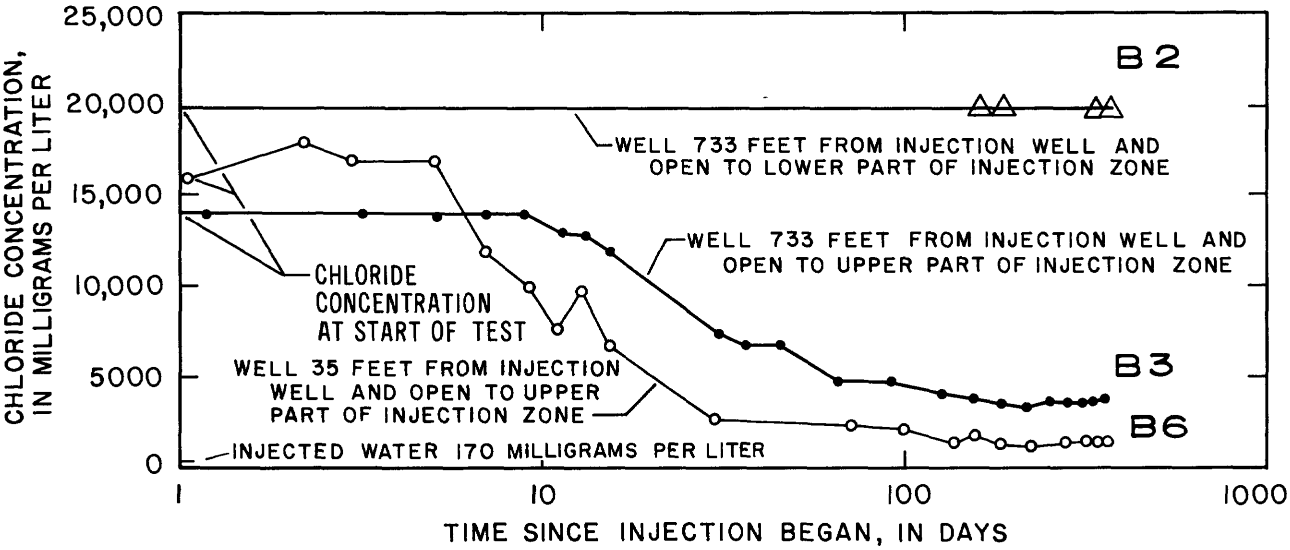

Figure 18. Chloride concentrations in water from observation wells at a St. Petersburg injection site during injection.

is open to the lower part. Two conclusions can be drawn from the graphs in figure 18. First, chloride concentrations changed only in the upper part of the injection zone, indicating that the less dense injected treated sewage rose to the top of the injection zone. Thus, within short distances (733 ft) from the point of injection, the injection zone became stratified with saline water in the lower part and treated sewage mixed with saline water in the upper part. Second, chloride concentrations in the upper part of the injection zone approached stabilization at levels substantially greater than the 170-milligram-per-liter chloride concentration of the injected wastewater. This suggests that saline formation water continually blends with injected wastewater as the injected wastewater moves radially outward in the top of the injection zone.

A few studies have been made of the alterations that injected waste liquids undergo in the subsurface. Ehrlich and others (1979) described short-term and long-term chemical changes in liquid waste injected in Santa Rosa County. The waste contained large concentrations of sodium nitrate, sodium sulfate, sodium thiocyanate, and various organic compounds including acrylonitrile. From analyses of samples collected from the injection well and from an observation well 1,050 ft from the injection well, they concluded that the waste underwent considerable chemical change in the subsurface. Differences in concentrations of nitrogen species in fluid from the injection wells relative to their concentration in the treated waste liquid were particularly evident (table 5). Nitrate was reduced to elemental nitrogen, and organic constituents were oxidized to carbon dioxide and ammonia. Ehrlich and others (1979) concluded that these reactions began immediately after injection and were caused by bacteria. By the time the waste reached the 1,050-foot-distant observation well, all of the nitrate had been converted to elemental nitrogen and organic constituents had been reduced to about 20 percent of their input concentrations. Other examples of microbial activity in the subsurface and accompanying alteration of injected industrial waste have been reported by Goolsby (1972) for a site in Escambia County and by Kaufman and others (1973) for a site in Palm Beach County.

Dissolution of Host Rock

In Florida, the injection zone rocks are carbonates and, therefore, can be dissolved by acidic liquid wastes. Notable dissolution has occurred at three injection sites in Florida. The greatest amount of dissolution is at the injection site in Polk County where the liquid waste is mainly hydrochloric acid with a pH of about 1. The acidic waste has created a cavity by dissolving the injection zone rock since injection began in 1972.

A comparison of 1976 and 1979 sonar caliper logs (measurements of hole diameter based on reflection of sound waves), in the form of cross sections of the cavity, is shown in figure 19. In 1976, the borehole had filled to about 4,360 ft below sea level from the originally drilled depth of 4,880 ft below sea level in 1972. Maximum diameter of the cavity in 1976 was 23 ft at a depth of 4,330 ft below sea level. In 1979, the hole had filled to about 4,300 ft, and the maximum diameter had increased to 36 ft at a depth of 4,270 ft below sea level. A sonar caliper log run in 1982 (Shannon and Wilson, Inc., 1983) indicated that the maximum diameter had increased to about 42 ft at 4,270 ft below sea level. Depth of the maximum cavity diameter was the same for the 1979 and 1982 logs. By 1982, the insoluble residue filling

Table 5. Concentration of selected chemical components in backflow and in waste liquid injected at the Santa Rosa County injection site, November 14–17, 1977

[Data in milligrams per liter, except as indicated. From Ehrlich and others, 1979]

Parameter	Waste liquid		Backflow			
Day of sampling (November 1977)	[1]13	[2]14	14	15	16	17
Elapsed time of backflow (hours)	--	--	1	16.0	40.0	64.5
Aquifer residence time (hours)	--	--	18	39	73	107
pH	6.7	6.8	8.1	8.2	8.0	7.9
Alkalinity	25	29	257	410	543	641
Bicarbonate (HCO_3^-)	--	35	313	500	662	781
Chemical oxygen demand (COD)	1,624	--	--	1,400	1,300	1,200
Dissolved organic carbon (DOC)	[3]290	330	430	400	--	320
Organic nitrogen (N)	197	190	160	120	120	100
Ammonium (NH_4^+-N)	30.5	38	70	84	95	100
Nitrate (NO_3^--N)	235	210	161	133	102	87
Nitrite (NO_2^--N)	0.5	1.3	8.8	10	10	9.3
Nitrogen (N_2-N)	--	--	24	--	28	43
Nitrous oxide (N_2O-N)	--	--	27	--	46	59
Total nitrogen (N)	463	--	51	--	404	402
Sulfate (SO_4^{2-})	--	--	1,200	1,300	--	1,500
Cyanide (CN^-)	7.5	--	8	5.5	--	3
Sodium thiocyanate (NaSCN)	57	44	35	55	--	41
Methyl alcohol (CH_3OH)	--	5.2	--	5.6	--	5.3
Acetone	--	1.6	--	1.4	--	1.5
Acrylonitrile	26	31	--	16	--	8.3

[1]Composite 24-hour sample of treated waste liquid.
[2]Waste liquid collected shortly before backflow started.
[3]Value is total organic carbon (TOC) concentration.

the bottom of the well had increased slightly from 1979 and reached between 4,295 and 4,298 ft below sea level.

State regulatory agencies are concerned because the cavity has the potential to cause either structural collapse of the well or collapse of the confining unit overlying the cavity. Either of these events could result in upward movement of waste and contamination of overlying freshwater. Geotechnical analyses of the cavity, performed by consultants since 1977, suggest that the cavity has been and will remain stable for some time, even though it is gradually enlarging (Shannon and Wilson, Inc., 1976, 1980, 1983).

WASTE MANAGEMENT THROUGH SUBSURFACE INJECTION

Waste management has been a major concern in the United States for the past 40 years. This is reflected in the number of Federal laws enacted during that period. Management of waste may become more difficult if the quantities of waste increase because of continuing urban, agricultural, and industrial growth and if more hazardous types of wastes are generated. The search for reliable and economic means to ensure that man's environment is minimally influenced by the residue of society has been, is, and will be an ongoing process.

Subsurface injection can offer a direct and effective means for managing liquid waste where hydrogeologic conditions are favorable. However, before injection can be used, at least two questions have to be addressed. The first is, Can an injection well be soundly constructed at the proposed site?; the second is, Can the hydrogeology of the proposed injection site and the surrounding area be described in sufficient detail so that flow paths of displaced native water and injected liquid waste can be determined and monitored with confidence?

Injection wells are constructed using well-established technology. Consequently, the principal engineering problem to be solved is selection of methods and materials suited to a site's hydrogeology and a waste's

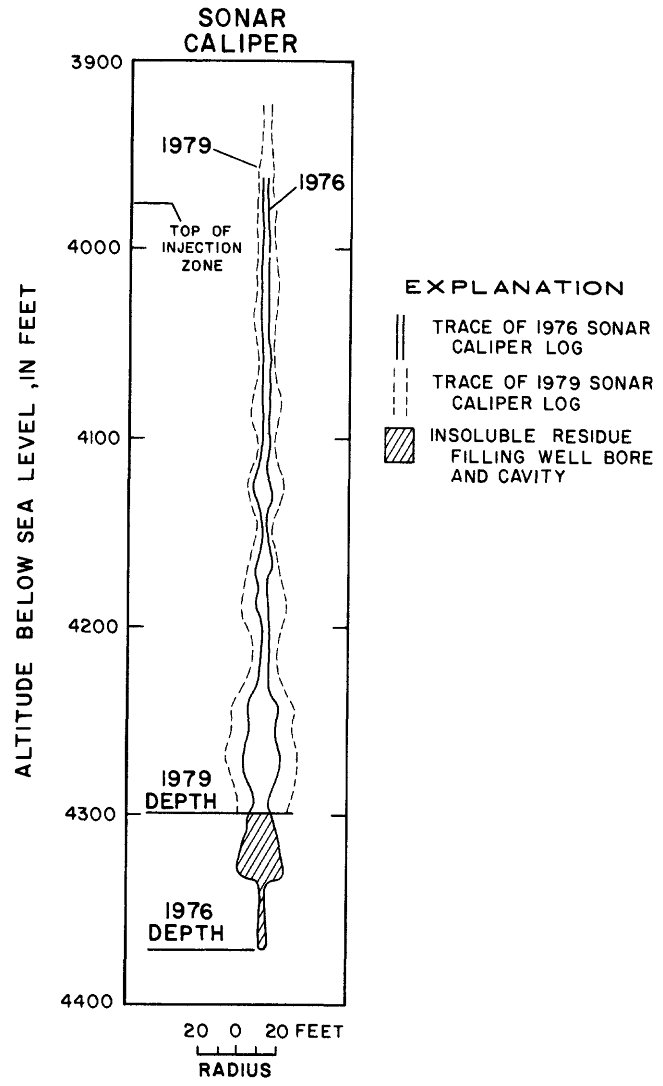

Figure 19. Comparison of 1976 and 1979 sonar caliper logs recorded in the Polk County injection well. (Data from Shannon and Wilson, Inc., 1976, 1980.)

composition. Although simple in concept, the task is not always easy in practice; it may not be possible to collect sufficient hydrogeologic data on which to base an appropriate selection of methods and materials. Most hydrogeologic terranes exhibit small-scale spatial variations in hydraulic characteristics. Important small-scale changes in hydraulic characteristics could be below the resolution limits of the available data. Incomplete data about permeable zones could lead to selection of an inappropriate cement type and emplacement method. This could cause incomplete cement coverage around casing strings, which in turn could lead to vertical migration of injected waste. Incomplete cement coverage is a potential shortcoming for all injection wells, particularly wells drilled in carbonate rocks. Whether or not incomplete cement coverage actually contributes to vertical migration depends on where the cement is missing. For example, cement could be missing from a small interval of a very thick confining bed and not contribute to vertical migration of waste, whereas cement missing from the same size interval in a thin confining bed could contribute to vertical migration of waste.

Hydrogeologic descriptions are based on borehole data collection and interpretative methods that generally are also well established. The principal hydrogeologic problem to be solved is the formulation of a three-dimensional description of hydraulic characteristics using data collected from widely separated boreholes. Areas that have significant variability in hydraulic characteristics cannot be described using widely spaced data. Areas that have relatively homogeneous, or at least mappable, hydraulic properties can be described. However, even in this case, the small-scale spatial variations of most hydrogeologic terranes cannot be readily assessed, and this introduces an element of risk. Because this risk is generally not measurable and could be very important, cautious hydrogeologic and engineering judgments are needed for making decisions about whether or not to use subsurface injection for waste disposal.

Under proper conditions, subsurface injection can be an appropriate and workable waste management alternative. However, because proper conditions are difficult to demonstrate conclusively in many geologic terranes, a cautious approach to the use of subsurface injection for waste management is a reasonable course of action.

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METRIC CONVERSION FACTORS

For use of readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
	Length	
in. (inch)	25.4	mm (millimeter)
ft (foot)	0.3048	m (meter)
mi (mile)	1.609	km (kilometer)
	Volume	
gal (gallon)	3.785	L (liter)
	3.785×10^{-3}	m^3 (cubic meter)
	Flow	
gal/min (gallon per minute)	0.06309	L/s (liter per second)
Mgal/d (million gallons per day)	3.785×10^3	m^3/d (cubic meter per day)
	Transmissivity	
ft^2/d (foot squared per day)	0.0929	m^2/d (meter squared per day)
(gal/d)/ft (gallon per day per foot)	0.0124	m^2/d (meter squared per day)
	Pressure	
lb/in^2 (pound per square inch)	6.894×10^3	N/m^2 (newton per square meter)
	Hydraulic Conductivity	
ft/d (foot per day)	0.3048	m/d (meter per day)

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