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UIC Evaluation of Salt Extraction Wells in NM

Wilson & Associates
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UIC EVALUATION OF SALT EXTRACTION WELLS IN NEW MEXICO

Submitted to:

Oil Conservation Division

Department of Energy and Minerals

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TABLE OF CONTENTS

1. INTRODUCTION

The Federal Underground Injection Control (UIC) program requires protection of existing and potential underground sources of drinking water against the possibility of pollution by the subsurface injection of contaminants.

One potential source of such pollution occurs from salt extraction wells. These wells inject fresh water into a salt-rich geologic formation, for one of these purposes.

a. Mining of an economically valuable mineral (eg. potash) from the formation; the mineral is removed from solution through some type of recovery process operated at the land surface.

b. Production of a briny water which is mixed with various chemicals to produce drilling muds. The muds, which are used in drilling of oil and gas wells, need to be chemically compatible with the (usually saline) water encountered during drilling. Some brine is used as is, for waterflood.

c. Creation of a subsurface cavity, which is then used for underground storage of hydrocarbons (especially liquified petroleum gas).

In 1981, the New Mexico Oil Conservation Division (OCD) contracted with Lee Wilson and Associates, Inc., for studies related to these wells. Specific elements of the contracted research included evaluation of whether or not the use of injection wells for purposes of salt extraction poses a hazard to Underground Sources of Drinking Water (USDW), and evaluation of regulatory approaches to such wells under UIC. Issues of particular concern were: possible migration of subsurface brines; alteration of hydrogeologic properties by dissolution; the potential for aquifer disruption as a consequence of catastrophic collapse; the potential for leakage due to corrosion of well casings; and the means by which wells may be properly abandoned (plugged) to avoid post-operation hazards. The study also is to inventory the chemical additives used in brine disposal/injection to determine if leaks or spills of these additives pose a potential threat to USDW (see separate report).

The basic information required for the evaluation was obtained through an inventory of active salt extraction wells (Chapter 2), and analysis of the hydro- geologic setting of the wells (Chapter 3). The interpretations with respect to potential risks to USDW are presented in Chapter 4; this chapter includes a brief literature review regarding the history of salt cavern collapses in other states with a discussion of how such collapses might be predicted in New Mexico.

2. WELL INVENTORY

The first step of the study was to inventory salt extraction wells in New Mexico. OCD personnel identified known brine supply and LPG wells from personal knowledge and agency files; all are located in Eddy and Lea Counties in the southeastern part of the State. The operator of each well was contacted and information gathered regarding the location, drilling/casing history, geology, hydrology, development/production history, and other aspects of the well construction and utilization. This information was recorded on a form developed especially for the study; a copy of the form is included in Appendix A. In some cases the form was completed by OCD personnel after discussions with the operator and review of file data; in other cases the operator completed the form and supplemental information was obtained through interview, corresponance, and/or field visits by OCD. The inventory indicated the existance of a number of abandoned wells; in most cases, little or no information could be obtained on such wells. Thus the compiled information concentrates on active wells, or those abandoned since the start of the project; data from abandoned wells is presented only where it has major implications for UIC.

Salt mining wells were identified in a somewhat different manner, either from the files of the New Mexico Environmental Improvement Division or through literature articles. Since none of these wells are active, no form was completed, but essential information was noted for inclusion in this report.

Table 1 summarizes the inventory results for brine supply wells. Table 2 summarizes the inventory results for LPG storage wells. Figure 1 shows the locations of the wells listed in the tables; it also plots salt mining wells discussed subsequently in the text. Appendix A contains information to supplement the tables, including: a map illustrating the grid location system used in the tables; full names and addresses of all operators; and a discussion of the methods and data used to calculate the approximate size of the cavity (cavern) associated with each well. Appendix B (single copy) transmits the inventory forms which are summarized in Table 1; Appendix C transmits the forms for Table 2. Major highlights of the inventory are summarized in the remainder of this section. Implications for USDW are discussed in Chapter 4, after consideration of the hydrogeologic setting of the wells which is presented in Chapter 3.

Brine Supply Wells. Seventeen brine supply wells were identified in the inventory. Three of these are not included in Table 1 because data forms were not completed prior to completion of this study. The three wells are:

Operator	Location
Brunson and McKnight	T19S R36E Sec 5
Truckers	T19S R35E Sec 1
Truckers	T18S R38E Sec 33

TABLE 1. CHARACTERISTICS OF CURRENTLY OR RECENTLY ACTIVE BRINE SUPPLY WELLS IN NEW MEXICO.

ID	OPERATOR	WELL NAME/NUMBER	LOCATION	COMPLETION: DATE/DEPTH	GEOLOGY: PRODUCTION FORMATION/DEPTH	HYDROLOGY: AQUIFERS/DEPTH	CAVITY VOLUME CU FT/DATE	COMMENTS
B1	Wasserhund	Eidson St. #1	16.35.31.333	8-80/2555	SS/1095-2555	OG/160-210	318,000/ 4-82	Water wells at 150 (supply) and 800 ft; P = 20,000; Q = 320,106
B2	Permian	State Lease 24 #1	18.28.24.341	4-55/740	S/397-740	SG/225-245	605,000/ 9-81	1955 dry hole reentered/replugged in 1978; casing leak at 42' 12/78; P = 25,000; Q = 298,670; produces through annulus at 416 ft
B3	Conoco	Warren McKee #1	20.38.2.233	2-78/2400	SA/1650-2400	NRP	6.6 million/ 10-81	supply = Hobbs sewage effluent; P = 237,700; Q = 267,320; used for waterflood
B4	Sims Est.	G.P. Sims #1	21.37.32.111	10-68/2125	S/1375-2100	NRP	1.5 million assumed/5-82	injects to B5, 170 feet away; Q = 325,000
B5	Sims Est.	G.P. Sims #2	21.37.32.111	5-77/2434	S/no data	NRP	see above	
B6	P and S	Eunice #1	21.37.34.334	7-80/1816	S/1250-1816	unknown	0.5 million assumed/4-82	P = 25,400
B7	Truckers	Carlsbad #1	22.26.36.144	8-76/930	S/715-930	NRP	1.6 million/ 9-81	P = 32,000; Q = 316,026; alternate withdraws in annulus, tubing
B8	Hardin	Tracy #3	22.27.3.33	9-70/1274	S/1060-1274	NRP	610,000/9-81	P = 27,000; Q = 260,000; reentry of old hole in 12-78
B9	Permian	Eugenie #1	22.27.17.332	6-78/663	S/456-592	/60	1.2 million/ 9-81	P to 60,000; Q = 340,633; plugged back to 587 feet
B10	Permian	Eugenie #2	22.27.17.332	11-79/618	S/580	NRP	see above	injects at bottom to B9 about 327 ft away; plugged back to 583
B11	Ortolnstool	Langlie Fed. #1	25.37.14.344	11-80/2015	S/no data	unknown	660,000/4-81	Q = 350,000; P = 43,700; very little data
B12	Permian	Arnott-Ramsay #2	25.37.16.444	?/1500	1100-?	see B13	unknown	withdraws through annulus; lost circulation, abandoned
B13	Permian	Arnott-Ramsay #4	25.37.16.444	3-81/1582	S/1269-1591	sand/400-500 wt-200	65,000/7-81	P= 10,000; withdraws through annulus
B14	Permian	Arnott-Ramsay #3	25.37.16.444	?57/1060	see B13	see B13	2 million/ 10-80	P= 37,000; withdraws through annulus; lost circulation, abandoned

Geology: SA = salt and anhydrite; S = salt; SS = Salado Fm. salt.
Hydrology: OG = Ogallala Fm.; SG = sand and gypsum; NRP = driller reported no water encountered
Comments: P = production in barrels per month; Q = total dissolved solids in mg/l

TABLE 2. CHARACTERISTICS OF CURRENTLY OR RECENTLY ACTIVE LPG STORAGE WELLS IN NEW MEXICO.

ID	OPERATOR	WELL NAME/NUMBER	LOCATION	COMPLETION: DATE/DEPTH	GEOLOGY: STORAGE FORMATION/DEPTH	HYDROLOGY: AQUIFERS/DEPTH	CAVITY VOLUME CU FT/DATE	COMMENTS
L1	Warren	Monument LPG Storage #2	19.36.36.122	8-53/1799	SS/1415-1480	unknown	6 million/6-78	Sonar caliper log; shallowest cavity at 1200 feet; main cavity is 250 ft wide
L2	Warren	Monument LPG Storage #1	20.36.1.222	5-51/1906	SS/1875-1905	unknown	6 million/6-78	Sonar caliper, other logs
L3	Gulf	Mark LPG #1	22.37.3.134	7-51/2000	SS/1310-2000	unknown	161,000/6-52	Extensive logs, detailed report on file; TA 1-82; brine extracted in annulus; no details on well #2, but location, history, size similar to #1
L4	Getty	Skelly GP#1, LPG #4	22.37.27.213	7/2065	Sim. to L5?	unknown	365,000/1-82	little information available
L5	Getty	J.V. Baker LPG #2	22.37.27.332	8-52/2075	SA/1848-2075	unknown	700,000/1-82	
L6	Getty	J.V. Baker LPG #1	22.37.27.432	55/2045	SA/1861-2057	unknown	935,000/1-82	abandoned #3 has similar size cavity
L7	EPNG	State LPG Storage #4	23.37.32.133	7-60/2680	SS/1666-2670	unknown	280,000/8-67	L7-L10 all have substantial accum. of material in bottom (40-50 ft. thick)
L8	EPNG	State LPG Storage #3	23.37.32.233	6-60/2677	SS/1666-2677	SR: 905-1158 WT = 250	280,000/8-67	Extensive logs
L9	EPNG	State LPG Storage #2	23.37.32.33	10-53/2040	SS/1672-2040	WS: 85-160	280,000/8-67	Extensive logs; casing leak repaired
L10	EPNG	State LPG Storage #1	23.37.32.433	11-52/1900	SS/1400-1900	WS: 85-160	280,000/8-67	Extensive logs

Geology: SA = salt and anhydrite; SS = Salado Fm. salt.
Hydrology: SR = Santa Rosa; WS = water sands; WT = water table elevation (static).
Comment: TA = temporarily abandoned

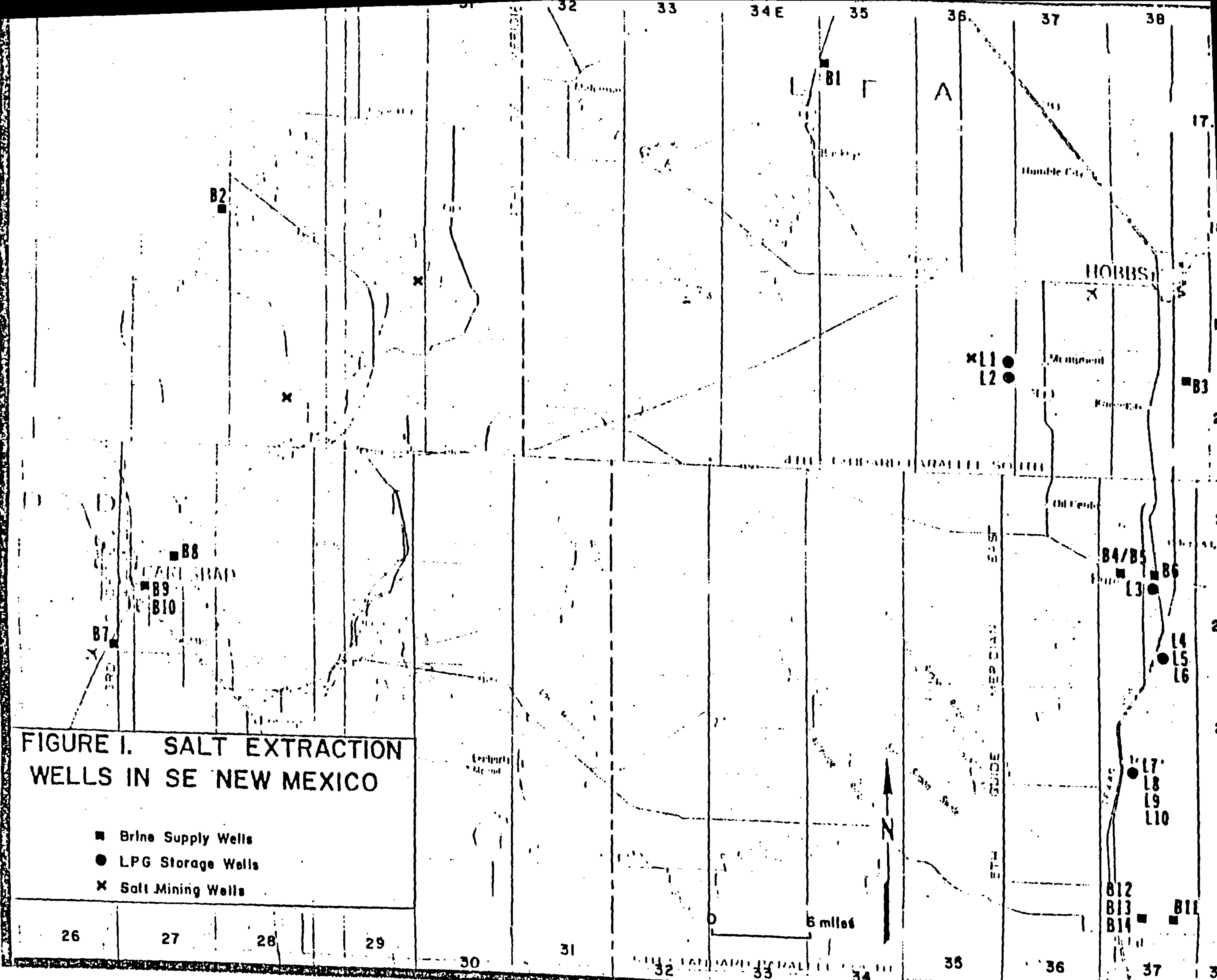

FIGURE I. SALT EXTRACTION WELLS IN SE NEW MEXICO

Of the remaining fourteen wells, four are part of injection/extraction doublets: well B4 injects to well B5; and well B10 injects to B9. Two of the wells (B12 and B13) have been abandoned. Thus, in effect there appear to be thirteen active brine supply locations in southeastern New Mexico, of which ten are included in Table 1. There are nine operators, each with one well with the exception of Permian Brine Sales and Truckers Water Company, each of which have three different facilities.

The remainder of this subsection describes the characteristics of 'typical' brine supply wells. This includes discussion of particular wells which may have characteristics of special importance to UIC.

Figure 2 illustrates the typical construction of brine supply wells. Generally, a 2 7/8 to 3 1/2 inch steel tubing is hung within a steel casing of 5 1/2 inch or larger diameter; the casing is cemented off at least to the depth where fresh-water aquifers may be penetrated. Fresh water is circulated down the annulus between the casing and tubing, where it dissolves out salt from the Permian Salado Formation. Pressures range from 100 to several hundred psi. The resulting brine is withdrawn through the tubing. The withdrawn brine is stored in surface pits or tanks, and sold in tank truck lots. A different circulation patterns occurs for wells B2, B12, B13, and B14 which inject fresh water through the tubing and withdraw brine in the annulus. Well B7 does both - alternating from tubing injection to tubing withdrawal. As noted previously, there are two doublet wells (B4 + B5; B9 + B10) in which hydrofractures have been developed so that fresh water from one

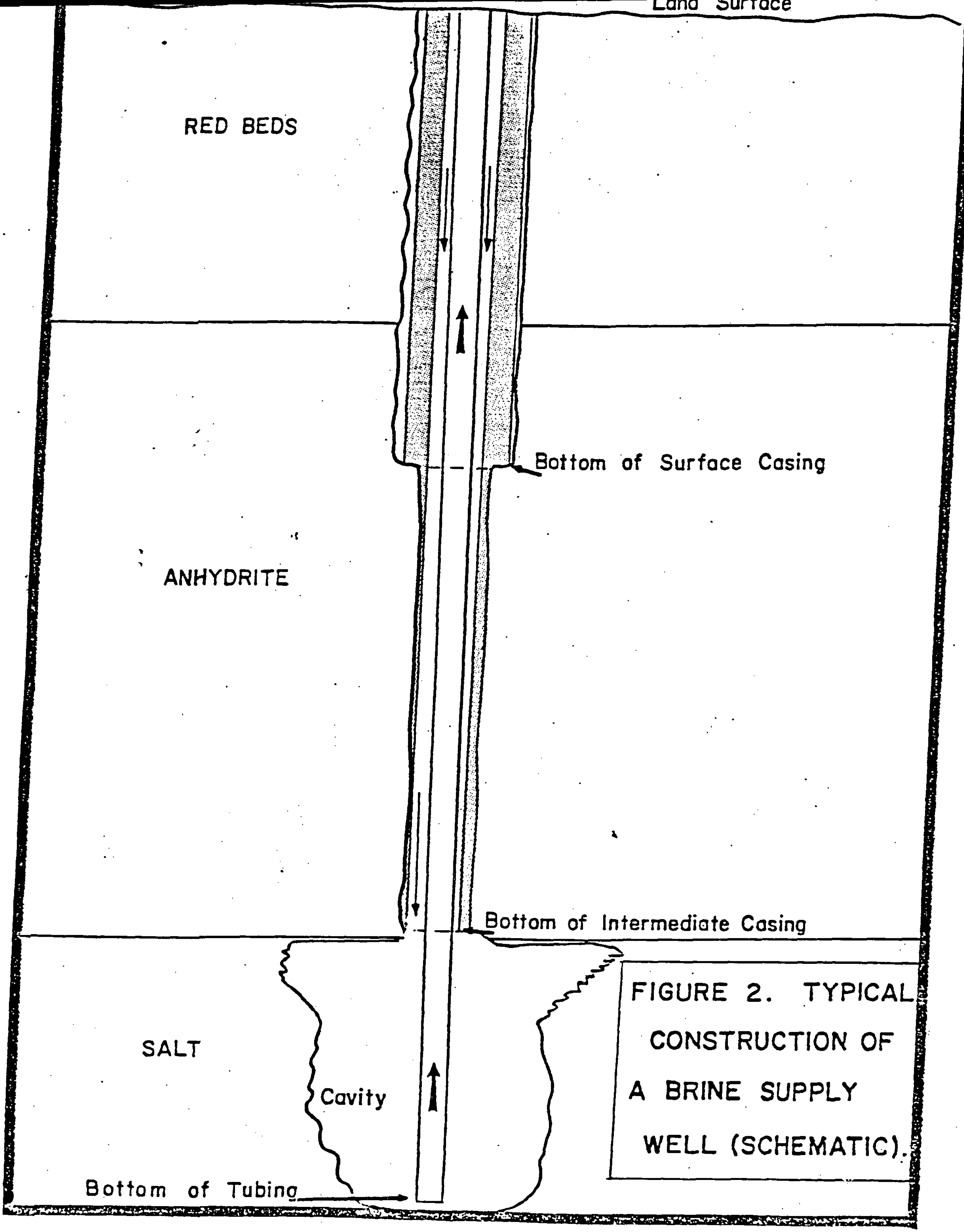

FIGURE 2. TYPICAL CONSTRUCTION OF A BRINE SUPPLY WELL (SCHEMATIC).

well can dissolve salt along a fracture plane, with the resulting brine removed at a second well. At wells B9/B10, the fracture was developed by pressure of 100-150 psi.

Brine supply wells are located near areas of active drilling, where fresh water is available, and on sites with good transportation access. As will be discussed in Chapter 3, the map pattern of the wells reflects locations of the salt beds - the Permian Salado Formation - in the active oil-producing province which occurs near the Capitan Reef. Well depths depend on the depth to the Salado. The formation is shallowest in the western part of the area (near Carlsbad), where the salt is found at depths as shallow as 400 feet, and well depths less than 1000 feet are common. On the east side of the area, the salt is found at depths of as much as 2500 feet, and wells are deeper accordingly.

More than half the brine supply wells have been drilled in the last five years; this includes some much older dry or abandoned oil wells which have been redeveloped for brine supply purposes (e.g. well B2). All the deep wells were drilled by the rotary method while most of the shallow wells were drilled using cable tool rigs. For wells where information is available, a salt mud was most often used, the cement was sometimes but not always salt saturated, and there usually was some type of casing test, usually lasting 1/2 hour to 2 hours with pressures in the 500-1000 psi range. A concrete or graded earth or caliche pad is found at all sites. Some wells have a well log and detailed casing record; however for most only scanty details are available as to drilling and construction history and characteristics.

Brine chemistries generally show water with a total dissolved solids of at least 250,000 mg/l, often approaching 350,000 mg/l. All available analyses indicate that a sodium chloride brine is produced; these two constituents typically account for 90-98 percent of the total dissolved solids. The remainder is usually calcium-magnesium sulfate, typically present at 7,000 - 10,000 mg/l. Other ions are found in amounts of a few hundred mg/l or less. The brines usually have a hardness of several thousand mg/l (as $CaCO_3$), a pH in the 6.0-7.5 range, and a specific gravity between 1.1 and 1.2.

Several of the specific wells are of interest. Well B2 is the shallowest salt extraction well identified in the inventory with a cavity top which may be as little as 416 feet beneath the surface. However, water is injected through the tubing at the bottom of the hole, indicating that the bulk of the cavity would be at depths greater than 600 feet. Well B3 has produced the largest cavity. The cavity had an estimated volume of 6.6 million cubic feet in late 1981. Based on the available data, it is growing at a rate of nearly 2 million cubic feet per year, indicating that as of this report the size is approaching 8 million cubic feet. Well B3 is unique in that it produces brine for waterflood use; also, the raw water is advanced treated Hobbs wastewater. Use of the effluent for this purpose has eliminated a major source of ground water pollution in the Hobbs area.

Withdrawal of the brine through the annulus greatly increases the risk of casing corrosion and leakage, although it has the benefit of causing the cavity formation to occur away from the contact between the salt and its overburden. Wells which withdraw through the annulus include well B2, which has water-bearing sands found at 225-245 feet, and wells B12, B13, and B14, with water-bearing sands at 500 feet. Withdrawal of brine through the annulus at wells B12 and B14 has caused problems in the past. Limited information on the reported loss of circulation in these wells identifies salt plugging as the cause. The circulation loss occurred following attempts to pressure and unplug the casing. In one case, the lost water caused fracturing of the Rustler Formation. Well B7 also withdraws brine through the annulus; however at this well no fresh water was found according to the drillers log.

LPG Storage Wells. Ten LPG storage wells were evaluated in the inventory (Table 2). Records of two abandoned wells also were reviewed; see Table 2, comments on wells L3 and L6. There are four operators, each with at least two wells. Not included in Table 2 is one active LPG well operated by Cities Service; that company did not return the inventory form prior to completion of the inventory step in our study. The remainder of this subsection describes the characteristics of 'typical' LPG storage wells, and includes discussion of particular wells which may have certain characteristics of special importance to UIC.

LPG storage wells are similar to brine supply wells in many respects, except that fresh water is injected only during the development stage of the well when the initial storage cavity is formed. After that time, brine is circulated (usually at 750 psi) when needed to displace the storaged LPG and there should be minimal potential for cavity enlargement. A minor difference is that in some wells the tubing diameter is as large as 5 1/2 inches. A more important difference is that LPG wells are generally located so that there is a considerable thickness of salt (a few hundred feet or more) above the cavity; this contrasts with brine supply wells, which often produce from the top of the Salado just below the Rustler anhydrite and/or redbeds.

LPG storage wells are all located in Lea County and each is adjacent to a refinery site. In all cases, well development occurred at least twenty years ago. As for brine supply wells, each well involves a cavern in the Salado Formation, which is quite deep in this area; thus the shallowest cavern identified is almost 1800 feet beneath the ground surface. Reflecting the depth, all the wells were rotary drilled. Other aspects of construction, casing tests and logging usually are as described for brine supply wells, if known at all; an exception is that these facilities all have a large brine pit for storage of the fluid which is used to displace the LPG. Because this water is recirculated, it should approach saturation, and injection cycles should cause minimal enlargement of the cavity. Injection preasures generally range from 350-750 psi.

Wells L1, L2 and L3 are unusual in that relatively detailed information is available as to the size and shape of the subsurface storage cavity. Figure 3 is a cross-section of the cavities at well L1, as determined by a Dowell Sonar Log in 1978. The multiple cavities reflect drilling history; only the bottom cavity is used for storage. The logs are run every few years to verify that the cavity is not endangered by the potential formation and breakage of ledges of insoluble rock. Well L2 extracts brine in the annulus.

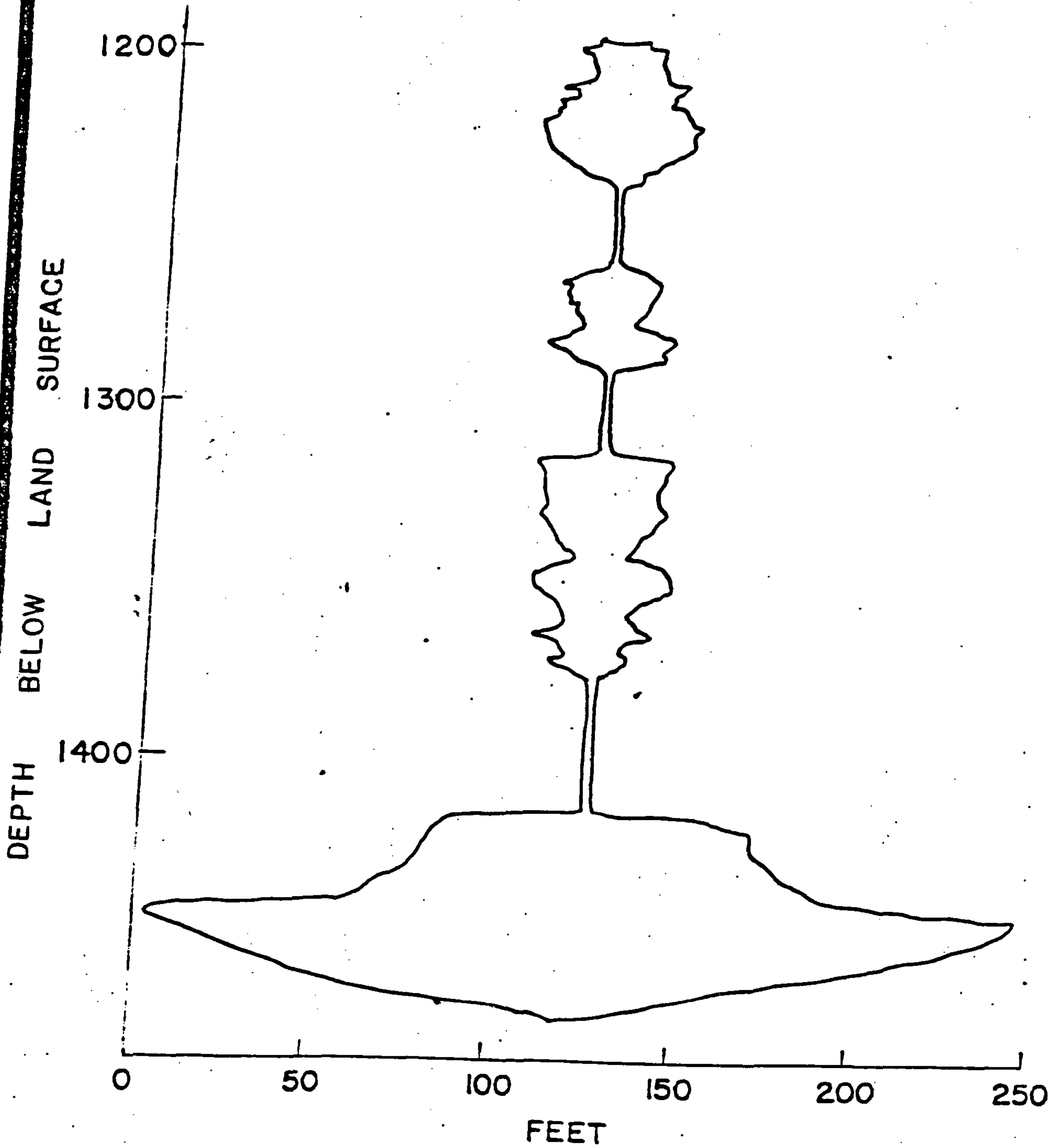

FIGURE 3.

SHAPE OF CAVITY AT WELL L1.
(BASED ON SONAR LOG - JUNE, 1978)

Wells L5 and L6 are conventional LPG wells with no unusual characteristics. However, they are part of what was originally a 3-well cluster. The third well was J.V. Baker LPG #3, operated by Getty and located at 22.37.27.342. Drilled in 1953 to a depth of 2064 feet, this well developed a cavity in the salt and anhydrite beds from 1848 to 2064 feet depth. The well was abandoned in 1974 because water entered into the cavern. This water probably orignated from a nearby waterflood well which experienced a cavity leak; the leak dissolved a channel between the two wells. Wells L7-L10 reportedly have experienced sloughing or caving, which has filled the cavity bottoms to depths of up to 50 feet.

Salt Mining Wells. Climax Corporation recently plugged and abandoned four salt mining wells located in Township 19S, Range 36E, Section 34. These wells extracted halite for purposes of producing sodium sulfate and hydrochloric acid. The information available on these wells indicates: the Salado salt was penetrated at about 1250-1300 feet depth (just beneath the anhydrite zone of the Rustler); the wells were cased through to the top of the Salado, and drilled to bottom of the formation, at 2400-2500 feet; recycled water was injected down a 5 1/2 inch tubing and withdrawn through the annulus; drilling dates ranged from 1962 for well #1, to 1977 for #4; water-bearing sands were found at 45-60 feet, and three 15 to 20-foot thick water bearing units were found in redbeds at depths of 320 to 760 feet.

Davis and Shock (1970) report on Conoco's pilot operation to solution mine potash. The project involved a multiwell operation, which is much more efficient than single wells. The following characteristics of the project are of interest:

- the mined horizon was a Salado Formation potash zone about 4 ft. thick located at 1150 ft. depth in T19S, R20E, Section 12;
- injection was in a center well to three wells 200 feet away;
- fracturing occured at 450 psi and took 5-10 minutes to extend the 200 feet; subsequent reopening of one fracture required 700 psi surface pressure;
- operations were conducted using double wells in which the recovery well was downdip from the injection well, in order to avoid solution channelling which can result from updip mining;
- specific solution rates of 3 pounds per square foot per hour were obtained under conditions of large-scale injection;
- an ovoid cavity was formed, being widest at the injection well; an elliptical cavity would have resulted from alternating injection between wells;

- the cavity was 280 feet long and generally less than 10 feet high; it had a volume of 175,000 cubic feet;

- the horizontal area affected by solution mining a two-well pattern could be approximated by squaring the discharge between the wells;

- the hydrostatic pressure of the brine counteracted about one-half the normal overburden pressure.

Brokaw el al. (1972) report on an earlier (1940's-1950's) project by Kansas City Testing Laboratory, which attempted to establish a connection between two boreholes about 200 feet apart in T20S, R29E, Section 22.

3. HYDROGEOLOGY

The extent to which salt extraction wells threaten USDW is a direct function of regional geology and hydrology, and in particular the relationship of the Salado Formation to area aquifers. Fortunately, this subject is relatively well known because of the extensive oil and potash development of the area, and the more recent investigation of the WIPP site. Figure 4 sketches some of the major geologic and hydrologic features of southeastern New Mexico; Figure 5 is a cross-section showing how the Salado lies in relationship to other rock units in the region.

Fresh water generally is not found below the Salado in the locations where the formation receives injection for purposes of salt extraction. Table 3 is a stratigraphic column which characterizes the Salado and younger formations of the area. Table 4 pulls together quantitative information on aquifers above the Salado. The Tables, and the discussion which follows, are based on: Mercer and Orr (1977), Nicholson and Clebsch (1961), Brokaw and others (1972), Jones, Cooley and Bachman (1973), Hendrickson and Jones (1952), Hiss (1976), Bachman (1976, 1980), Mercer and Gonzales (1981), and DOE (1981).

It should be noted that the hydrogeology of the region is a much-debated subject with respect to the potential safety of the WIPP project. The major controversies over WIPP reflect considerations of very long-term phenomena of a type which would not be expected to be important for a short-lived salt-well

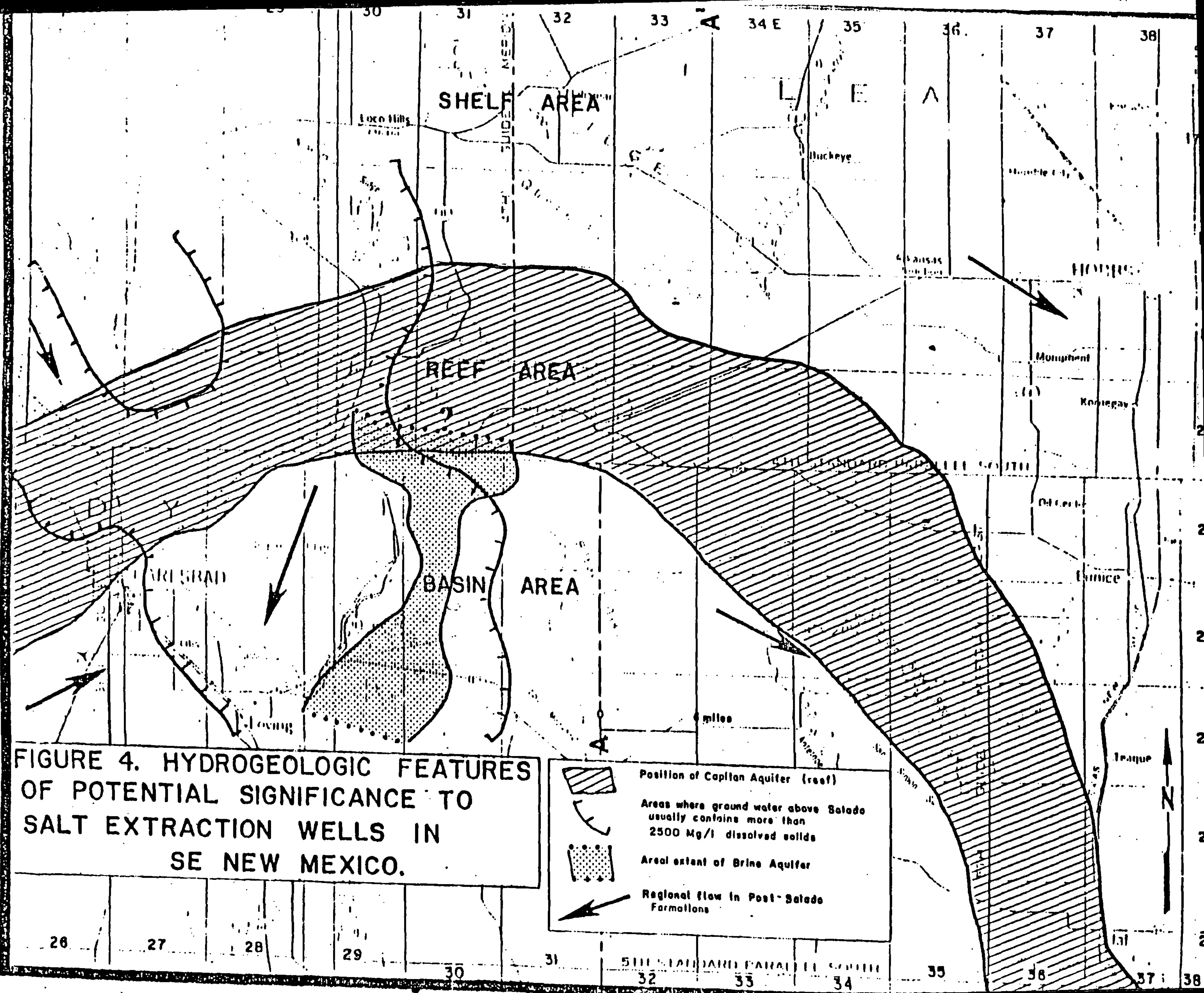

FIGURE 4. HYDROGEOLOGIC FEATURES OF POTENTIAL SIGNIFICANCE TO SALT EXTRACTION WELLS IN SE NEW MEXICO.

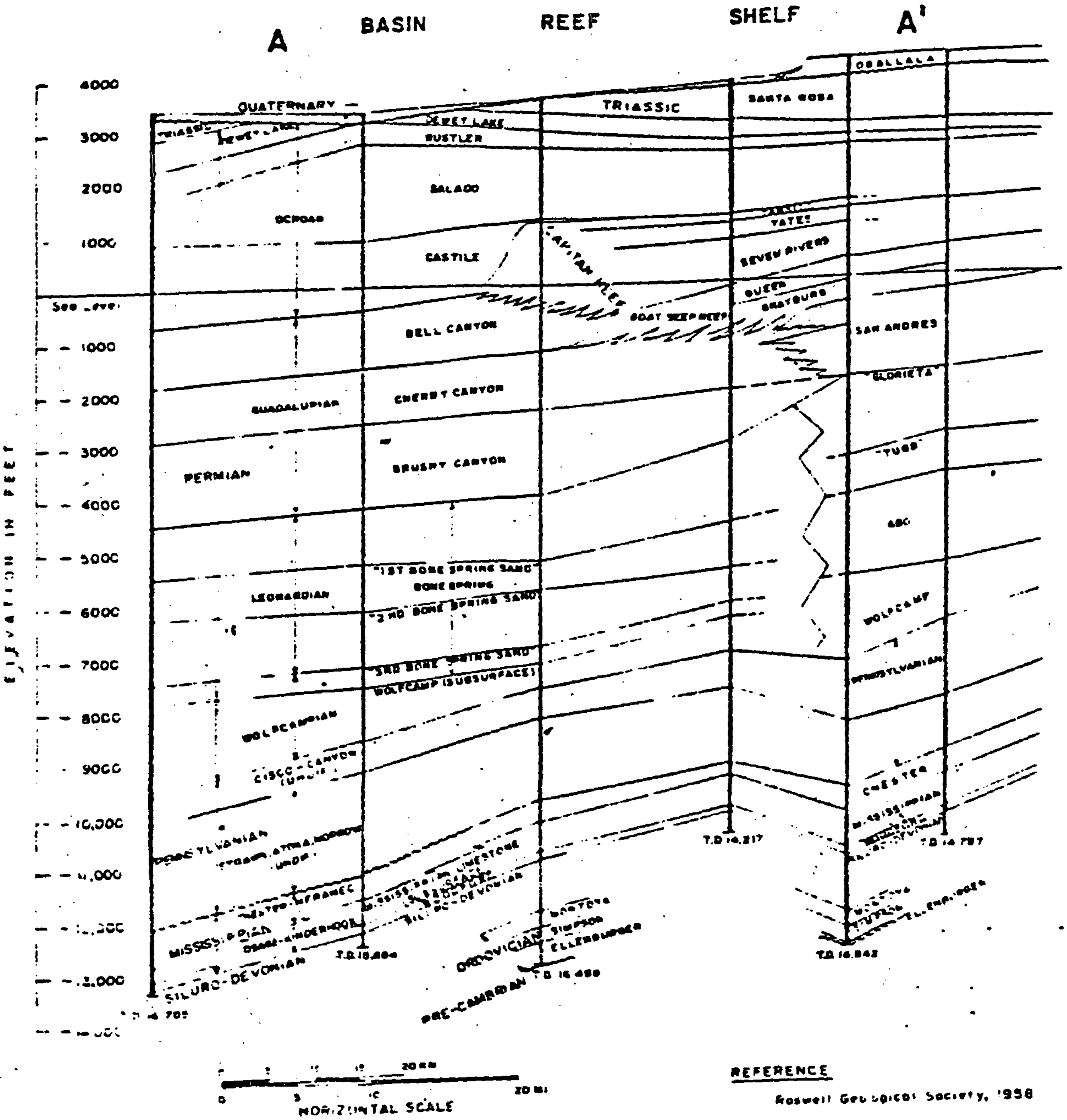

FIGURE 5.

GENERALIZED GEOLOGIC CROSS-SECTION, SE NEW MEXICO.

TABLE 3. Stratigraphic Column of Salado and Younger Formations, Southeastern New Mexico.

	FORMATION	THICKNESS (feet)	DISTRIBUTION	LITHOLOGY	WATER BEARING PROPERTIES
QUARTERNARY	Mescalero sand	0-15	Local deposits in west Lea County and east Eddy County.	Fine grained dune sand; light brown to reddish brown.	Above zone of saturation.
	Alluvium	0-400	In major valleys and closed basins, Eddy County, and southwest and central Lea County.	Sand, silt, and conglomerate.	Locally a major aquifer. Where in contact with the Ogallala formation, they form a continuous aquifer.
	Mescalero Caliche	0-5	Locally in southwest Lea County and southeast Eddy County.	Limestone, chalky w/fragments of underlying rock.	
	Gatuna Formation	0-375	Locally in southeast and east-central Eddy County.	Sandstone and siltstone, poorly indurated; red to orange.	Contains water in sand and gravel lenses; limited yields.
TERTIARY	Ogallala Formation	0-300	North, east, and central Lea County.	Fine-medium grained calcareous sandstone with caliche cap-rock; tan, pink and grey.	Where present, the Ogallala is the major water bearing formation. Saturated thickness ranges from 25-175 feet.
TRIASSIC	Unnamed	0-35	Locally present in subsurface.	Small, isolated and buried residual blocks of limestone.	Unknown.
	Chinle Formation	0-1270	Present in the subsurface under much of Lea County. Thins to the west. Crops out in northeast and southeast Eddy County, and western Lea County.	Shaly mudstone, with minor fine grained sandstone interbeds; red-brown to grey-green.	Data scarce. Generally poor quality with high salinity and high sulfate; low yields.
	Santa Rosa Sandstone	140-300	Present in the subsurface under much of Lea County. Crops out in northeast and southeast Eddy County.	Fine to coarse grained sandstone with minor interbedded siltstone; grey to yellow-brown.	Low to moderate yields of high sulfate water.
	Dewey Lake Red beds	200-600	Crops out in east-central Eddy County. Present in subsurface in Lea County.	Thinly interbedded fine grained sandstone and siltstone; red-orange to red-brown.	Unknown. May yield very small quantities of poor quality water from sand lenses.
PERMIAN	Rustler Formation	200-600	Crops out in a north-south trending band in central Eddy County. Present in the subsurface in east Eddy County and all of Lea County.	Cherty anhydrite, halite, dolomite, sandstone and claystone.	Contains 3 major water bearing horizons: the Magenta dolomite, the Culebra dolomite, and a basal solution breccia zone. Hydrologic properties variable, related to fracture and solution activity. Water quality variable.
	Salado Formation	1200-2300	Present in subsurface under eastern Eddy County and all of Lea County. Outcrops composed of insoluble residues are present in west-central Eddy County.	Halite, anhydrite, polyhalite, potash, and magnesite evaporite beds, with minor clastic lenses.	No water wells penetrate this unit. It is impermeable and dry except for local brine and gas pockets which may be pressurized.

Note: older units (shown on Figure 5) generally contain no fresh water in areas where salt extraction wells have been developed.

TABLE 4. Aquifer Characteristics

Values given as range or (average).

AQUIFER	USE	TOTAL DISSOLVED SOLIDS (mg/l)	TRANSMISSIVITY (Ft^2/day)	STORAGE COEFFICIENT	SPECIFIC CAPACITY (gal/min/ft)	YIELD (gal/min)	PERMEABILITY (milli-darcies)	POROSITY (percent)	GRADIENT (ft/mi)
Alluvium	Municipal Stock Domestic	310-1,500	13,600		12-200	0-1,200 (30)			Variable
Ogallala Formation	Municipal Stock Domestic		0-10,000 (5,000)		1-100 (20)	30-1,000 (70)		5-30 (20)	10-50 ft/mi (15) to the east-southeast.
Chinle Formation	Stock Domestic	900-5,200				0-700 (70)			
Santa Rosa Sandstone	Municipal Stock Domestic	370-580			0.14-0.2	0-100 (10-20)		10-13	Flow to south-west.
Dewey Lake red beds	Stock Domestic								
Rustler Formation -Magenta dolomite			0-0.5						40 ft/mi to the southwest.
Rustler Formation -Culebra dolomite	Industrial Stock Domestic	1,500 to 10,200	0-500 (120)			0-700 (100)	6,000	10	10-40 ft/mi to the southwest.
Rustler Formation basal solution breccia	Industrial		0-0.2						25 ft/mi to the southwest.

cavity. Nonetheless, any conclusions presented here may be considered subject to modification as research on the WIPP site proceeds.

General geology. The study area is located in the geologic regions known as the Permian Basin and High Plains, and is characterized by relatively level terrain and desert vegetation. The geology of southeastern New Mexico predominantly reflects rocks deposited in Permian time (about 280 million years ago), and subsequent depositional/erosional events. The oldest Permian rocks of the region record a transgression of seas across older rocks; following the transgression there was a relatively continuous marine or epicontinental environment throughout the remainder of the Permian. The geography during the Permian reflected the existence and growth of a massive limestone reef which lay between a backwater shelf area to the north and an ocean basin (Delaware Basin) to the south. The reef rocks are today known as the Capitan Limestone; they are interbedded with shelf deposits (Artesia Group) to the north and marine deposits (Bell Canyon and Cherry Canyon Formations) to the south (see Figure 5). A series of evaporites which overly the Capitan and related units are of Late Permian (Ochoan) age and include the Castile, Salado and Rustler Formations.

All salt extraction wells identified in this report are developed in the Salado salt. As shown on Figure 4, most of these wells are located in the shelf area, behind the Capitan Reef. However, brine supply wells near Carlsbad are located in the Delaware Basin just 'offshore' of the reef. In most of the areas where salt wells are developed the underlying rocks are part of the shelf rocks (e.g. the Tansill Formation of the Artesia Group, see Figure 5). In Carlsbad the Castile is the underlying unit.

The Castile Formation is an evaporate sequence composed primarily of anhydrite and gypsum interbedded with halite and minor amounts of sandstone and limestone. The upper unit, in contact with the Salado, is a massive anhydrite. The formation is 1300 - 2000 feet thick in the basin, but is thin above the reef and disappears basinward (Figure 5).

Except for thin wedges of the underlying Castile Formation, the Permian Salado Formation is the oldest evaporite unit to transgress the Capitan reef and be deposited in the shelf environment. The Salado Formation ranges from 1200 to 2300 feet in thickness and includes three laterally persistent and conformable members each consisting of cyclic deposits which include anhydrite - polyhalite, rock salt (halite), and clay seams. The salt beds are thick and persistant throughout the area, except where thinned by dissolution (see subsequent discussion). The middle member, the McNutt potash zone, is the only member which contains sylvite and langbeinite, economically valuable potassium minerals.

The Salado Formation is overlain by the Rustler Formation, also of Permian age, 200-600 feet thick, which consists of, in ascending order: an unnamed gypsum and anhydrite bearing siltstone member; the Culebra dolomite member; the Tamarisk evaporite member; the Magenta dolomite member; and the Forty-Niner gypsum and siltstone member. The Rustler is dominantly anhydrite and salt. In the western part of the study region there is a widespread zone where the base of the Rustler and the Upper Salado have been dissolved by natural processes. In this area, the basal contact of the Rustler Formation is marked by the occurance of rubble zones and breccia formed of nalitic clay and other insoluble residues.

The Rustler Formation is overlain by the Dewey Lake red beds (Triassic), 200-600 feet thick, consisting of well sorted quartz rich sandstone, and the Triassic Dockum Group, which includes the Chinle Formation, 0-1270 feet of shaly mudstone with sandstone interbeds, and the Santa Rosa Sandstone, 140-300 feet thick. In the eastern portion of the study area the Triassic section is unconformably overlain by the Tertiary Ogallala Formation, a calcareous, fine grained sandstone which thickens from 0 to 300 feet to the east. Locally Quaternary deposits are present, including the Gatuna Formation (a bolson deposit), the Mescallero caliche, bolson and stream alluvium, and dune sands.

The cross-section in Figure 5 is north-south. An east-west section would show a regional eastward dip of the Permian units of less than 2 degrees. The top of the Salado is at elevations of 3000 feet (msl) or above in the Carlsbad area where the Rustler is the major overburden, and 2000 feet (msl) or below in the Hobbs-Jal area where the overburden includes the Triassic units and Ogallala.

Hydrogeology. The Salado Formation is essentially impermeable with values of hydraulic conductivity less than 10^{-6} ft/day. The impermeability reflects a low porosity, the virtual nonexistance of interconnected pores, and the high plasticity of the material which limits the size and lifetime of open fractures. Clay seams in the unit are not significantly more permeable. In most locations the unit is bounded by formations of low permeability (Rustler and Castile anhydrites), which isolate the Salado from circulating waters.

Water in the Salado Formation does occur in at least two circumstances. A few very small isolated pockets of pressurized brine have been found during potash-mining operations. There is no apparent interconnection of these pockets; their origin is uncertain. Large amounts of brine are found in the 'brine aquifer', discussed below.

The formations underlying the Salado in the study area are mostly characterized by saline waters or have low permeability. The major exception is the Capitan Aquifer (Figure 4), which contains substantial amounts of fresh water in and west of the Carlsbad area. This aquifer is artesian in most areas and has the potential to move upward into the Salado and cause deep dissolution. Whether such dissolution actually occurs is a matter of some debate, but as yet there is limited direct evidence to indicate that it is a major active process.

All the formations above the Salado contain water which varies in quantity and quality from formation to formation. According to Brokaw et al (1972) these formations seem to be connected hydrologically and can be considered to constitute one multiple-aquifer system. Reflecting the eastward dip, the older rocks of the interconnected aquifer are the main sources of the water in the western part of the area, while the younger units become important to the east. Specifically, the Rustler Formation is the major aquifer (other than the Capitan) in the potash mining region north and east of Carlsbad. The Culebra dolomite member of the Rustler Formation yields up to 700 gpm (averaging 100 gpm) to wells. Permeability is related to solutioning along fractures and cavern development, and quality is extremely variable (1,500 to 10,200 mg/l TDS). Figure 4 shows that much of the western portion of the study area contains water with more than 2500 mg/l dissolved solids.

Few data are available for natural waters in the Magenta dolomite member of the Rustler Formation, or the Dewey Lake red beds. It is reported that yield from these units would be low, and quality generally poor. The Chinle Formation yields low to moderate quantities of fair to poor quality (900-5,200 mg/l TDS) water for stock and domestic use. The Santa Rosa Sandstone, found only in the eastern part of the area, yields low quantities of generally fair quality (370-580 mg/l TDS) water for stock, domestic and municipal use (City of Jal).

In Lea county, the Ogallala Formation is the principal source of water. The saturated thickness of the Ogallala ranges from 25-175 ft. In general, the lower half of the unit is saturated, and in places, the water table rises into the overlying alluvium. Yields range from 30-1000 gpm and average approximately 70 gpm. Locally the alluvium is an important aquifer, and yields up to 1,200 gpm have been observed.

In the pre-Cenozoic rocks of the interconnected aquifer, subsurface flow is generally southwesterly towards the Pecos River, the only through-flowing surface drainage in the region (Figure 4). In the Ogallala Formation, the flow gradient is down-dip towards the southeast. The alluvium exhibits locally variable gradients.

Bachman (1980) and others have described how dissolution of the Ochoan evaporites has occurred since at least Triassic time, to produce a complex of karst features, including collapse sinks and breccia deposits. For example, during middle Pleistocene time, breccia chimneys or collapse sinks formed over the Capitan aquifer system, as the result of unsaturated water rising under a strong hydraulic head through fractures and dissolving upward into the Castile evaporites. Bachman concludes that subsurface evidence does not suggest that deep dissolution is presently an active process in the Castile Formation beneath thick beds of Salado salt, possibly because discharge points elsewhere (e.g. Pecos River or San Andres Formation) take most of the Capitan flow. Anderson and Kirkland (1980) disagrees and has postulated a process in which Capitan water dissolves upward into the salt and then, due to the density of the resulting brine, moves back down again for ultimate discharge elsewhere.

Dissolution in the Nash Draw area has removed considerable salt from the base of the Rustler and the Upper Salado, leaving behind a residue which forms the 'brine aquifer' (Figure 4). Recharge from the land surface moves along the top of the Salado, thereby increasing its salinity until it discharges at least a few hundred gpm to the Pecos River, near Malaga Bend. This aquifer has a transmissivity of 8000 ft^2/day and a gradient of 25 ft/mi to the southwest. The water is highly saline and fit only for limited industrial use. The dissolution front is gradually moving eastward.

Dissolution has substantially reduced the Salado thickness in and near the outcrop, west of the Pecos River, where most halite has been removed. In this area the remaining rubble is relatively impermeable gypsiferous material. Throughout, the western part of the study area there is evidence of local collapses of the land surface as, over geologic time, underlying evaporites have removed in solution. In addition to natural collapse, subsidence has been observed over the potash mines (Brokaw et al., 1972). The subsidence, which is about equal to 100 percent of the mined height, produces gentle surface depressions. The material overlying the mined chambers appears to have subsided as cohesive blocks.

In summary, the Salado Formation is a thick, halite-rich evaporite overlying Permian shelf-reef-basin rocks and overlain in turn by evaporites, redbeds and alluvial deposits. The formation itself is essentially impermeable. Fresh water is relatively scarce in most of the under and overlying rocks. Natural solution of the Salado has occurred, both at depth (but this may not be active today) and near the surface (still active, e.g. in the area of the brine aquifer. Karst topography including surface collapse features are one result of this solution activity.

4. POTENTIAL FOR CONTAMINATION OF USDW

As stated on page 2, five potential impacts of underground safe drinking water were considered in this study: possible migration of subsurface brines; alteration of hydrogeologic properties by dissolution; the potential for aquifer disruption as a consequence of catastrophic collapse; the potential for leakage due to corrosion of well casings; and the means by which wells may be properly abandoned (plugged) to avoid post-operation hazards. Each impact type is discussed in a separate subsection of this Chapter.

The evaluations which follow were conducted at a reconnaissance level, primarily for the purpose of determining whether concerns over salt extraction wells are sufficiently serious to warrant special regulatory attention. Site-specific geotechnical studies were not performed and the overall analysis was generalized. The conclusion reached - that salt extraction wells as a whole currently appear to pose minimal hazard to USDW in New Mexico - does not ensure that particular hazards do not exist at specific wells.

Brine Migration. This impact would result if the injection of water into the salt formation produced a brine which then migrated out of the formation into a fresh-water aquifer. Migration requires two conditions - a driving force (e.g. potentiometric gradient or other mechanism); and pathways along which flow may occur. In the case of salt extraction wells, the injection of fresh water in itself is a driving force, but one that is essentially negated if all injected water is then withdrawn.

A second driving mechanism could result while the brine is undersaturated with respect to dissolved solids; in effect the water could dissolve its way through salt until the salinity reaches an equilibrium defined by temperature and pressure conditions. Indeed, this migration does occur and is part of the basic mechanism of cavity formation at a salt extraction well. However, so long as there is no large surplus of injected water to withdrawn water, the extent of migration would be small and essentially limited to the cavity area. The conclusion, then, is that there is no evident driving mechanism for brine migration outward from a salt extraction cavity, provided that the water injected is balanced by the water withdrawn.

The Salado Formation is generally considered impermeable (see Chapter 3), hence pathways for fluid movement are lacking. Natural fractures do occur, but tend to be short-lived as they are healed by salt flowage. It is probable that in at least some wells the injection process itself creates fracturing. This conclusion is based on a comparison of injection pressures reported at existing wells versus the pressure known to have caused fracturing at doublet well operations and at the Conoco experimental site (see Chapter 2). A conservative assumption is that such fractures could extend up to several hundred feet outward from affected salt extraction wells, and would be the locus along which cavity enlargement occurs. The fractures would be expected to seal gradually after injection ceases, and could effectively close within a few years.

So long as the volume of withdrawn water equals the volume of injected water, the creation of fractures is not in itself necessarily a concern. The major potential for a problem would be if the cavity is located near a formation contact, in which case the fracturing might reach to the contact and provide a conduit to a potentially more permeable unit. This risk could be minimized by appropriate location of cavities away from contacts with permeable formations, and could be monitored by a water balance. A loss of fluid might also result from cavities located near the 'brine aquifer' (see Chapter 3), although in this case no fresh water would be threatened.

A review of the wells identified during this study indicate that most are located either well within the Salado salt or near the contact with the Rustler anhydrite, a unit of low permeability. However, formation data are lacking for some wells and, for wells where data are available, at least one (Well B2) appears to be located very near Rustler redbeds (although below the reported water-bearing zone). Thus, migration of brine cannot be ruled out for all existing wells.

In summary, the potential for brine migration appears to be limited to the immediate vicinity of a cavity. No risk to USDW would be expected unless: a) there is a net loss of injection water; and, b) the cavity formed by injection is located very near a contact with a permeable rock formation. The implications for regulatory action are as follows.

1. Although no problems are evident at existing wells, review of site stratigrapny would be useful during any permitting process which applies to existing wells. Well B2 would be an appropriate prototype for sucn a review.

2. Stratigrapnic considerations should be included in any regulations drawn up for new wells.

3. Most important, it clearly is vital for existing and new operations to monitor closely both the amount of water injected into any salt extraction well, and the water withdrawn. Loss of fluids would require immediate reporting to the regulating agency and could be provided for closing of an operation, depending on the results of site-specific analysis.

It should be noted that this analysis does not discuss brine migration in association with a casing leak, cavity collapse, or in the event that the salt-extraction process changes properties of the injection formation; such potentials are discussed in the appropriate subsections, following. Also, as discussed in Chapter 3, there is some controversy about the hydrogeology of the salt formations in the study area, and the conclusion that the formation is impermeable might be revised based on the results of ongoing and future studies. Finally, according to Anderson and Kirtland (1980), there may be some dispute over tne conclusion that dissolution effects occur only near the cavity; more complex and distant transport of injected water has been reported.

Alteration of hydrogeologic properties. This impact assumes that the presence of injection itself, and the associated cavity, might in someway change the hydrogeologic environment and allow fluid movements that cannot now occur. For example, a cavity and its associated fractures certainly create a region of very large permeability in an otherwise impermeable formation; possibly this would provide a pathway for fluid movement of natural brines found under artesian conditions in deeper formations.

The evaluation of this impact is similar to the previous analysis. Because the impacts of salt extraction wells are very localized, and the Salado is very thick, significant risks should be limited to wells which are very near to the formation contact. In order to provide a pathway for underlying artesian water (which, once in the salt, might dissolve its way upward) a cavity would need to be located near the bottom of the Salado and above a permeable formation. None of the wells studied appear to fit this description, but as noted before information on many wells is limited. This type of risk can be assessed through review of site stratigraphy during the permitting process.

Aquifer disruption as a consequence of catastrophic collapse. Cavities produced by salt extraction wells are not always stable. In a comparatively small number of instances, such cavities have failed and caused surface subsidence, collapse of overlying rocks into the cavity, and aquifer disruption; examples of failures exist from Grosse Ile, Michigan, Windsor, Canada, Hutchinson, Kansas, and Cheshire, England among other locations.

In southeastern New Mexico, natural collapse features have formed because of long-term solution of the Permian evaporites; also, widespread subsidence has resulted from conventional mining of the potash minerals in the Salado Formation. Clearly this indicates a potential for cavities in the Salado to cause surface disturbance and, possibly, aquifer disruption.

Because cavity failure appears to be a potentially significant mode of aquifer disruption, this study included an extensive review of available information to determine whether or not it is possible to define the probability of cavity failure in southeastern New Mexico, and to evaluate the relative stability of the various cavities identified in the inventory.

A primary information source was Coates et al. (1981) which compiled and to some extent evaluated 150 germane references. Our study also reviewed additional sources such as: Dowhan, 1976; Walters, 1978; Piper, 1980; Ege, 1982; Serata, 1982; Kansas regulations which pertain to salt extraction wells; and the DOE studies of subsidence potential at the WIPP site. The problem of cavity collapse was discussed with persons knowledgeable in the subject, including: George Bachman, U.S.G.S. geologist who has written extensively on the New Mexico evaporites; Robert Walters, who performed a comprehensive investigation of collapse features in the Permian salts of Kansas; Jim Nye, one of many professionals at Sandia National Laboratories; R.T. Myers of Dowell Sonar Services; and Peter Spiegler of New Mexico's Environmental Evaluation Group. Finally, we attended a meeting of the Solution Mining

Research Institute, held in Albuquerque in April, 1982, at which the subject of cavity collapse was discussed in two presentations.

The major findings of the information search are as follows.

1. The literature on this subject is comparatively scant, and the state-of-the-art in predicting cavity failure is very limited. This is partly because cavity failures have been rare and partly because few studies provide much details on the nature of the failure. For example, in very few cases is the pre-failure cavity geometry known. Because cavity stability and faiure mechanisms are poorly understood, the most effective models are those which define conditions at which cavities are almost certainly stable. These define 'safe' conditions and are useful in design of secure salt caverns. However, the models are not considered to be reliable with respect to predicting conditions which are, of a certainty, 'unsafe'.

2. The mechanism of cavity failure is usually described as involving creep of the salt in the cavity roof which causes increased load on the comparatively brittle overlying strata which then sag into the cavity. Vertical tension fractures propagate downward from the top of the brittle bed which overlies the periphery of the unsupported roof. More intensive fractures propagate upwards from the bottom of the bed over the cavity center. If stresses exceed the strength of the roof rocks, shearing occurs along these fractures and the overburden

fails. The mode of failure is poorly defined and may vary among cavities. One type of failure is progressive stoping of the brittle layers; this is the predicted failure mode at the WIPP site. Based on very limited evidence, it is often assumed that the collapsing material has a bulking rate of 140 percent. That is, if some roof material having a volume of 100 units should fall into a cavity, the resulting rubble has a volume of 140 units. For failure to propogate to the surface, cavity space must be sufficient to store the bulked material.

3. Roof fractures may become pathways for <u>water</u> movement through previously impermeable rocks. This may cause piping and/or the weakening of the brittle overburden, which increases the potential for failure.

4. Trough <u>subsidence</u> is almost always observed prior to formation of a collapse feature such as a surface sinkhole. In most of the documented failures, the site was active (mined) for at least a few decades prior to collapse. Subsidence rates increased from a fraction of an inch per year to as much as a few feet per year before collapse occurred. Subsidence is observed to slow and cease soon after salt extraction ends. Damage to the well casing is another common precursor of collapse.

5. The literature consistently indicates that the risk of collapse is greatest for large and/or shallow cavities, but provides limited quantification of these terms. The following guidelines can be inferred from the literature, and must be considered as very crude, empirical rules of thumb to be used with considerable caution.

a. Failure potential increases if there is a large unsupported roof span for the cavity. Short, wide cavities tend to produce larger stresses than do high, narrow cavities of equal volume. Based on regulations adopted in Kansas, roof spans less than 300 feet may be considered as relatively stable. Based on the design of caverns in the strategic petroleum reserve, cavities with roofs 270 feet across are stable (but see subsequent comment on roof salt). Smaller dimensions may have caused collapse where the cavity was only a few hundred feet deep and the overburden was exposed to water during well operation. It should be noted that the practice of annulus injection of fresh water, which tends to protect against casing corrosion, has the adverse side effect of creating a 'morning glory' shaped cavity with a comparatively large roof span. The natural density layering of brine also leads to dissolution of the roof rocks and a morning-glory shape.

b. If the cavity roof is very near the contact between the salt and an overlying more brittle formation, the risk of instability is substantially increased. Conversely, roof stability is greatly enhanced if there is an undissolved section of salt above the cavity. Based on regulations adopted in Kansas, the undissolved roof salt should be at least 40 feet thick. The cavities designed for the strategic petroleum reserve have 500 feet of roof salt to support a 270 foot roof span. Roof protection is enhanced by doublet wells where the withdrawal is downdip; and by use of adjustable tubing to control the injection and withdrawal depths. Alternately, a roof may be protected by ceasing operations before the integrity of the overburden is threatened.

c. Cavity depth and volume are clearly important factors, but no rules of thumb are evident. Surface collapse has occurred from cavities at depths of a few hundred to more than 1000 feet beneath the surface. Shallow cavities offer more potential that failure will reach the land surface, but overburden pressures are less and may not provide enough stress to cause failure. Cavity volumes at failure sites have ranged from several hundred thousand to several hundred million cubic feet. As discussed subsequently, one outcome of this study has been to develop a possible rule of thumb for defining when a cavity volume and depth is of concern.

d. One reason for uncertainty in any stability analysis is that collapse depends not only on cavity characteristics, but also on the rock mechanics properties of the overlying materials. In this context it is useful to note that in Kansas, Permian redbeds not dissimilar to those found in formations such as the Rustler are considered as having minimal strength. Further, an assumption of incoherent overburden is often utilized in the modelling of LPG cavities (so that cavity stability is accomplished by minimizing roof spans and providing sufficient undissolved roof salt rather than by relying on coherence of the overlying rocks). (Note that at the WIPP site, the overburden is considered capable of supporting 20 tons per sq. foot.)

6. Deep cavities used for LPG storage have been known to lose capacity as a result of flowage closure, but such failures have not been observed to cause surface sinkholes. This problem appears to have been reported only from depths of at least a few thousand feet. Concerns over the problem relate to the economic value of the cavity and its contents, and not to surface impacts. The state of the art in predicting such closures is much more advanced than for cavity collapse.

7. Walters (1978) studied thirteen subsidence areas in Kansas, five associated with the mining of salt, and eight resulting from oil and gas wells where casing failures led to flow of unsaturated brine through a salt layer. He found that use of fresh water during modern rotary drilling does enlarge boreholes to three times the diameter of the drilled hole, but the resulting cavity is too small to cause surface subsidence.

Based on this summary, it is not possible to quantify the probability of cavity failure and aquifer disruption in southeastern New Mexico. Coates et al. (1981, p. 4) summarized the situation by stating that 'proven capability is not available to perform stability and failure analyses of cavities, and therefore, needs to be developed'. At best, any evaluation of particular cavities will be crude and based on empirical rules of thumb.

The rules of thumb provided above indicate that the probability of a cavern being stable is enhanced if the roof span is less than 300 feet and there is an undissolved roof salt of at least 40 feet or more. A major problem in applying these rules is that roof characteristics are known for very few salt extraction wells; cavity surveys are available for only three LPG wells and no brine supply wells in New Mexico. Clearly, at least for this study, it would be useful to express the rules of thumb using quantities which are known (or which can be inferred) for many New Mexico cavities: depth and volume.

In order to assess the possible stability of cavities identified in Chapter 2, the empirical rules of thumb noted above have been combined into a simple model which defines cavity depths and volumes which are likely to be stable. The outline of the model is as follows:

- all cavities are assumed to have a roof span of 300 by 300 feet, with no undissolved roof salt and with an incoherent overburden;

- therefore all cavities are assumed to have the potential to collapse;

- the upward extent of collapse is limited by the height of the cavity and the fact that the collapsed material will bulk;

- specifically, the cavity height in feet is defined as the cavity volume in cubic feet divided by the assumed roof area of 90,000 square feet;

- therefore each cavity is assumed to have a height of about 11.1 feet for each million cubic feet of volume; and this height should approximate the maximum impact on overlying materials;

- assuming a bulking rate of 140 percent and that stoping failures occur along vertical fractures at the margins of the cavity, then for each 4 feet of cavity height, a maximum of 10 feet of overburden will fail; this material will bulk to occupy 14 feet - 4 feet in the cavern and 10 in the overburden;

- for each million cubic feet of cavity volume (hence 11.1 feet of cavity height) the failure will involve up to about 28 feet of overburden;

- thus, if a one million cubic foot cavity is at least 30 feet beneath the land surface, there should be comparatively little risk of surface collapse, although subsidence may occur;

- the rule of thumb could be that relative stability exists if a cavity has at least 30 feet of overburden per million cubic feet of volume;

- conical failures would extend upward faster (but involve increasingly smaller areas);

- to account for this, and otherwise ensure a conservative analysis, the rule of thumb is adjusted so that '<u>relative stability exists if a cavity has at least 50 feet of overburden per million cubic feet of volume</u>';

- note that this simple model is based entirely on the assumption of a 140 percent bulking rate, and the notion that if a cavity depth is sufficiently large compared to its volume, and failure does occur, the overburden will fill the cavity and the failure will not promulgate to the surface; for example, if the bulking rate is 120 percent, the rule of thumb is not correct;

- the simple, mechanical nature of this model is appealing, but its lack of theoretical support must be recognized and there certainly is no guarantee that a cavity with more than 50 feet of overburden per million cubic feet of volume is stable, especially if the overburden were weakened by water;

- note also that the model is based on many conservative assumptions, and in particular assumes no undissolved roof salt when in fact most cavities have some roof support;

- thus a cavity which does not meet the depth-volume rule of thumb cannot be considered unstable, but rather must be viewed as being of greater concern than a deeper, smaller cavity;

- looking at the literature, the better known failures appear to have involved depth-volume ratios of less than 10 feet per million cubic foot, which might be considered as a second threshold value for assessing cavity stability.

To summarize, for purposes of this study the rule of thumb that will be used is that cavity stability is 'relatively high' if the cavity has at least 50 feet of overburden per million cubic feet of capacity. Where the depth-volume ratio is less than 50 feet per million cubic feet, factors of roof salt thickness, actual roof span, and overburden mechanics would obviously be important in determining the real potential for failure.

It is difficult to overstress that this rule is preliminary and for guidance purposes only. Specifically, the technique used and the site-specific information available provide no assurance that <u>any</u> particular cavity is either stable or unstable. Only detailed studies and models could provide a firm basis for reaching conclusions about the risks to USDW from the salt extraction wells of New Mexico. Moreover, the method addresses only collapse failures. No analysis is provided regarding subsidence, which is likely to occur above any of the salt extraction cavities if and when they are left empty for a prolonged period. Presumably subsidence would not impact

USDW, and therefore is not a part of this study, but this does not ensure that adverse effects to surface structures would not occur. (Note that the Conoco experimental wells found that a water-filled cavity is stronger than an empty one, which suggests that subsidence problems could be minimized if abandoned wells are filled with saturated brine before plugging.)

A calculation of depth-volume ratio can be made for most of the cavities identified in Tables 1 and 2. The results are as follows (values rounded off):

Well	Ratio	Well	Ratio
B1	6000	L1	235
B2	650	L2	300
B3	200 (as of 5/82)	L3	8100
B4	900	L4-5	2600
B7	2500	L6	2000
B8	450	L7-9	6000
B9	380	L10	5000
B12-14	630		

Well B3 has the lowest ratio. The ratio would approach 50 when the cavity volume approaches 33 million cubic feet. Based on historic rates of brine production at well B3, a volume of 33 million cubic feet could be reached before the end of 1990. Similar calculations for well B9 indicate the ratio of 50 might be reached in the early 1990's. Neither well B3 or B4 has a significant salt roof, but both have anhydrites in the immediate overburden.

Wells L1 and L2 have comparatively low ratios, but are not being expanded. All other wells for which data are available have a higher ratio and slower growth rate than wells B3 and B9.

These conclusions apply to disruption of an aquifer just beneath the land surface. For a few wells, aquifers are known to exist at depths far below the surface. These aquifers could be disrupted by collapse, without major effects being observed at the surface. Depth-volume ratios for the affected wells are as follows.

B1	5600	L8	1800
B2	250	L9	5400
B9	330	L10	2100
B-12-14	380		

This does not change the basic conclusion previously presented, but it does identify wells B2, B9 and B12-14 as potential candidates for future studies. Note that for most other wells the available records lack any information on aquifers; only a few wells are known to be completed entirely through non-water-quality units. The absence of calculations for wells B6, B11, and L1-7 simply reflects the lack of information on which to make an elevation. However, based on regional geology, collapse of a deep aquifer is an unlikely problem in most of the area, since in most locations the usable fresh water is limited to the near-surface.

The implication of these findings is that at this time there is a reasonable prospect that cavities formed by salt-extraction wells in New Mexico pose a relatively small risk of aquifer disruption. However, problems could occur in the future. Wells B3 and B9 would be the obvious target for more specific studies to ensure that the risks are minimal. Other wells may also deserve study, depending on the results of site-specific data obtained as well operators file operators file discharge plans.

Detailed studies could involve two related activities: monitoring and modelling. Several types of monitoring have potential, including: flow volumes in and out to ensure no fluid loss; dissolved solids monitoring to allow calculations of cavity growth rates; direct survey of the cavity using sonar logs; roof salt surveys using gamma-neutron logs; and subsidence monitoring through installation of monuments and annual third-order surveys. Of these, the most exotic technique is sonar logging, which would cost about $10,000 for a single cavity (but with sizeable savings if several wells are done at a package rate).

The best models identified during this study are those at Sandia, used for design of cavities for the Strategic Petroleum Reserve. Assuming that rock mechanics data from the WIPP site are suitable, the estimated cost of a model study to encompass two similar cavities is $25,000. Note that some of the monitoring and modelling costs could be met from the private sector, either tyhrough data obtained from discharge plans, or on a cooperative basis with operators such as Conoco, who have an undoubted interest in the development of well B3.

Leakage due to corrosion of well casings. Wells which withdraw brine in the annulus are certainly subject to accellerated corrosion of the casing; historic loss of circulation in such wells was discussed in Chapter 2. This represents a clear threat to USDW unless there are no good aquifers anywhere near a particular well site. Casing leakage into rocks which overly a cavity may weaken that material, increasing the risk of collapse. There appears no question that the risk of corrosion is sufficient to warrent regulatory attention.

To minimize the corrosion problem, new wells could be required to inject fresh water down the annulus and withdraw brine in the tubing, which in fact is now the practice required for new wells by OCD District Offices. For existing wells such as B2 or B13, a change in operating practices would be desireable unless the aquifers at those sites are saline. In the alternative casing tests may be required.

As noted previously, annulus injection concentrates salt solution at the top of the cavity, which adversely affects roof stability. This fact, and the rules of thumb about cavity stability, indicate that new wells should be drilled so that there is a significant salt thickness between the top of the Salado and the cavity. Based on the Kansas regulations, a 40 foot thickness would be the minimum acceptable; greater protection might be desireable if it is known that a particular cavity will be very large, or if the cavity will be developed at a shallow depth. Requirements to drill wells deeper would add a small amount to drilling and pumping costs of the affected wells.

Abandonment. The literature suggests that salt extraction wells are like other wells with respect to abandonment: they cause problems if abandoned improperly, but not if proper procedures are followed. Experience in Kansas indicates the proper approach is to pull the tubing; fill the cavity with a saturated brine; place a bottom plug; and fill the casing with cement. Except for the brine filling, this appears to conform to current practices in New Mexico.

5. SUMMARY AND CONCLUSIONS

Summary. This study has involved two major components: an inventory of salt extraction wells in New Mexico, in the context of their hydrogeologic setting; and a generalized evaluation of potential ways in which these wells might adversely impact underground sources of drinking water (USDW).

The inventory demonstrated that salt extraction wells are varied in many respects, but all involve dissolution of the Permian Salado Formation, an impermeable rock unit largely isolated from USDW. Well types found in New Mexico include brine supply wells (single and doublet operations), LPG storage wells, and experimental halite and potash mining wells. Cavities as large as 8 million cubic feet have been created; cavities larger than 1 million cubic feet occur within 500 feet of the land surface.

Among the concerns identified in the inventory are: lack of good information for most wells, especially the absence of data from which to determine cavity size and verify that fluids are not being lost from a well; several operations which involve brine withdrawal in the annulus, which greatly increases the potential for casing leaks; some wells with a history of fluid loss and/or cavity deterioration; and the geologic history of the area, which demonstrates that natural dissolution of the Salado has produced collapse features at the land surface.

Based on the impact evaluations, the greatest potential for harm to USDW from salt extraction wells probably comes from casing leaks, especially in wells which withdraw brine in the annulus.

An assessment of the state-of-the- art indicates that it is difficult to assess the potential for aquifer disruption which would result from cavity failure and surface collapse. In order provide at least some guidance regarding collapse hazards, a simple model was prepared as part of this study. The model is based on empirical observations which suggest that failure is most likely where the cavity has a roof span of 300 feet or more, and the thickness of salt between the roof and overlying brittle rocks is less than 40 feet. For such cavities it is assumed that failure will be by stoping, and that the failed material will have a bulking rate of 140 percent. If so, then simple mechanics indicate that the risk of catastrophic collapse is small if a cavity has at least 50 feet of overburden per million cubic feet of volume. Where the overburden is less, collapse would still be a rare event, but sufficiently possible that site-specific analysis may be warranted.

None of the salt extraction cavities in New Mexico have a depth-volume ratio less than 50, but two of the largest and fastest growing could reach that value within 8-10 years. Monitoring and modelling studies would be required if a detailed evaluation of collapse hazards is to be obtained.

wells. In addition, because of historic collapse events, the State of Kansas has established a set of permitting requirements and performance criteria keyed specifically to the problem of avoiding cavity collapse and other hazards of the type discussed in Chapter 4. Although the Kansas regulations are arbitrary in the sense that they are based on empirical rules of thumb rather than any comprehensive theory of cavity stability, they appear to be practical. The complete Kansas regulations are provided in Appendix D of this report, and may be of value in providing specific language to be included in any rules adopted in New Mexico. Regulatory needs can be divided into three categories: siting and construction; operation and monitoring; and abandonment.

Siting and Construction. No salt extraction wells should be constructed unless approved as the result of some type of permitting procedure which allows for submittal of site-specific documents. Siting requirements in the Kansas regulations include the following: wells must be 300 feet from any other well of any type (except a properly abandoned well); 150 feet from existing surface structures or transportation arteries (except those owned by the applicant); and 150 feet from the property line.

The most important aspect of well construction is to ensure roof support by minimizing the roof span and providing for sufficient roof salt. The Kansas regulations require closure of a well when the salt roof is less than 40 feet thick or the roof span from a single well exceeds 300 feet. More complex and less restrictive requirements are associated with doublet wells

- gamma-neutron monitoring of roof thickness at specified intervals;

- installation of monuments and performance of annual surveys to detect subsidence (e.g. see Wong, 1975).

- tests of casing integrity, such as required for other wells regulated under UIC;

- sampling of shallow and deep monitoring wells (required by Kansas for hydrocarbon storage wells).

At our request, Tierra Engineering Corporation of Santa Fe has outlined the concepts and costs of subsidence monitoring. Their memo on this subject is submitted separately.

Abandonment. Standard abandonment procedures are appropriate for salt extraction wells: plugging, cementing, recording. One additional measure worth consideration is to require that the cavity be filled by saturated brine or another appropriate substance in order to provide added roof support.

Detailed studies. As discussed on p. 45, site-specific analysis at wells B3 and B9 would be a logical extension of this study, in order to better define hazards to USDW, especially resulting from catastrophic collapse. A well such as B13 would be of interest for detailed assessment of casing leak problems, and to determine if annulus withdrawal should be prohibited at (termed galleries). For existing wells, Kansas has the option to require roof surveys. The Kansas regulations contain conventional casing/cementing requirements, including specification for centralizers and mudcake removal; the production casing must extend a minimum of 45 feet into the salt formation.

Kansas has slightly different regulations for hydrocarbon wells, including: a 100 foot roof thickness is required; the maximum vertical deviation of the hole is 1.5 degrees; and fracturing is prohibited.

Operation and Monitoring. Two requirements are paramount: injection of fresh water through the annulus, to minimize the potential for casing corrosion; and close monitoring of the water balance to detect fluid losses. Fluid monitoring basically requires totalizing meters to record the volume of fluids injected and withdrawn; data on injection pressures are also needed. Kansas requires these data to be maintained on a weekly basis, to be available on request, and to be submitted in an annual report. Immediate reporting is required when there is any evidence of fluid loss or other problems.

More extensive monitoring, at least on a routine basis, may not be appropriate in New Mexico, depending on the outcome of more detailed studies on New Mexico wells. The options available include the following:

- sonar logs of cavities, to be performed at specified volumes or periods (e.g. every 5 years; every 500,000 cubic feet);

Another potential threat to USDW, brine migration, would mostly likely occur if there is a loss of fluid from the cavity. Data on injection and withdrawal volumes are needed to determine the extent of this problem. Because nearby aquifers are limited, brine migration is probably a minor problem at most salt extraction wells in New Mexico.

Conclusions. Although most salt extraction wells in New Mexico evidence a comparatively small risk to USDW at this time, the risks clearly are not zero, and may increase in the future as new wells are developed and existing operations are expanded. Salt extraction wells are already subject to regulation in New Mexico. LPG storage wells are covered by the Oil and Gas Act, while brine supply and salt mining wells are subject to ground-water discharge plan requirements established pursuant to the New Mexico Water Quality Act. One outcome of this study has been to note that discharge plans are not on file for the existing brine supply operations; OCD has notified operators of the need to file such plans, which should allow them to be treated under UIC as 'permitted by rule'.

The question, then, is not whether to regulate these wells but how to regulate them most effectively. For this report, attention has been limited to the key provisions which should be contained in any regulations; no comments are provided regarding appropriate regulating agencies or authorities.

The findings summarized above provide the basis for identifying items which are essential to the safe and efficient operation of salt extraction existing wells. Well B2 would be of interest to determine if brine migration might occur from a cavity which has little or no roof salt.

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APPENDIX A. SUPPORTING INFORMATION FOR WELL INVENTORY

a. Master Form

A detailed form was used to compile data on LPG and brine supply wells in southeast New Mexico. A copy of the form is provided at the end of this appendix, and indicates the types of information solicited. For most wells, only a small fraction of the potential information proved to be readily available.

b. Operators

The following gives the full name and address for all operators listed in Tables 1 and 2.

Table 1.

Truckers:	Truckers Water Company (Rowland Trucking Co.) P.O. Box 1499 Hobbs, New Mexico 88240

Hardin:	Hardin/Houston Inc. (Champion Chemical Corporation) Box 4188 Odessa, Texas 97760
or	P.O. Box 2181 Hobbs, New Mexico 88240
Permian:	Permian Brine Sales, Inc. P.O. Box 1591 212 W. 5th St. Odessa, Texas 79760
Brininstool:	W.H. Brininstool Drawer A Jal, New Mexico 88252
Wassenhund:	Wassenhund, Inc. Box 249 Lovington, New Mexico 88260
Conoco:	Conoco, Inc. Box 460 Hobbs, New Mexico 88240

Sims Est:	Estate of G.P. Sims Box 1046 Eunice, New Mexico 88231
P & S:	P & S Brine Sales Box 1075 Eunice, New Mexico

Table 2.

Warren:	Warren Petroleum Company, Division of Gulf Oil P. O. Box 1589 Tulsa, OK 74102
or	P.O. Box 67 Monument, NM 88265
Gulf:	Gulf Oil Corporation P.O. Box 1197 Eunice, NM 88231
Getty:	Getty Oil Co. Box 1137 Eunice, NM 88231

EPNG: El Paso Natural Gas
El Paso Log Files
Midland, TX

or P.O. Box 1384
Jal, NM

3. Locations

Figure A-1 explains the New Mexico grid system used to record well locations in Tables 1 and 2.

4. Cavity Volume

Depending on the available data, cavity volume was estimated by one of three methods: directly from reported storage capacity; from logged cross-sections; or based on the weight of salt known to have been removed.

Storage capacity. For several LPG storage wells, the storage capacity in barrels was determined during the inventory. This was multiplied by 5.615 to give the equivalent volume in cubic feet. This approach was used for the following wells:

Well Number	Volume in Barrels
L3	28,666 (June, 1952)
L4	65,000

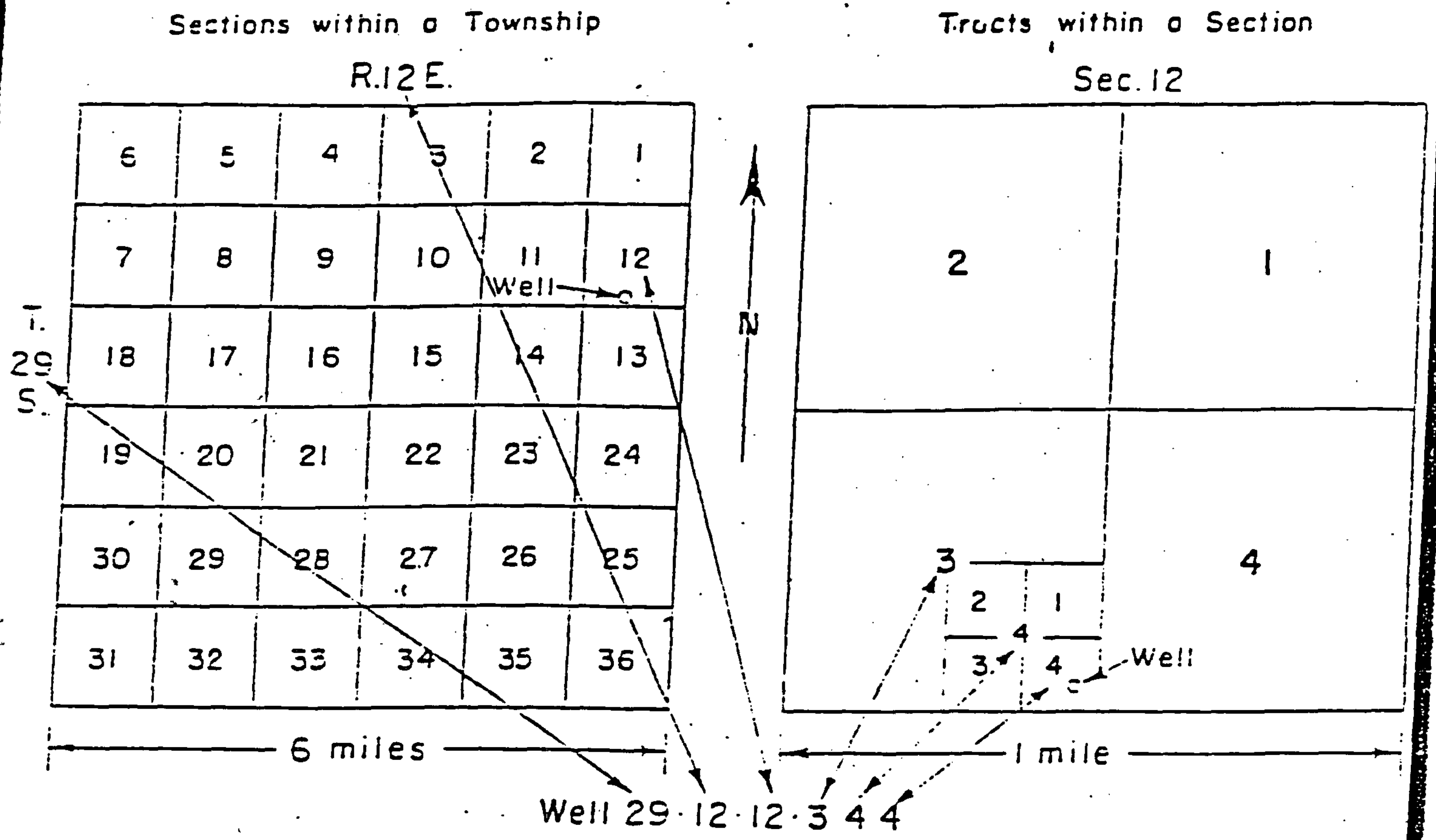

FIGURE A-1.

SYSTEM OF NUMBERING WELLS

IN NEW MEXICO

L5	124,000
L6	167,000
L7-L10	50,000 each (August, 1967)

Cross-sectional area. The following method was used to estimate the storage volume of LPG wells numbers L1 and L2, for which a Dowell sonar log was available. First, the total storage for each well was broken down into separate cavities (4 for L1 and 5 for L2). Then, the average cross-sectional area for each cavity was determined from the Dowell Sonar Log. Next, the formula $R= (A/Pi)^{0.5}$ was used to find the radius of a circle with equivalent area to each of the cavity cross-sections. The radius values were then plugged into the equation $V = 4/3 \, Pi \, R^3$ to approximate the volume of each cavity. Finally, the volumes of the cavities were added to obtain the total storage volume.

The volumes are as follows:

L1: upper cavity: 0.25 million cubic feet
second cavity: 0.10 million cubic feet
third cavity: 0.48 million cubic feet
fourth cavity: 5.07 million cubic feet
total: 5.90 million cubic feet

L2: upper cavity: 0.12 million cubic feet
second cavity: 0.06 million cubic feet

third cavity: 0.08 million cubic feet

fourth cavity: 3.36 million cubic feet

fifth cavity: 2.41 million cubic feet

total: 6.03 million cubic feet

Information provided by the owner indicates there volumes may be low by about 10 percent.

Weight of Salt Removed. These calculations involve the following basic relationships:

1. density of rock salt = 2.14 g/cc or 134 #/cubic foot
   (therefore, 1 ton of salt produces a 14.9 ft^3 cavity; 1 metric ton of salt produces 0.467 m^3 cavity)

2. 1 barrel of water = 159 liters = 5.615 ft^3.

3. For a brine containing 350,000 mg/1 total dissolved solids:
   each barrel removes 55.65 kilograms and creates a 0.026 m^3 cavity
   each barrel removes 122.6 pounds and creates a 0.9157 ft^3 cavity

For any brine of known TDS concentration, C (in mg/1), and production rate P, in barrels per some unit of time, the cavity volume, V (in cubic feet per the same unit of time as P), can be calculated as follows:

$$V = C/350,000 \times P \times 0.9157$$

The calculation for B1 is given fully, below.

P = 20,000 bbl/month for 19 months from 1/80, start up, to 4/82, when this report was being prepared

C = 320,000 mg/l net increase of TDS in product water compared to injected water

$$V = 320,000/350,000 \times 20,000 \times 0.9157 = 16,744 \text{ ft}^3 \text{ per month or}$$
$$V = 318,400 \text{ ft}^3 \text{ for the entire 19 months}$$

Note thate C is the net change in TDS, and is less than the gross TDS of the produced water (Q in Table 1).

For other wells where P or C is known, the input and output values of the calculation are summarized in a tabulation on the next page. Note that rounding of values occurs throughout the table. Also, for wells where inventory information was incomplete, assumed values have been used for P and C; in such cases P equals 30,000 bbl/month (a value typical of other operations, and probably a maximum for the small facilities where the inventory was incomplete), and C = 350,000 mg/l. Use of these values should lead toward a worst-case estimate of V.

Well	P	C	V/Month	Months (ending)	Total V
B2	25,000	298,000	19,500	31 (9-81)	605,000
B3	237,700	266,600	165,500	40 (10-81)	6,620,000
B4/5	30,000 a/	325,000 b/	25,500	60 (5-82)	1,530,000
B6	25,400	350,000 a/	23,300	21 (4-82)	490,000
B7	31,400	315,000	25,880	62 (9-81)	1,604,500
B8	17,000	260,000 b/	18,400	33 (9-81)	610,000
B9/10	36,350	307,000	29,200	36 ?(9-81)	1,050,000
B11	45,000	340,000 b/	43,700	15 (4-82)	660,000
B13	10,000	350,000 a/	9,200	7 (7-81)	65,000
B14	37,000 c/	350,000 a/	34,000	60 (12-80)	2,040,000

a. Assumed value.

b. Estimated as 1.65 x chloride concentration.

c. From 1976-80; unclear if operated at earlier time, in which case cavity could be larger.

* = please attach pertinent documents

I. OPERATOR / LOCATION INFORMATION

Operator ______________________________

Address ______________________________

______________________________ Phone ______________

Well unit # __________ Location ______________________________

T. ________ R. ________ Sec. ________ ________ 1/4 ________ 1/4 ________ 1/4

County __________

Purpose of well (brine supply, LPG storage, potash dissolution) ______________

____

II. DRILLING / SITING INFORMATION

Contractor ______________________________

Date drilling started ______________ Date drilling completed ______________

Drilling method ______________________________

Elevation of ground surface ____________ How measured ______________

Date measured ______________ Order of survey ______________

Name of surveyor ______________________________

Total depth of hole ____________

Attach schematic of well, include open hole interval, perforations, etc. *

Type of drilling fluid ______________________________

Type of drilling mud if used (brand if known) ______________

____

List any additives to the drilling mud, or any other chemicals put down well:

____

____

Describe casing tests performed ______________________________

____

____

Other tests ______________________________

____

* = please attach pertinent documents

II. DRILLING / SITING (continued)

Casing, tubing, and cementing record (please attach copy)*

Note: if a copy is not available detail casing record on back of this sheet using the following format. Include brand or type of cement if known.

From	To	Size of Hole	Size of Casing	Weight per Foot	Sacks of Cement	Estimated Top of cmt.

Was mudcake on bore wall removed before cementing production casing? _______

Was salt saturated cementing material used opposite salt formation? _______

Is site within 1/2 mile of another well? If so, use note to explain. _______

____

____

Site preparation (concrete pad, graded dirt, pit, etc) _______

____

____

____

Type of surface seal or well-head (locking security cap, welded, etc.) _______

____

Comments (include problems encountered while drilling, loss of circulation, deviation of hole from vertical, centralizers used, tools lost or stuck, fracturing techniques used, etc.) _______

____

____

____

____

____

____

_______________ (use back of sheet if more space is required)

* = please attach pertinent documents

III. FORMATION INFORMATION

Formation Record

From	To	Thickness	Formation (name, description)

Logs (specify type) ________________________________

____

____

Identify where logs are on file ________________________________

____

____

* = please attach pertinent documents

IV. AQUIFER INFORMATION

Aquifers encountered during drilling

From	To	Aquifer Description	Amount of Water entering hole	Quality of Water

Note: if water quality analyses are available please attach.*

Source of aquifer description ______

Depth at which water was first encountered ______

Depth to which water rose ______

Source of water level data ______

Comments (include information regarding determination of piezometric level and method of sealing off water zone) ______

* = please attach pertinent documents

V. PRODUCTION / BRINE STORAGE INFORMATION

Method of production (describe fully) ______________________________

____

____

____

____

____

____

Was well used previously for some purpose other than brine supply, potash dissolution, or LPG storage. If so use note to explain. ______________

____

Use of brine ______________________________

Source of injection water (be specific) ______________________________

____

Attach detailed production history (include dates of production, amount of water injected, injection rates, amount of brine produced, production rates, method of gaging injection/production rates)*

Note: If the cavity was used for LPG storage include volumes of product injected and withdrawn as well as a summary of the maximum and minimum pressures during injection, storage and withdrawal.

Chemical analyses of injection water (attach)*

Note : Chemical analyses should include sampling point and method, pH,temperature,method of analysis, name and location of laboratory, etc.

Chemical analyses of water produced (attach)*

* = please attach pertinent documents

V. PRODUCTION / BRINE STORAGE (continued)

Brine storage facilities (describe) ______________________________

____

____

____

Current condition/status of brine storage pit ______________________________

____

____

Is brine storage pit currently being monitored for leakage? ____________

Specify company or agency which is monitoring leakage ______________________________

____

If pit leakage has been monitored in past use note to explain. ____________

____

____

____

Comments on production history (note if production rates or brine ____________ concentrations have changed through time) ______________________________

____

____

____

____

____

____

____

* = please attach pertinent documents

VI. ABANDONMENT / PLUGGING RECORD

Date well abandoned/plugged ______________________________

Reason for well abandonment or plugging ______________________________

____

Method of Plugging (describe fully, include amounts of cement, est. top, plug type, depth, etc.) ______________________________

____

____

____

____

____

____

____

VII. Further comments (subsidence noted, subsidence monitoring, leakage noted, natural subsidence features noted nearby, LPG storage data, etc.)

____

____

____

____

____

____

____

Recorded by ______________________________

Date ______________________________

CIVIL AND SOILS ENGINEERING
LAND SURVEYS AND DEVELOPMENTS
TIERRA ENGINEERING CONSULTANTS, INC.
632 PASEO DE PERALTA
SANTA FE, NEW MEXICO 87501
505/982-2845

July 21, 1982

Lee Wilson and Associates
P.O. Box 931
Santa Fe, New Mexico 87501

RE: Subsidence Monitoring Program

Dear Mr. Wilson:

We have reviewed the requirements for a subsidence monitoring program for brine supply wells in Lea and Eddy County. Based upon your data vertical displacements of up to one (1) inch per year could be significant. In order to monitor possible subsidence I would recommend the installation and monitoring of a network of surface monuments to measure vertical movements. It is recommended that 4 to 8 monuments be installed along radials from each well at distances from 100 to 900 feet. The monuments will be tied to at least two control points located outside the area of influence of the wells. The monuments should be inbedded in the ground by means of a steel pipe at least 5 feet long encased in a column of concrete. For expedience during surveying the top of the monument should be smoothed for exact seating of the level rod. After installation a precise survey should be conducted to obtain the initial elevations of the monuments. All devices must be protected from disturbance by equipment.

It is anticipated that the layout and initial installation for 5 wells would cost between $10,000.00 and $12,000.00. Thereafter annual surveys would be in the range of about $1,000 - 1,250.

If you have any questions, please contact me.

Sincerely,

Thomas A. Ortiz
P.E. & L.S.

TAO:11