USE OF GROUNDWATER IN THE ARID AND SEMI-ARID WESTERN UNITED STATES: IMPLICATIONS FOR YUCCA MOUNTAIN AREA

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1 INTRODUCTION

Yucca Mountain (YM), Nevada, has been proposed as a deep geologic repository for high-level radioactive waste due in part to its hydrogeologic regime. Moisture fluxes within the 700 m thick unsaturated zone at YM are believed to be small due to the region's arid climate and the low permeability of the tuff units comprising the mountain (U.S. Department of Energy, 1988). Low moisture fluxes reduce the rate of waste canister corrosion, subsequent dissolution of the exposed waste form and transport of radionuclides to the accessible environments. However, if the regulatory period of concern is long enough [the National Academy of Sciences (NAS) has recently recommended a period of 10^6 yrs (National Research Council, 1995)], the waste form will eventually dissolve and migrate. Radionuclides that are not sorbed by the zeolitic bedded tuffs that underlie the repository (e.g., technetium, iodine, neptunium), or diffused from fluid-conducting fractures into the rock matrix within welded tuff units, will enter the water table, which, based on current engineering designs, lies 250 to 300 m below the repository. Current hydrogeologic studies (Czarnecki and Waddell, 1984; TRW 1995a) indicate that radionuclides that enter the saturated zone beneath YM will generally flow to the south-southeast into western Jackass Flat within the welded tuff aquifer and then south-southwest into the Amargosa Desert where the water table lies within an alluvial aquifer. To meet a risk- or dose-based standard, the U.S. Department of Energy (DOE) Waste Containment and Isolation Strategy places additional emphasis on the role of saturated zone transport in decreasing radionuclide concentrations through dilution.

Saturated zone dilution depends on the bulk flow rate of water beneath YM at locations where radionuclides enter the water table, the degree of mixing caused by large-scale variations in the groundwater velocity field in the welded tuff and alluvial aquifers, and mixing in boreholes where water may be pumped for domestic or agricultural use. Clearly, the amount of dilution depends on the duration and degree of mixing along the radionuclide transport path, while the estimated risk or dose depends on the use of water pumped from the aquifer. Estimating dose or risk requires definition of a potentially exposed population and the potential biosphere pathway by which an individual would be exposed to released radionuclides (TRW, 1995a). In the TSPA-95 (TRW, 1995a) it was assumed that the peak dose to the maximally exposed individual is received by a person drinking 2 liters of water per day pumped from the welded tuff aquifer at a location just outside the boundary of the controlled area (5 km outside the repository footprint). However, NAS recommendations may require determining the peak dose to the average member of a critical group, defined based on current water and land use practices in the YM area.

The critical group is a major element of the NAS's recommendation. Its definition is best described by the following citation (NAS, 1995):

> More specifically, we recommend the following definition of the critical group for use with the individual-risk standard: The critical group for risk should be representative of those individuals in the population who, based on cautious, but reasonable, assumptions, have the highest risk resulting from repository releases. The group should be small enough to be relatively homogenous with respect to diet and other aspects of behavior that affect risks. The critical group includes the individuals at maximum risk and is homogenous with respect to risk. A group can be considered homogenous if the distribution of individual risk within the group lies within a total range of a factor of ten and the ratio of the mean of individual risks in the group to the standard is less than or equal to one-tenth. If the ratio of the mean group risk to the standard is greater

> than or equal to one, the range of risk within the group must be within a factor of 3 for the group to be considered homogenous. For groups with ratios of mean group risk to the standard between one-tenth and one, homogeneity requires a range of risk interpolated between these limits.

Regarding the actual size, demographic makeup, and lifestyle of the critical group the National Research Council (1995) states:

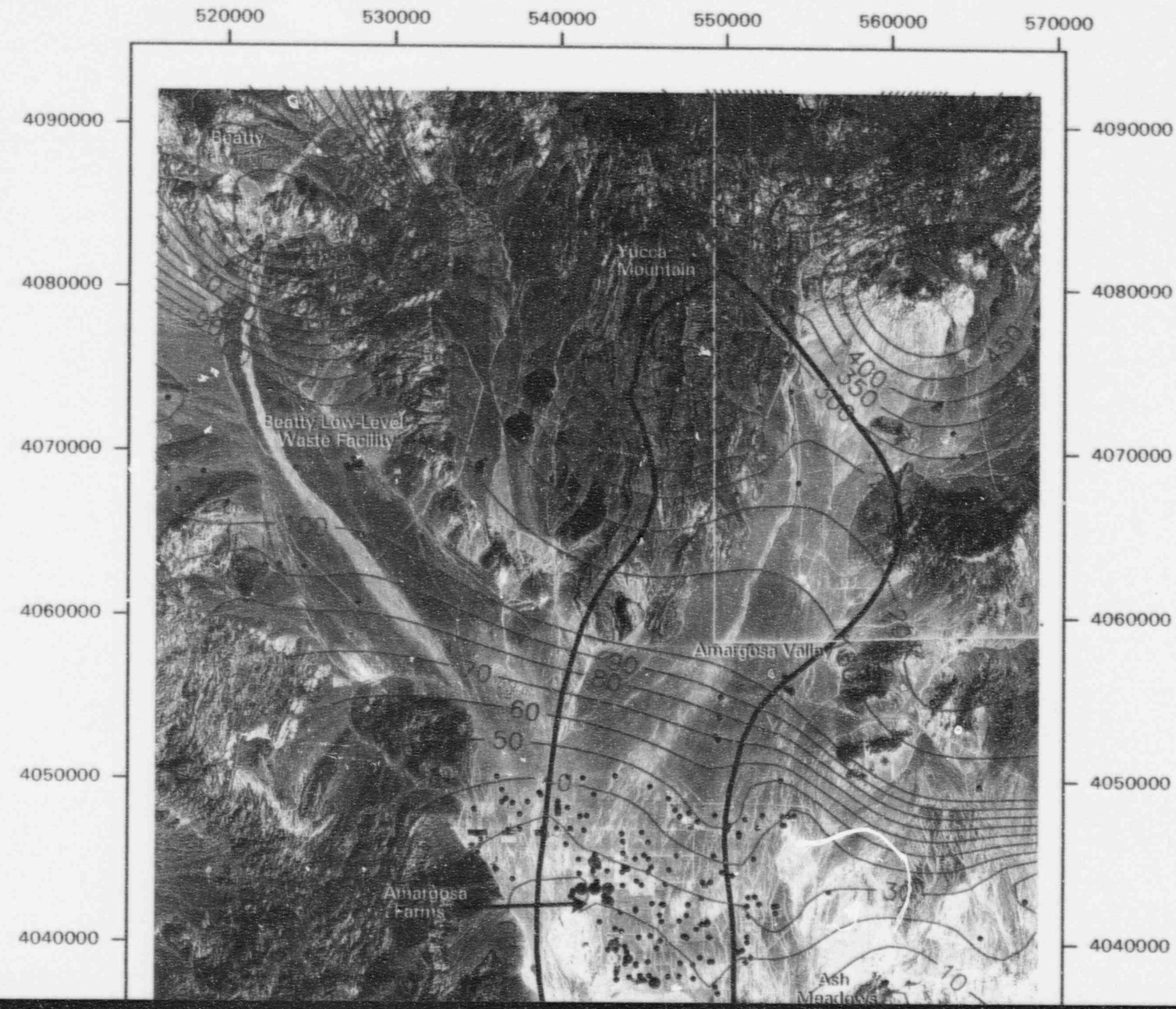
> In the present and near future, these persons are real; that is, they are the persons now living in the near vicinity of the repository and in the direction of the postulated flow of the plume of radionuclides. For the far future, however, it will be necessary to define hypothetical persons by making assumptions about lifestyle, location, eating habits, and other factors. The ICRP recommends use of present knowledge and cautious, but reasonable assumptions.

At present, the YM critical group would consist of those individuals living and working at the Nevada Research and Development Area (NRDA) facility in Jackass Flat, those living in the town of Amargosa Valley, and those farmers in the Amargosa Farms area. However, a prudent analysis must recognize that withdrawal of land by the Federal Government for the Nevada Test Site (NTS) and Nellis Air Force Base bombing range have precluded private development in the immediate YM area. Therefore, it is appropriate to examine the range of land and water use practices occurring elsewhere that may have occurred in the YM area in the absence of current institutional land control, before finalizing a description of the present critical group.

1.1 BACKGROUND

This study proposes to assess water and land use practices not currently in evidence in the region and to suggest those aspects for consideration when defining a critical group for the YM area. Inasmuch as most of the land in the immediate YM area was withdrawn from private sector development by the DOE and the U.S. Air Force in the 1950's, it is difficult to determine if current water and land use practices are solely the result of obvious topographic, hydrogeologic, climatologic, and pedologic factors. In order to determine the type of water and land use practices that might have existed in the vicinity of YM in the absence of current governmental controls, it may be reasonable to extrapolate water and land use practices from similar regions.

In addition to governmental land control, factors that appear to have affected land and water use in the Jackass Flats and Amargosa Desert area include (i) depth to water, (ii) water quality, (iii) proximity to railways and highways, (iv) occurrence of economic mineral deposits, and (v) suitability of soils and topography for irrigated agriculture. Depth to groundwater varies from over 700 m directly below the repository block at YM to less than 10 m along a short reach of the Amargosa River in the south central portion of the Amargosa Desert (Figure 1). Water quality throughout the YM and Amargosa Desert region is generally adequate for drinking, stock, and agriculture except for areas in the southern Amargosa Desert where evaporites from lacustrine deposits cause the groundwater to have total dissolved solids concentrations in excess of 10,000 ppm (Winograd and Thordarson, 1974). As can be seen in Figure 1, there are small clusters of wells near the communities of Amargosa Valley and Death Valley Junction, located at highway crossroads. Until recently, some water was used for processing specialty clays and zeolites mined from lacustrine deposits in southern Amargosa Desert and in Ash Meadows. Agricultural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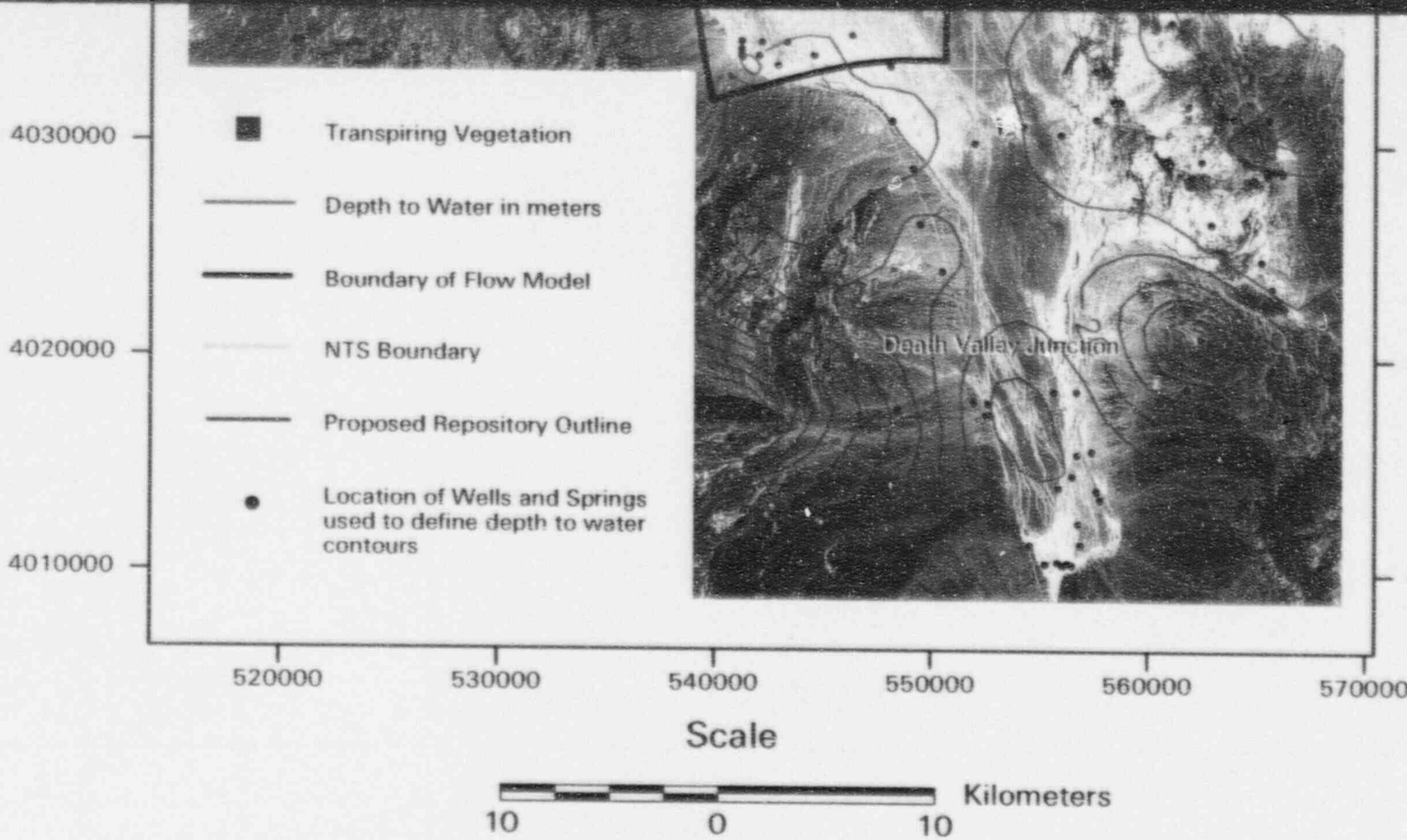

Figure 1. Map of Yucca Mountain and Amargosa Desert region. Landsat TM data used to produce background image. Red circular shapes in Amargosa Farms are quarter-section center pivot irrigation plots; rectangular-shaped red patches are flood-irrigation plots. Irregular red patches in Ash Meadows represent transpiring wetland vegetation. Contour lines show depth to water table in meters. Black dots are locations of wells and springs used to define depth to water contours.

development is currently confined to the southern Amargosa Desert area where depths to water range from 10 to 40 m and the topography is suitable for flood and center pivot irrigation.

The greatest depths to water in wells currently being pumped to supply agricultural or domestic needs in the immediate YM region occur in the town of Amargosa Valley where depths to water range from 100 to 120 m. Well J-13 in Jackass Flats on NTS pumps water from a depth of 280 m to supply drilling and tunneling operations for the Yucca Mountain Project; however, this may be considered an exceptional practice for this region. Depth to water increases monotonically from approximately 100 to more than 300 m along a trajectory extending from the town of Amargosa Valley in the south and terminating in the north approximately 10 km from the perimeter drift of the proposed YM repository (Figure 1). This trend of increasing depth to water is roughly coincident with the estimated trajectory of radionuclides exiting the repository. Thus, radionuclide concentrations due to releases from the repository would generally decrease north to south along this trajectory due to macro-scale dispersion.

1.2 HISTORY OF INHABITATION OF AMARGOSA DESERT AND ASH MEADOWS

Historically, in the arid Southwest and elsewhere, Native Americans and settlers have chosen to establish camps, homesteads, outposts, and eventually cities where perennial water supplies are readily available. In southern Nevada, to the south of YM, the springs in Ash Meadows (Figure 1) have provided water for agriculture, livestock, and humans both in the past and present.

The grasslands of Ash Meadows, framed by the leather-leaf ash trees, provided a lush oasis in the otherwise sere Mohave Desert. Paiute and Shoshone Indians camped near the waters while foraging for pine nuts, seeds, and wild game in the highlands of Ash Meadows (McCracken, 1992). Explorers, gold seekers (Forty-Niners), and settlers sought out and used the Ash Meadows waters. Eventually, settlers and farmers cultivated alfalfa to support small cattle operations and grew various fruit and vegetable crops including potatoes, tomatoes, melons, apples, pears, peaches, and more recently pistachios. Baths were routinely taken by some in Devil's Hole and more than one settler's child enjoyed fishing in Ash Meadows waters for "minews" (probably one of several species of Desert pupfish) and feeding them to their cats (McCracken, 1992). Until recently (early 1950's), there were never great numbers of permanent inhabitants of Ash Meadows and Amargosa Valley.

Although the soil is not rich, the presence of available water in the Amargosa Desert, coupled with a long, hot growing season allowed permanent inhabitation of this otherwise inhospitable portion of Nevada. However, these local farmers have not been capable of growing all of their own food. Farming was used to produce cash crops such as fruits, vegetables, and hay (alfalfa). Permanent inhabitation remains tenuous in the region, with mineral production (specialized clays and borax) and rail transportation (Tonopah and Tidewater and Las Vegas and Tonopah) as the catalyst to continuing human presence before development of the NTS. Numerous jobs and local development of habitations and associated amenities that the NTS generated in the early 1950's have continued through the 1990's.

NTS employment opportunities encouraged an increase in the population of the Amargosa Desert. The community of Amargosa Valley (as specified by tax boundaries established by the Nye County Board of Commissioners), formerly known as Lathrop Wells, includes about 1300 km^2 (500 mi^2) with a population of 909 for an average of about 0.7 per km^2. The low average population per km^2 of Amargosa Valley is misleading because most of the tax district is uninhabited except for the Amargosa

Farms. There are approximately 60 industrial/commercial establishments supported by about 350 housing units averaging 2.6 individual people (TRW, 1995b).

In 1994, housing units in Amargosa Valley increased from 352 to 365—attributed to single-family units. This represented a 3.7 percent increase annual growth with an attendant population growth of about 33 (assuming 2.5 individuals per new house). Additionally, Amargosa Valley has a school with about 150 children enrolled and present on a normal school day.

There is a relatively new dairy at the southern end of Amargosa Valley. Locally grown alfalfa provides about 10 percent of the fodder for the dairy herd. In 1984, 2,376 diary cows were reported at the Amargosa Valley operation and over 2.4 km^2 (600 acres) nereby were planted in alfalfa, yielding about 2,500 metric tons (2,800 tons) of alfalfa in 1994 (Raines, 1996).

Amargosa Valley was identified in the National Research Council 1995 report, "Technical Bases for Yucca Mountain Standards," as the location for the critical group to include individuals at maximum risk and homogeneity with respect to the risk (National Research Council, 1995). The postulated critical group is designed to be similar to the existing population in terms of characteristics and habits or behaviors that cause contact with the water supply down gradient from YM (Raines, 1996).

Currently, the nearest private water well to YM and the proposed geologic repository is found at the Cind-R-Lite mining facility at the Lathrop Wells volcanic cinder cone just north of the town of Amargosa Valley (formerly Lathrop Wells). Only two employees (Raines, 1996) work at the facility and it is not clear whether water is used solely for processing cinders or for human consumption as well. The next nearest non-NTS commercial activity, where groundwater is pumped is at the junction of US Highway 95 and Nevada State Highway 373 at Amargosa Valley. At least four individuals reside there continuously and others live there during the weekdays. Additionally, there is a 91 unit recreational vehicle park completed in late 1995. At present, the Amargosa Valley community does not include families with children. It is likely the nearest residential area with a concentration of families with children is found about 32 km to the south of YM near the school and community center at Amargosa Farm Road (known as Amargosa Farms) (Raines, 1996).

Ash Meadows is a National Wildlife Refuge and has been spared from commercial development, however, not without a struggle. In 1980, Preferred Equities of Pahrump, Nevada, purchased about 68.9 km^2 (17,000 acres) in Ash Meadows and moved forward with plans to subdivide its holdings there, anticipating eventual development of 33,600 residential lots and a community population of 50,000 (McCracken, 1992). Upon learning of the plans environmentalists moved to block further development. Eventually, the Nature Conservancy purchased 51 km^2 (12,613 acres) of land and water rights owned by Preferred Equities in Ash Meadows. In 1984, the U.S. Fish and Wildlife Service purchased the Conservancy's Ash Meadows interests and established the Ash Meadows National Wildlife Refuge to conserve threatened and endangered species found there, to promote all native wildlife, and to provide the public with recreational opportunities that would not threaten the wildlife. It must be stressed that current knowledge of the regional groundwater flow system in the YM area suggests that water discharging at Ash Meadows from the Paleozoic carbonate aquifer is part of the Ash Meadows groundwater basin, while groundwater flowing beneath YM being pumped in the Amargosa Farms region is from the Alkali Flat-Furnace Creek Ranch groundwater basin. Hence, it is less likely that radionuclides that reach the saturated zone beneath the proposed repository would be discharged at Ash Meadows.

The Preferred Equities planned scenario in Ash Meadows, where thousands of hectares of unique habitat supported by free-flowing springs draining the carbonate rock beneath southern Nevada are disrupted and replaced with thousands of homes with lush lawns, did not come to fruition (McCracken, 1992). Such development, had it occurred, may have led to residential sprawl encroaching on the YM area and increased the population in the region likely to be impacted by radionuclides migrating from the repository.

1.3 SCOPE OF STUDY AND METHODS OF ANALYSIS

The scope of this study has been limited to gathering data from Arizona, New Mexico, southern Nevada, and the Trans-Pecos region of west Texas on groundwater utilization practices that might have been employed in the YM and Amargosa Desert area in the absence of Federal land withdrawals. The climate of this region of the southwestern U.S. generally ranges from arid to semi-arid, except in higher elevations where orographic effects result in a humid, temperate climate. Based on the Köppen-Geiger climate classification scheme, the climate at YM is arid (see appendix A). Hence, certain water use practices, such as pumping groundwater for cattle grazed on marginal, semi-arid lands, should perhaps not be extrapolated to YM.

Tables and maps in this report present data on wells deeper than 150 m. Since a large number of wells have depths to water in excess of 150 m but less than 240 m in the areas studied, a detailed summary of these data was not included in appendix B. The discussions in appendix B focus on wells where depths to water equal or exceed 240 m, regardless of location similarity to YM.

Basic data on wells and water levels were obtained from the USGS GWSI database for Arizona, New Mexico, and Nevada. Because the data for each state were obtained from that state's USGS Water Resources Division Office, format and content of the data varied somewhat. Data for Texas were obtained directly from the Texas Water Development Board. Additional water well and depth to water data were obtained from various reports prepared by state and federal agencies. Anecdotal information about the occurrence of wells with great depths to water was obtained during telephone conversations with USGS personnel, groundwater supply consultants, and local well drillers.

2 EXPLOITATION OF DEEP GROUNDWATER

Outside of a few, very deep (greater than 240 m) wells drilled on the NTS to supply water to remote locations and several wells that supply water to mining operations in Crater Flat (e.g., Sterling Mine) and the Greenwater Range (U.S. Borax), most domestic and agricultural wells in the YM area are located where the water table is from 10 m to 100 m deep. This is in accord with the assumption that water wells tend to be drilled where the depth to water is shallowest to limit development and production costs. Clearly, the occurrence of valuable mineral deposits may make the construction of a 500 m deep well economically feasible for a mining company, whereas a farmer might be unlikely to expend funds on such a well to irrigate alfalfa. The extremes to which a commercial enterprise will go to secure a water supply depends wholly on the marginal value that a unit of water has in producing a commodity (e.g., ounce of gold, bale of alfalfa). At the Sterling Mine, on the eastern flank of Bare Mountain at an altitude of approximately 1150 m, water is currently trucked in from borehole VH-2 in Crater Flat to supply operations. For this case, it appears cost of transporting water a distance of some 8 km is less than pumping expenses in conjunction with the amortized cost of constructing a well at the mine. It is noted

that VH-2 was constructed as part of the YM Project before being ceded to the Sterling Mine, so costs borne by the mining company do not reflect actual costs of borehole construction.

Because water used to supply basic human needs tends to have a higher marginal utility than water used for mining and agriculture, householders are more willing to pay for water than nonagricultural, commercial, and industrial users, who in turn have a greater willingness to pay for water than agricultural users (SAIC, 1991). Although householders tend to be willing to pay for water, they generally use far less water than industrial and agricultural users. Based on this pattern of consumptive behavior alone, one would expect domestic water use to predominate where water is expensive and agricultural use to predominate where water is inexpensive. Of course other physiographic factors influence the development of a region: (i) climate and native vegetation, (ii) topography, and (iii) soil fertility. For this study, it is assumed the two primary factors affecting groundwater use are depth to the water table and climate. Depth to groundwater directly affects the cost of obtaining water while climate influences agricultural practices.

Current well drilling and pump technology allows water to be pumped from extreme depths (in excess of 1,000 m); however, its potability and, thus, suitability for watering stock or irrigating cropland generally decreases with depth. The power that must be delivered to a pump is proportional to the product of pump discharge and total lift, while the capital cost of a well depends on the rated power of the motor and capacity of the pump, diameter, length, and composition of the casing and well screen, and the method used to drill the well. As an illustration of pumping costs consider two cases: (i) a domestic well that annually supplies 617 m^3 (0.5 acre-ft, about 150 gallons per person per day for a household of 3) of water to a home from a depth of 30 m (approximately 100 ft) and (ii) an agricultural well used to supply 1.52 m (5 ft) of water to 64.7 ha (160 acres) of cropland during the growing season from a depth of 7.6 m (25 ft). Assuming a composite well efficiency of 60 percent, annual operating expenses (excluding maintenance and amortized capital costs) for the domestic well based on electricity costs of 100 mil/kWh would be \$8.40[1]. Assuming 60 percent well efficiency and electricity costs of 100 mil/kWh, annual operating expenses for the agricultural well would be \$3,391.04. If the pump lift for both the domestic and agricultural wells was increased to 240 m (787 ft), annual energy costs would rise to \$67.20 and \$32,553.98, respectively. This example illustrates the effect of depth to water on variable pumping expenses and highlights the costs of irrigating cropland where the depth to water is large.

2.1 EXPLOITATION OF DEEP GROUNDWATER IN ARIZONA

Records for 1,172 wells with depths to water equal to or greater than 150 m (approximately 500 ft) were obtained from the USGS GWSI database for Arizona. A general breakdown of these occurrences by depth to water and, where known, use of water is given in table 1. Note that the entries in the Total column exceed the row total because some well records have no entry under the water use data field. The locations of water wells in Arizona with depths to water equal to greater than 150 m are shown in figure 2.

Many of the wells with depths to water from 150 to 180 m are in the major agricultural areas of Pinal County and southern Maricopa County; however, these depths to water reflect extensive groundwater overdraft that occurred over the past 30 to 60 yr, rather than natural predevelopment hydrogeologic conditions. Since agricultural development began, water levels have declined 137 m (450 ft)

[1] Volume Pumped (617 m^3) × Pump Lift (30 m) × Unit Weight of Water (9,800 N/m^3) ÷ Efficiency (0.60) ÷ Conversion from Joules to Kilowatthours (3.6×10^6 J/kWh) × Unit Cost of Electricity (0.10 Dollars/kWh) = \$8.40.

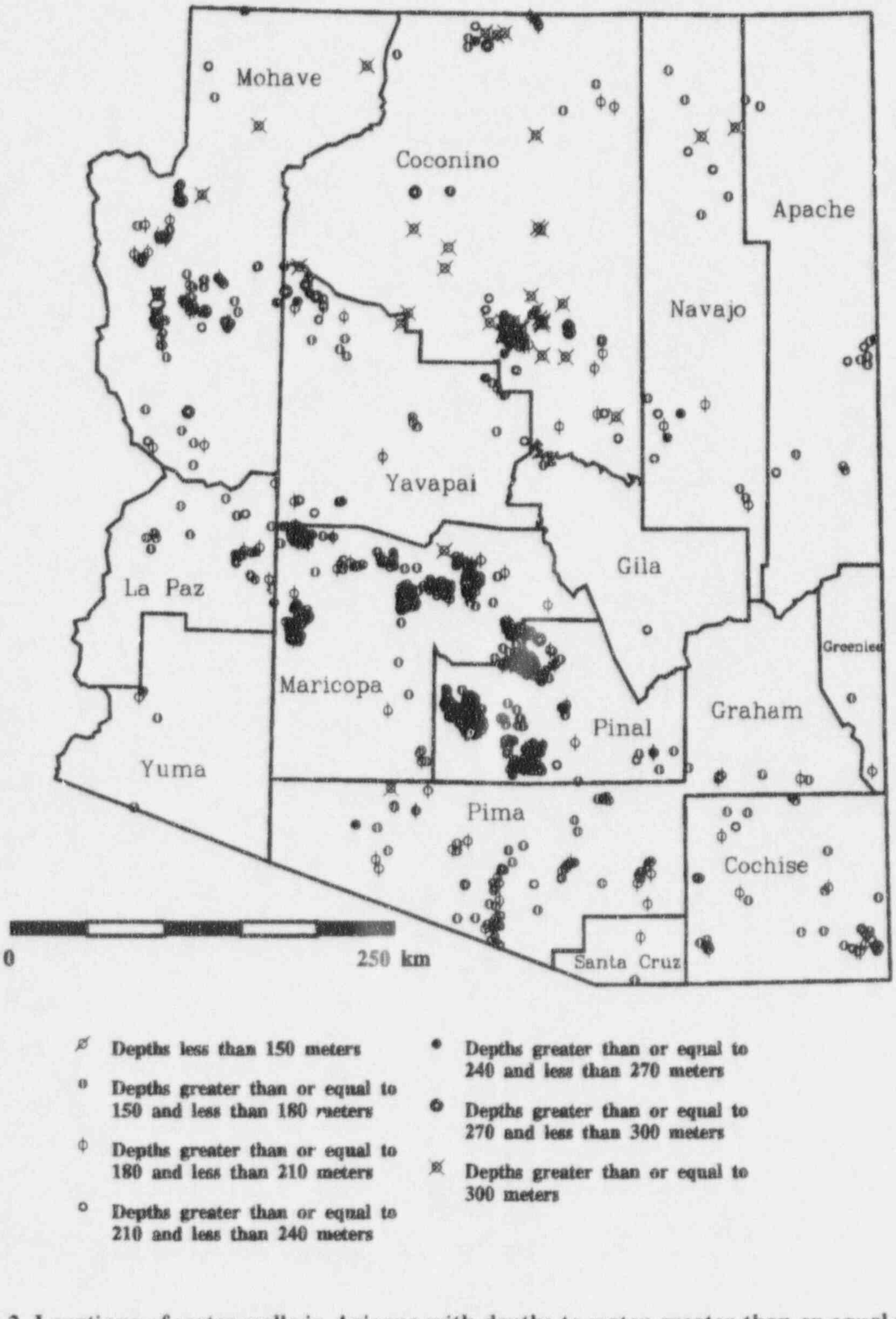

Figure 2. Locations of water wells in Arizona with depths to water greater than or equal to 150 m

Table 1. Use of water in wells with depth to water greater than 150 m in Arizona

Depth to water (m)	Irrigation	Public	Stock	Industrial	Domestic	Commercial	Unused	Total	Total with Specified Use
150–180	282[a]	76[b]	50	5	80	0	184	717	493
180–210	110[a]	29[c]	28[d]	4	26	1	51	262	198
210–240	25[e]	11[f]	12	5	13	0	22	96	66
240–270	2	7	4	3	4	0	4	31	20
270–300	0	6	3	0	2	0	5	17	11
300–330	0	3	1	0	1	0	2	8	5
330–360	0	3	2	0	3	0	1	9	8
360–390	0	6	0	0	1	0	3	10	7
390–420	0	2	1	0	1	0	4	8	4
420–450	0	3	1	0	0	0	1	5	4
450–480	0	2	0	0	1	0	1	4	3
>480	0	1	0	0	0	0	2	5	3
Totals	419	149	102	17	132	1	280	1172	822

[a] Primarily Pinal, Maricopa, and La Paz Counties
[b] Phoenix and Chandler areas
[c] Tucson, Casa Grande, Chandler, Phoenix, Flagstaff, and Kingman areas
[d] Casa Grande area
[e] Cave Creek–Carefree area

in the Stansfield Basin in western Pinal County, 128 m (420 ft) southeast of Chandler, and more than 61 m (200 ft) in the Eloy Basin in central Pinal County (Anderson, 1995). These depths to water do not reflect predevelopment conditions, hence it was felt that water use practices in these areas could not be used to infer water use practices that would have prevailed in the absence of current governmental controls in the relatively undeveloped welded tuff of the immediate YM vicinity.

Therefore, analysis of the data instead focused on the occurrence of clusters of wells with depths to water in excess of 240 m (approximately 800 ft). Table 2 indicates the percentage of wells in a specified depth to water range that are used for a given purpose. Table 2 clearly shows that as the depth to water increases, the percentage of wells used for agriculture decreases while the percentage of wells used for public supply, stock water, and domestic supply increases. This pattern in part reflects the higher value placed on water for drinking and hygiene; uses which consume very little water compared to irrigated agriculture. For wells with depths to water in excess of 240 m, public and domestic use accounts for 65 percent, stock water for 19 percent, and irrigation use for 3 percent. Of the 97 wells in Arizona with depths to water greater than 240 m, 53 are located north of the 35th parallel and east of the 113th meridian on the highlands of the Colorado Plateau, 29 are north of the 35th parallel and west of the 113th meridian in the transition zone between the Colorado Plateau and eastern Mohave Desert, and the remaining 15 wells are scattered throughout a wide area south of the 35th parallel. Table 3, which gives a breakdown of wells with depth to water in excess of 240 m as a function of land surface elevation, indicates that 63 percent of these wells are located in regions where the elevation exceeds 1,500 m. For approximately 40 of these 97 deep wells, detailed descriptions of locations and climatologic and topographic conditions are presented in Section B.1.

2.2 EXPLOITATION OF DEEP GROUNDWATER IN NEVADA

Records for 58 wells with depths to water equal to or greater than 150 m were obtained from the USGS GWSI database for Nevada. Of the 58 wells, 49 lie in the southern half of Nevada within the counties of Nye (4 wells), Lincoln (6 wells), and Clark (38 wells), and one well in these data is in Death Valley National Monument, Inyo County, California. Of the 16 wells in Nevada with depths to water equal to or greater than 240 m, 13 are in the southern Nevada counties of Nye (1), Lincoln (5), and Clark (7). A general breakdown by water use for all 58 deep wells in Nevada is listed in table 4. The locations of water wells in Nevada with depths to water in excess of 150 m are shown in figure 3. Detailed descriptions of water wells with depths to water equal to or greater than 240 m are given in section B.2. In the alluvial aquifer in the Amargosa Farms region, there is presently an estimated 30 percent groundwater overdraft (US DOE SCP, 1988).

2.3 EXPLOITATION OF DEEP GROUNDWATER IN NEW MEXICO

Records for 94 wells with depths to water equal to or greater than 150 m were obtained from the USGS GWSI database for New Mexico. Additional data on water wells were extracted from Orr (1987). Of the 94 wells, 83 are located in the northwestern quadrant of New Mexico in the counties of San Juan, Rio Arriba, Taos, McKinley, Sandoval, Santa Fe, Cibola, and Bernalillo. Elevations in this region range from 1,500 m (5,000 ft) near Four Corners and along the Rio Grande near Albuquerque to 4,011 m at Wheeler Peak in the Sangre de Cristo Mountains (13,161 ft). Although no references on the climate of northwestern New Mexico were available at the time this report was prepared, it is estimated the climate varies from cool semi-arid at the lower elevations to cool humid at the higher elevations. This wide range in climatic conditions is typical of so-called highland climates where enclosed valleys, plateaus,

Table 2. Percentage water use for wells in Arizona

Depth to water (m)	Irrigation	Public	Stock	Industrial	Domestic	Commercial
150–180	57	15	10	1	16	0
180–210	56	15	14	2	15	1
210–240	38	17	18	8	20	0
240–270	10	35	20	15	20	0
270–300	0	55	27	0	18	0
300–330	0	60	20	0	20	0
330–360	0	38	25	0	38	0
360–390	0	86	0	0	14	0
390–420	0	50	25	0	25	0
420–450	0	75	25	0	0	0
450–480	0	66	0	0	33	0
>480	0	100	0	0	0	0
>240	3	52	19	3	13	0

and exposed peaks in a highland region are very different climatically (Trewartha, 1954). A general breakdown by water use for all 94 deep wells in New Mexico is listed in table 5. The locations of water wells in New Mexico with depths to water in excess of 150 m are shown in figure 4.

Twenty-seven of these 34 wells occur in clusters in the northwestern quadrant of New Mexico in McKinley, Cibola, Sandoval, and Bernalillo Counties. Because the data received from the USGS for New Mexico did not include well head elevation in the well records, a table similar to table 3 for Arizona was not prepared. Detailed descriptions of wells with depths to water equal to greater than 240 m are given in section B.3.

2.4 EXPLOITATION OF DEEP GROUNDWATER IN TEXAS

Records for 220 wells with depths to water equal to or greater than 150 m were obtained from the Texas Water Development Board water well database. Additional data for the Trans-Pecos region were extracted from Rees (1987). Of the 220 wells, 168 are located in the Trans-Pecos, (area in Texas west of the Pecos River) and in the adjoining counties of Upton, Crockett, and Val Verde, immediately to the east of the Pecos River. The Trans-Pecos region as a whole is arid to semi-arid with mean annual precipitation of approximately 30 cm, although there are isolated mountain ranges where precipitation may exceed 40 cm/yr, such as the Chisos Mountains where average annual precipitation at the Chisos Basin is 42.4 cm/yr (Bomar, 1983). The remaining 52 wells are located in the Llano Estacado and Panhandle regions of the

Table 3. Arizona wells with depth to water in excess of 240 m as a function of well head elevation

Land Surface Elevation (m)	Number of Wells
0–300	1
300–600	5
600–900	12
900–1200	9
1200–1500	9
1500–1800	21
1800–2100	27
2100–2400	13

High Western Plains great physiographic province where mean annual precipitation is 45 cm (Bomar, 1983) and the climate is semi-arid steppe. General exploitations by water use of all 220 wells and the 168 wells in the Trans-Pecos region are listed in tables 6 and 7, respectively. The locations of water wells in the Trans-Pecos region of Texas are shown in figure 5.

Well construction practices for low-discharge, high-lift stock and domestic wells used in the Trans-Pecos region and New Mexico may have implications for water use within 10 km of the proposed repository where depths to water exceed 240 m. Typical stock and domestic wells only need to be capable of pumping 1.26×10^{-4} to 3.79×10^{-4} m^3/s (2 to 6 gpm). For example, the Pate Altuda Ranch near Alpine, Brewster County, Texas[2], has three wells that each pump 1.26×10^{-4} m^3/s (2 gpm) from depths to water of 335, 396, and 430 m. One of the Pate Altuda wells is pumped with a 3.7 kW (5 hp) submersible, while the other two use pump jacks[3]. Pump jacks or sucker rods are commonly used to extract heavy oils from reservoirs that have de-pressurized; however, using pump jacks for deep water wells is uncommon in most of the U.S. According to local drillers in Brewster County, pump jacks are regularly used for high-lift, low-discharge water wells. Because several of the deep water wells in the Trans-Pecos region were originally drilled as oil or gas tests, the use of pump jacks may reflect the drillers experience with and preference for oilfield technology rather than a decision based on economic or technical considerations. Windmills are also used for high-lift, low-discharge wells in the Trans-Pecos region. A typical windmill may employ a 6 m (20 ft) Aermotor turbine mounted on a 18 m (60 ft) tower[4].

2.5 ESTIMATED WELL CONSTRUCTION COSTS IN YUCCA MOUNTAIN AND AMARGOSA DESERT REGION

As illustrated in section 2, pumping costs vary in direct proportion to the depth to water. Capital costs of a well depend on the total borehole depth, well diameter, and rated capacity of the pump. A detailed well construction cost study was conducted to estimate capital costs for four wells typical of the YM and Amargosa Desert regions. Wells 1 and 2 are based on the actual design of Wells J-13 and J-12, respectively (Young, 1972). Well 3 is based on a generic design for a well that would be used to supply water to a quarter-section, center-pivot irrigation plot in the Amargosa Farms area. Well 4 is based on a generic design of a well used to supply domestic or public water to the community of Amargosa Valley (formerly Lathrop Wells). Detailed construction and completion costs are shown for each of these four wells in appendix C.

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[2] Personal communication, W. Skinner, July 1996.

[3] Ibid

[4] Ibid

Table 4. Use of water in wells with depth to water greater than 150 m in Nevada

Depth to water (m)	Irrigation	Public	Stock	Industrial	Domestic	Commercial	Unused	Total	Total with Specified Use
150–180	1	3	2	1	4	0	6	21	11
180–210	0	0	3	2	5	0	6	16	10
210–240	0	0	1	0	2	0	2	5	3
240–270	0	0	3	0	1	0	7	12	4
270–300	0	0	1	0	0	0	2	3	1
300–420	0	0	0	0	0	0	1	1	0
Totals	1	3	10	3	12	0	24	58	29

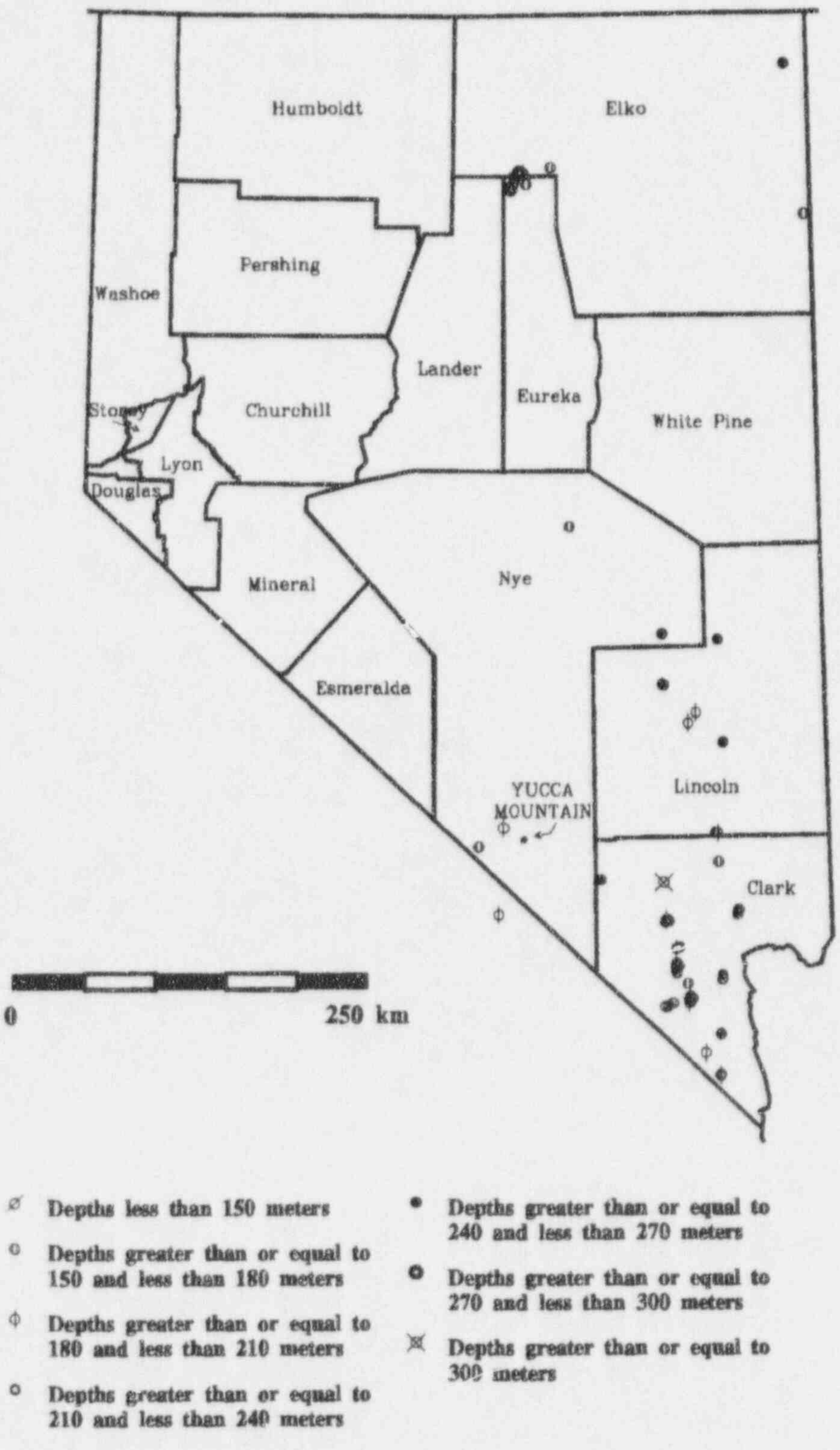

Figure 3. Locations of water wells in Nevada with depths to water greater than or equal to 150 m

Table 5. Use of water in wells with depth to water greater than 150 m in New Mexico

Depth to water (m)	Irrigation	Public	Stock	Industrial	Domestic	Commercial	Unused	Total	Total with Specified Use
150–180	1	9	2	2	0	0	6	22	14
180–210	1	7	3	2	0	1	6	20	14
210–240	0	4	4	1	0	0	8	18	9
240–270	0	1	1	3	1	2	4	12	8
270–300	0	2	5	0	0	1[a]	2	11	8
300–330	0	1	1	0	1	0	6	9	3
330–360	0	1	0	0	0	0	0	1	1
360–480	0	0	0	0	0	0	0	0	0
>480	0	0	0	1	0	0	0	1	1
Totals	2	25	16	9	2	4	32	94	58

[a]Institutional water use

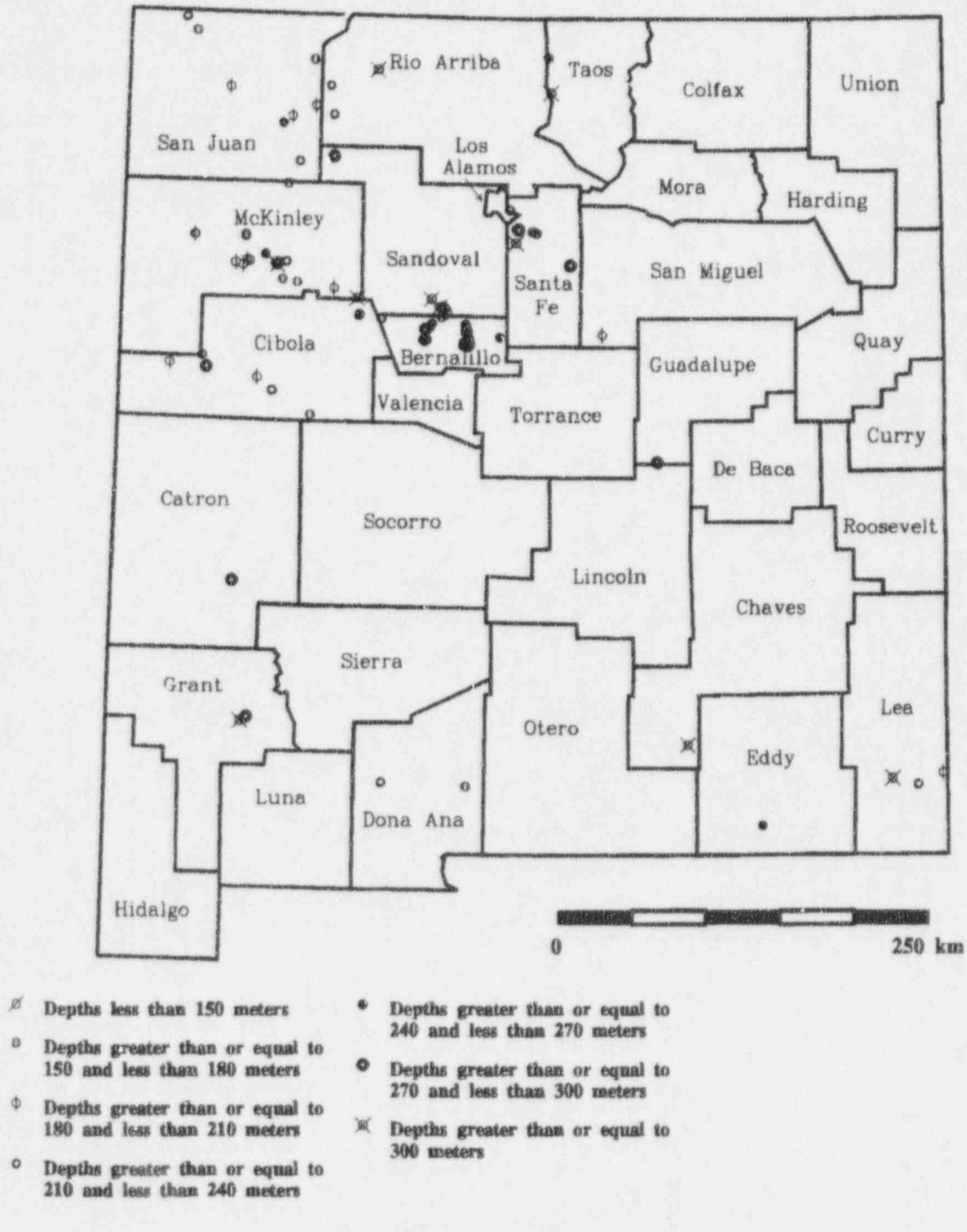

Figure 4. Locations of water wells in New Mexico with depths to water greater than or equal to 150 m

Table 6. Use of water in wells with depth to water greater than 150 m in Texas

Depth to water (m)	Irrigation	Public	Stock	Industrial	Domestic	Commercial	Unused	Total	Total with Specified Use
150–180	9	6	38	4	11	1	17	87	69
180–210	2	3	20	6	8	0	14	53	39
210–240	0	0	9	4	3	0	7	24	23
240–270	0	0	7	5	2	0	4	19	14
270–300	0	3	4	2	1	0	8	18	10
300–330	0	0	1	2	1	0	2	6	4
330–360	0	0	2	0	1	0	1	4	3
360–390	0	0	0	4	0	0	1	5	4
390–420	0	0	0	1	0	0	0	1	1
420–450	0	0	0	0	0	0	0	0	0
450–480	0	0	0	0	1	0	0	1	1
>480	1	0	1	0	0	0	0	2	2
Totals	12	12	82	28	28	1	54	220	163

Table 7. Use of water in wells with depth to water greater than 150 m in the Trans-Pecos region of Texas

Depth to water (m)	Irrigation	Public	Stock	Industrial	Domestic	Commercial	Unused	Total	Total with Specified Use
150–180	0	3	36	0	11	1	13	64	51
180–210	0	2	20	5	8	0	11	46	35
210–240	0	0	9	0	3	0	7	20	19
240–270	0	0	7	0	2	0	3	13	9
270–300	0	3	4	2	1	0	8	14	10
300–330	0	0	1	1	1	0	2	5	3
330–360	0	0	2	0	1	0	1	4	4
>360	0	0	1	0	1	0	0	2	2
Totals	0	8	80	8	28	1	45	168	133

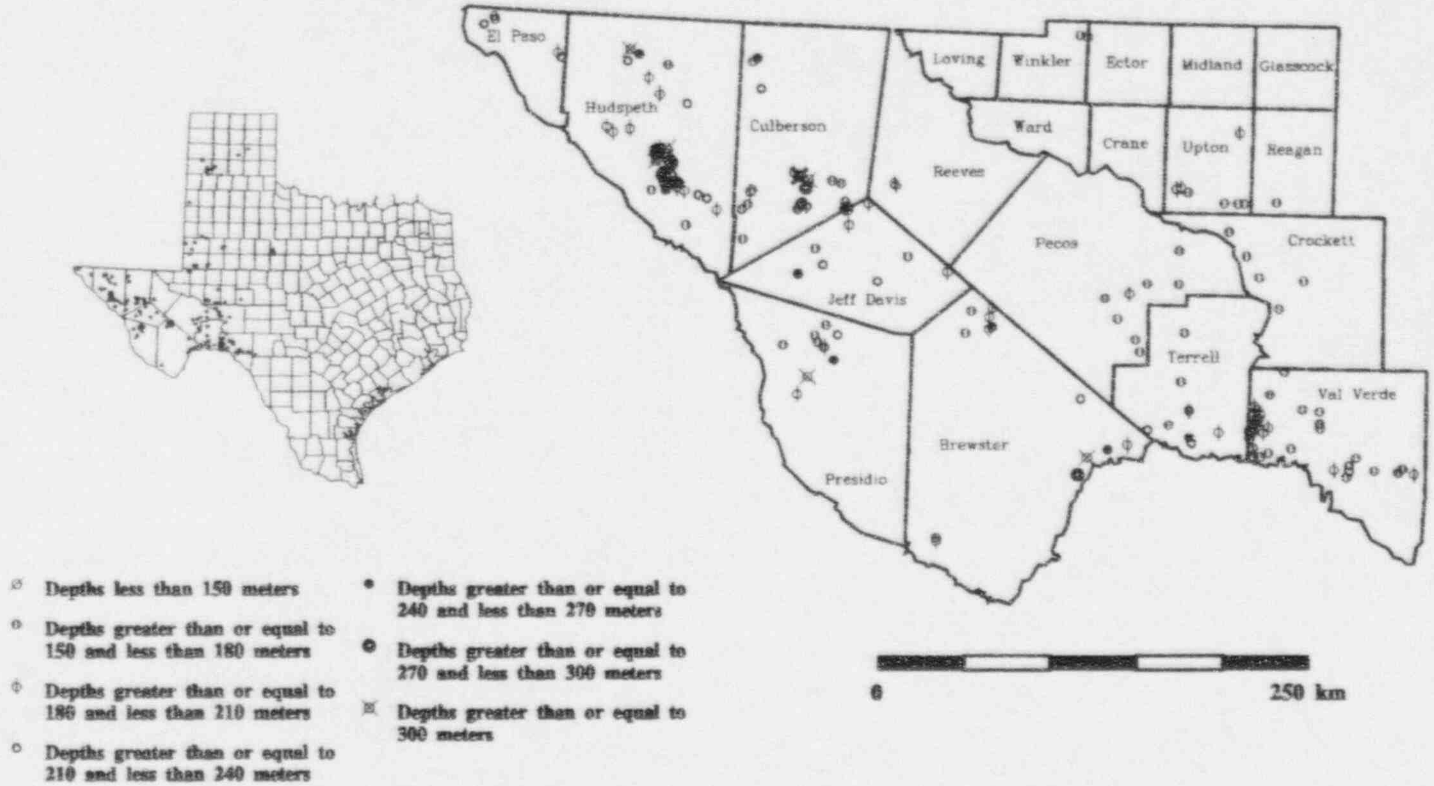

Figure 5. Locations of water wells in the Trans-Pecos region of Texas with depths to water greater than or equal to 150 m

Using current construction practices, the total cost of installing a well similar to J-13 (Well 1) is $1,117,670 (all prices in 1996 dollars). This large expenditure is primarily due to the great depth of Well J-13 (1,066 m, 3,500 ft), directly reflected in the costs of drilling, casing, screening, and installing the gravel pack (table C–1). Because J-12 (Well 2) is only 274 m (900 ft) deep, its estimated cost is $229,145 (table C–2). The generic Amargosa Farms irrigation well (Well 3), which is 97 m (320 ft) deep, pumps from a depth of 30 m (100 ft) and has a rated pump capacity of approximately 0.15 m^3/s (2,400 gpm) and costs $167,745 (table C–3). The Amargosa Valley domestic well (Well 4), which has a total depth of 183 m (600 ft), a depth to water of 91 m (300 ft), and a rated pump capacity of only 0.00063 m^3/s (10 gpm) costs $161,470 (table C–4).

Examples of unit and total pumping costs for each of the four archetypal YM and Amargosa Desert region wells are illustrated in table 8. The unit water costs for Wells 1 and 2 can be compared; however, because the unit amortized capital cost decreases as water use increases, unit water costs for Wells 1 and 2 cannot be compared to those for Well 4, which is also used for public supply. Well 3 supplies water for agricultural use, thus its unit costs should not be compared to any of the other three wells.

Construction methods used for water wells in the Trans-Pecos region of Texas and in New Mexico suggest that the installation of a small-diameter, high-lift, low-capacity domestic well powered by either a pump jack or a windmill is possible for the area near YM where the depth to water is approximately 300 m. Such a well may be economically feasible for drinking water only. Construction cost estimates for such a well, pumped by a submersible turbine, are shown in table C–5. As shown in table C-6, substituting an appropriately-sized windmill costs approximately $10,000 more than the submersible, although unit pumping costs for the windmill would be minimal. A comparable pump jack would probably cost somewhat less than the submersible.

3 SUMMARY OF OBSERVATIONS AND IMPLICATIONS

Data from Arizona, southern Nevada, New Mexico, and the Trans-Pecos region of Texas, indicate that groundwater is pumped from aquifers in arid to semi-arid regions where the depth to water is as great as that in Jackass Flat to the east of YM. Table 9 lists the number of wells with depths to water greater than 240 m by state and type of water use. Based on the percentage of total water use by type shown in the last row of table 9, it appears that pumping groundwater for irrigation from depths greater than 240 m is a rare practice (1.7 percent) and probably should not be considered likely to occur in the immediate vicinity of YM. A significant percentage (33 percent) of these deep wells is used to supply stock water, so this scenario may need to be considered when defining a YM critical group. Public and domestic water supply account for 54.8 percent of all deep water well occurrences, suggesting this scenario should be considered when defining the YM critical group.

As noted in section 1.3, cattle ranching requires rangeland capable of producing grasses suitable for forage stock water. While ranching can be practiced in semi-arid regions, such as the Trans-Pecos region northwest of the Rio Grande Valley or in the highlands of New Mexico and Arizona, grass cover is generally insufficient in arid regions such as Las Vegas, Nevada. Although feral burros in Crater Flat west of YM are apparently able to sustain themselves on the meager grasses that grow in this region, it seems unlikely that less hardy cattle could find sufficient forage.

Table 8. Unit water costs for four YM-Amargosa Desert wells

	Well 1	Well 2	Well 3	Well 4
Unit Pumping Cost ($/m^3) [a]	0.128	0.102	0.0136	0.0413
Annual Consumption (m^3)	622,000[b]	622,000[b]	771,000[c]	8,300[d]
Amortized Capital Cost ($) [e]	117,687	24,127	17,669	17,012
Unit Amortized Capital Cost ($/m^3)	0.189	0.0387	0.0229	2.05
Total Unit Cost ($/m^3)	0.317	0.141	0.0365	2.091
Total Annual Cost [f] ($)	197,174	87,515	28,141	17,355

[a]Following formula in footnote 1
[b]Population of 3000, daily per capita water use 0.57 m^3 (150 gpd)
[c]Alfalfa Farm, 1.52 m (5 ft) of water per season, on 50.7 ha (125 ac)
[d]Population of 40, daily per capita water use 0.57 m^3 (150 gpd)
[e]Economic lifetime 30 yr, interest rate 10%
[f]Does not include distribution and maintenance costs

The water well data suggest that water use practices in the immediate vicinity of YM may have included a small cluster of homes supplied by one or more small-diameter, low-discharge, high-lift wells or a community or suburb supplied by wells similar in construction to J-13 had the land not been withdrawn by the Federal government. Approximately one-third of the public supply wells listed in table 9 are found in the Flagstaff, Arizona, area which has a much cooler and wetter climate than YM. However, these data can still be used to support the proposition that communities will construct extremely deep water wells to meet public demands. The proposed development of Ash Meadows as a residential community based on availability of water at the surface could encourage suburban sprawl which might eventually expand to the Jackass Flat area some 40 km to the north. Such a scenario for urban growth and associated suburban sprawl in an arid environment which originally attracted settlers because of the perennial springs that watered an extensive meadow (*vegas* in Spanish) has been demonstrated in the development of the Las Vegas Valley.

Table 9. Use of water in wells with depth to water greater than 240 m in Arizona, southern Nevada, New Mexico, and the Trans-Pecos region of Texas

State	Irrigation	Public	Stock	Industrial	Domestic	Commercial	Total with Specified Use
Arizona	2	33	12	3	13	0	63
Nevada	0	0	4	0	1	0	5
New Mexico	0	5	7	4	2	2	20
Trans-Pecos Texas	0	3	15	3	6	0	27
Totals (% Total)	2 (1.7)	41 (35.7)	38 (33.0)	10 (8.7)	22 (19.1)	2 (1.7)	115

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APPENDIX A

CLASSIFICATION OF CLIMATE AT YUCCA MOUNTAIN, NEVADA

In the Köppen-Geiger system of climate classification, the annual precipitation boundary between humid and arid/semi-arid precipitation/climate regimes is determined for places where the winter is the wet season (like YM vicinity) by the following equation:

$$\mathbf{R(Humid/Sub\text{-}humid\ boundary) = .44(T\text{-}32)}$$

where R is the average annual boundary precipitation in inches and T is the average annual temperature in Fahrenheit degrees.

For YM which has an average annual temperature of about 16 °C or 61 °F, the boundary between a humid and sub-humid climate would be 12.8 in. of precipitation annually.

The boundary in the Köeppen-Geiger climate classification between semi-arid and arid climates is one-half the precipitation value obtained for the humid/sub-humid boundary. The formula is

$$\mathbf{R(Semi\text{-}arid/Arid\ boundary) = .22(T\text{-}32)}$$

Thus, the precipitation boundary for an arid climate classification at YM would be 6.4 in. annually.

The approximate average annual precipitation at YM is 150 mm or 5.9 in. YM classifies as an arid climate according to the Köeppen-Geiger climate classification scheme because its precipitation is below the 6.4 in., the boundary between arid/semi-arid climates at sites that have winter dominated precipitation and an average annual temperature of 61 °F.

APPENDIX B

DETAILED DESCRIPTIONS OF DEEP WELLS

B.1 DEEP WELLS IN ARIZONA

The City of Flagstaff in Coconino County has developed two well fields that pump from the Coconino Sandstone aquifer. Five municipal wells in the vicinity of Woody Mountain southwest of Flagstaff have depths to water that range from 337 to 433 m, while a second well field in the vicinity of Lake Mary southeast of Flagstaff have depths to water that range from 100 to over 300 m. Although the Coconino Sandstone can be quite productive where extensively fractured, most of the Flagstaff municipal wells produce 0.006 m^3/s (100 gpm) or less[5]. Analysis of electronic maps constructed from USGS data, indicates two other clusters of wells northeast of Flagstaff with depths to water ranging from 388 to 458 m, which, based on the relatively small diameters of the casings (20 cm), appear to be water supply wells for mountain subdivisions[6]. Well head elevations in the Flagstaff area range from 1,940 to 2,195 m. The average annual precipitation at the Flagstaff meteorological station is 53 cm (Sellers et al., 1985). Using the Köppen climatological classification system, the climate of Flagstaff is *Dfa*, or humid temperate. According to Fairbridge (1967), Flagstaff is in the special highland climate category.

Two wells in the vicinity of the towns of Twin Arrows and Angell in Coconino County have depths to water of 280 and 287 m. One of these wells is used for domestic supply; the other well water use is not specified. Well head elevations are 1,760 and 1,790 m. Twin Arrows lies approximately 35 km east of Flagstaff on Interstate Highway 40. The nearest meteorological stations to Twin Arrows are those at Walnut Canyon National Monument 20 km to the west and Meteor Crater 35 km to the east-southeast with measured mean annual precipitation of 45 and 21 cm, respectively (Sellers et al., 1985). Because of the extreme variation in precipitation between the nearest meteorological stations, it is difficult to classify the local climate; however, it is estimated that the area has a cool to cold semi-arid climate (*BWk* to *BWk'*).

In the vicinity of Gray Mountain in Coconino County are two wells with depths to water of 360 and 377 m that are used for domestic and public water supplies. Gray Mountain is located about 65 km north of Flagstaff on US 89 near the southern boundary of the Navajo Indian Reservation. Well head elevations are approximately 1,500 m. Gray Mountain meteorological station recorded mean annual precipitation of 13 cm; however, this station only recorded data from 8/56 to 4/62, during which Arizona experienced two prolonged droughts (Sellers et al., 1985). Wupatki National Monument, approximately 20 km south of Gray Mountain, has a record of 34 yr and mean annual precipitation of 20 cm, while Cameron lying about 16 km to the north has a record of 20 yr and mean annual precipitation of 14 cm (Sellers et al., 1985). Gray Mountain probably has a cool to cold semi-arid climate (*BWk* to *BWk'*).

In the northeastern end of the Sacramento Valley, approximately 15 km west of Kingman in Mohave County, there are three public water supply wells with depths to water that range from 309 to 321 m. Seven other wells in the Sacramento Valley have depths to water ranging from 265 to 406 m; all lie within three adjacent townships (T21N R18W, T22N R18W, and T23N R18W). Of these seven wells, two are for industrial use, one is for domestic use, and the remaining four are now unused. Well head elevations in this area range from 800 to 1,030 m. The average annual precipitation in Kingman is approximately 26 cm (Sellers et al., 1985). Köppen's climatological classification for Kingman is *BSh*, or tropical steppe.

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[5] Personal communication, R. Wilson, June 1996.

[6] Ibid

Four wells in the eastern part of the Detrital Valley near Dolan Springs in Mohave County have depths to water that range from 215 to 240 m. Although the depth to water in these wells does not equal or exceed 240 m, a detailed description was provided because the climate may be similar to that of YM under pluvial conditions. Two of these wells are unused and the remaining two wells appear to be pumped for domestic use. Elevations of the well heads range from 900 to 920 m. According to a description of the pedology of this region, the soils and climate support native vegetation consisting of blackbrush, creosote bush, Mohave yucca, rayless goldenhead, big galleta, and desert needlegrass[7]. The same source states that the rangeland is suited for wildlife habitat and grazing livestock. Dolan Springs is approximately 40 km northwest of the Kingman meteorological station (elevation 1050 m).

Within a 1100 km^2 area of northwest Yavapai County, including the 12 townships from T22N R10W to T25N R8W, are two clusters of three wells each and four additional isolated wells which have depths to water that range from 244 to 406 m. Nine of the ten wells have depths to water between 244 and 290 m. One cluster lies within a 14 km radius of the town of Yampai, while the second cluster lies within a 5 km radius of the town of Pica—a rail stop on the Atchison, Topeka, and Santa Fe railroad. The three wells near Yampai are currently unused, while two of the three wells near Pica are for stock water, and the third for public supply. Elevations of the well heads range from 1,570 to 1,720 m. Peach Springs meteorological station, lies approximately 25 northwest of Yampai and Pica along Route 6., at an elevation of 1,510 m and has average annual precipitation of 28 cm (Sellers et al., 1985). Based on Arizona isohyet map (National Oceanic and Atmospheric Administration, 1974), it seems reasonable to assume that the average annual precipitation in the general area is less than 30 cm. Meteorological data from Peach Springs are incomplete so data from nearby Truxton Canyon were used to estimate the region's climate. Using Köppen's climatological system, the climate of the region is *BSh*, or tropical steppe.

On the Paria Plateau, north of the east end of Grand Canyon National Park, there are four stock wells and one domestic well with depths to water that range from 262 to 457 m. Well head elevations for these wells range from 1,875 to 1,950 m. The Paria Plateau appears to have an average elevation of approximately 1,850 m, some 300 m lower than the Kaibab Plateau to the west where the average annual precipitation at the Jacob Lake meteorological station is 52 cm (Sellers et al., 1985). House Rock, Arizona, which lies 16 km west of Jacob Lake at an elevation of 1,640 m, has average annual precipitation of 18 cm (Sellers et al., 1985). Based on the magnitude of local orographic effects, it is estimated that the mean annual precipitation on the Paria Plateau ranges from 30 to 40 cm. Because meteorological data for House Rock are incomplete, it is difficult to accurately determine the climate of the Paria Plateau. The Paria Plateau is approximately 580 m lower in elevation than the meteorological station at Jacob Lake, which has a climate similar to Flagstaff, hence the plateau probably has a cool semi-arid to highland climate.

At the extreme north central part of the state is a cluster of three wells located in the vicinity of Wahweap and Glen Canyon Dam State Park with depth to water that ranges from 259 to 268 m. Two of the wells are pumped for public water supply, while the use of the third well is unknown. Well head elevations are approximately 1,250 m. Average annual precipitation in Wahweap is only 15 cm (Sellers et al., 1985). The Wahweap area has a climate that is similar to that of Las Vegas, which is classified as cool arid or as mid-latitude desert (Fairbridge, 1967).

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[7] Information found on World Wide Web: (http://www.statlab.iastate.edu/soils-info/osd as of 8/7/96) for Nealy series soil. Web page describes the Nealy series soil, type location 9 miles southwest of Dolan Springs, Mohave County, Arizona. Server located at Iowa State University.

The city of Williams, Coconino County, Arizona, is considering constructing a municipal supply well that would pump water from the Redwall unit where the depth to water is approximately 600 m [8]. Williams is located about 45 km west of Flagstaff on I-40, and appears to have a similar highland climate.

B.2 DEEP WELLS IN NEVADA

Of the six wells in Nye and Lincoln Counties with depths to water in excess of 240 m, five are unused test boreholes associated with the MX mobile ICBM study and were constructed by the USGS for the Department of Defense during the late 1970's and early 1980's. Depths to water in these test boreholes range from 245 to 263 m. Well head elevations for three of the test boreholes in Coal Valley range from 1,550 to 1,710 m. Because these boreholes were constructed for national defense, it seems that few inferences can be drawn from their existence regarding water well development near YM. The use of the sixth deep well (265 m) is unspecified.

There are seven wells in Clark County with depths to water that range from 250 to 407 m. Four of these wells are scattered from west to east across a wide area north of Las Vegas extending from 12 km southeast of Mercury (256 m) to the southeastern terminus of the Desert Range (407 m), to a narrow valley between the Dry Lake Range and Muddy Mountains in far eastern Clark County (251 and 251 m). The well southeast of Mercury has a well head elevation of 1,087 m, and pumps water for unspecified use from the Bonanza King formation. The very deep well southeast of the Desert Range has a well head elevation of 1,272 m, and is currently unused. The two wells in far eastern Clark County have well head elevations of 789 and 791 m; one well is currently unused, the other supplies stock water. Three other deep wells are located south of Las Vegas. One currently unused well is located in the south end of Hidden Valley directly to the west of the McCullough range at an elevation of 924 m and has a depth to water of 290 m. South of Boulder City near the northwestern terminus of the Black Hills at an elevation of 707 m is a domestic well with a depth to water of 250 m. Approximately 16 km north of Searchlight along U.S. 95 there is a stock well at an elevation of 925 m that has a depth to water of 262 m. It is assumed the climate for most of this area is similar to that of Las Vegas or mid-latitude desert.

B.3 DEEP WELLS IN NEW MEXICO

In Bernalillo County, to the west of Albuquerque, there are three wells that pump from depths to water of 237[9], 263, and 270 m, which are located on top of a north-trending mesa some 60 to 70 km in length. Two of the wells are located near the three volcanoes, which are approximately 10 km west of Albuquerque. Two of the wells on the mesa are currently unused and one is a commercial well. Two other wells with depths to water of 256 and 281 m are located east of Albuquerque near the town of Sedillo and near Bear Canyon, respectively. The deep well located near Sedillo is also a commercial well; however, Bear Canyon well water use is not specified.

In south central Sandoval County near the county line with Bernalillo County there are three public supply wells with depths to water of 276, 307, and 342 m. All three wells are located in or near the town of Alameda, approximately 20 km north-northwest of Albuquerque on a mesa rising about 300

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[8] S. Leake personal communication, July 1996

[9] Included because of association with other wells deeper than 240 m.

m above the Rio Grande Valley. Alameda is primarily an upper middle-class residential community. The elevation of Alameda is approximately 1,800 m. Alameda probably has a cool semi-arid to arid climate similar to Albuquerque.

Within Santa Fe County (east of Sandoval County) there are three wells with depths to water of 276, 299, and 318 m. The two deeper wells are located in the Santa Fe National Forest near Pankey Peak, which has an elevation of 2,200 m. Both of these wells are powered by windmills and used to supply stock water. The shallowest well is located on Glorieta Mesa approximately 13 km southwest of Pecos, New Mexico. This well also supplies stock water; however, it is pumped by a gasoline-powered pump jack. This region's climate would probably be classified as highland.

Within Taos County, which is north-northeast of Santa Fe County, there are two wells with depths to water of 247 and 329 m. The deeper of the two wells is located about 10 km south-southeast of Tres Piedras near Highway 285. This well is used for domestic supply and is pumped by a gasoline-powered pump jack. The shallower well is located about 14 km north of Tres Piedras and appears to be operated by the Johns Mansville Perlite Corporation for industrial purposes.

West of Albuquerque in McKinley and Cibola Counties there are a number of deep wells located on or near Indian reservations. Fourteen kilometers north-northeast of Cebolleta (Seboyeta), Cibola County near Canon de Marques in far southeastern McKinley County there is an unused well with a depth to water of 314 m. Eight kilometers east-southeast of Cebolleta in Cibola County there are two deep industrial wells located along Meyer Draw each with a depth to water of 258 m. Elsewhere in McKinley County there are two unused wells located 21 and 23 km south of the Chaco Culture National Monument with depths to water of 288 and 314 m, respectively. A fourth deep well in McKinley County is located 5 km west of Borrego Pass Trading Post, has a depth to water of 240 m, and is pumped for domestic use. On the Ramah Navajo Indian Reservation located in west central Cibola County approximately 13 km south of the community center, there is a well with depth to water of 298 m. Orr (1987) designates this as the Ramah-2 well and notes that it pumps from the Glorieta-San Andres aquifer. The Ramah-1 well is located within the same quarter-section as Ramah-2 and pumps from the Glorieta-San Andres aquifer at a depth to water of 291 m (Orr, 1987). Well head elevations for Ramah-1 and Ramah-2 are 2,269 and 2,279 m, respectively. The Cheechilgeetho School in Cheechilgeetho, Cibola County, approximately 35 km south-southwest of Gallup, New Mexico, at an altitude of 2,076 m, had a well that pumped from the Glorieta-San Andres aquifer with a depth to water of 339 m, before it was plugged (Orr, 1987).

In southwestern New Mexico near Silver City, Grant County, there are two wells with depths to water of 299 and 594 m. The shallower well is located about 4 km east of the mining town of Turnerville and is used for public supply. The deep well is located about 3 km south of Turnerville and is used for industrial supply. The extreme depth to water recorded in this latter well may reflect pumpage to de-water underground copper mine adits.

B.4 DEEP WELLS IN TEXAS

In the Trans-Pecos region there are 38 wells with depths to water that equal or exceed 240 m. Twenty-two of these deep wells are located in Hudspeth County with 20 being in the general vicinity of the town of Sierra Blanca. Diamondhead Corporation owns seven wells to the northwest of Sierra Blanca that have depths to water ranging from 287 to 339 m. Two of Diamondhead wells are used for public water supply, one for stock, one for industrial supply, one for domestic supply, and one former public

supply well is currently unused. All of Diamondhead wells pump from the Cretaceous aquifer and produce from 0.00019 m^3/s (3 gpm) for stock water to 0.032 m^3/s (510 gpm) for public supply. Well head elevations for the Diamondhead wells range from 1,393 to 1,522 m. Sierra Blanca Corporation owns two wells near Sierra Blanca with depths to water of 271 and 275 m. One of Sierra Blanca Corporation deep wells is unused while the other is used for stock water. Nine other wells near Sierra Blanca have depths to water ranging from 240 to 341 m and are primarily used to supply stock. In northern Hudspeth County, approximately 40 km south of Dell City, there are two wells that pump from a Paleozoic aquifer at depths to water of 244 and 347 m.

In Culberson County, which lies immediately east of Hudspeth County, there are seven wells with depths to water in excess of 240 m. Five of these wells are located in a cluster northwest of the town of Kent near the Apache Mountains. Two of these five wells are owned by the Foster Ranch and used to supply domestic and stock water. One of the Foster Ranch wells is a converted oil test well and pumps from a depth to water of 463 m. The second Foster Ranch well pumps from a depth to water of 276 m. The other three wells of this cluster are owned by the Apache Ranch and are abandoned industrial wells originally owned by Elcor Chemical Corporation. These three wells have depths to water that range from 307 to 323 m; two wells are used to provide water for stock tanks, the third is unused. In northern Culberson County south of the city of Pine Springs, which lies at the southern end of the Guadalupe Mountains, the Six-Bar Cattle Company operates a well for stock water that has a depth to water of 244 m. In the immediate vicinity of Kent, Reynolds Cattle Company pumps stock water from a well with a depth to water of 293 m. The five wells in the Apache Mountains area and the one well near Kent pump from the Permian Capitan Reef Complex aquifer. The well near Pine Springs pumps from the Paleozoic Bone Spring limestone aquifer. Well head elevations for the Apache Mountains cluster range from 1,350 to 1,543 m. The Reynolds Cattle Company well head elevation is 1,359 m and the Six-Bar Cattle Company well head elevation is 1,391 m.

Scattered along the Rio Grande River in southeastern Brewster County are three wells used by local ranches for domestic and stock water that have depths to water ranging from 245 to 328 m. This area is significantly lower in elevation than most of the Trans-Pecos region, with well head elevations ranging from 745 to 804 m. Two of these wells pump from the Edwards-Trinity Plateau aquifer.

Other deep wells in the Trans-Pecos region include (i) one in Jeff Davis County near the town of Valentine, (ii) one in Terrell County south of the town of Dryden, and (iii) one in southwestern Val Verde County. The depths to water in these very widely scattered wells range from 241 to 293 m.

APPENDIX C

WELL CONSTRUCTION COSTS
(prepared by D. Williams)

C.1 DESCRIPTION OF WELLS

Drilling and installation costs for five separate wells were estimated. The completion details for four of the five wells were based on existing wells; the fifth well was a non-specific, low-cost well for supplying a stock pond. Not all well completion details were available for the four existing wells, therefore some standard well installation practices were assumed.

All drilling costs are for air rotary drilling. All casing costs are for low-carbon steel casing. Replacement wells for the four known wells were completed as gravel packed wells. For consistency, all wells used the same screen—louvered Johnson Irrigator screen.

The five wells are described in the following paragraphs.

Well 1

Well 1 is a 3,385 foot deep well, completed in welded and bedded tuffs. Completion details of Well 1 are shown on table C-1 and include the following

Total borehole depth	3,500 ft
Well depth	3,385 ft
Borehole diameter	26 in.
Casing diameter	14 in.
Total Screen length	2,162 ft

The well that Well 1 replaced was a telescoped well, with casing diameters of 18 in., 13 3/8 in., 11¾ in., and 6 in. The original Well 1 was completed as a telescoped well because of problems encountered during drilling. Well 1 will be simpler to install as a single casing diameter well.

Well 1 is outfitted with a submersible pump that was sized to produce 700 gallons per minute (gpm) against a static head of 1,000 ft.

Well 2

Well 2 is an 887 foot deep well, completed in welded and bedded tuffs. Completion details of Well 2 are shown on table C-2 and include the following

Total borehole depth	900 ft
Well depth	887 ft
Borehole diameter	22 in.
Casing diameter	12¾ in.
Total screen length	75 ft

Well 2 is outfitted with a submersible pump that was sized to produce 800 gpm against a static head of 800 ft.

Well 3

Well 3 is a 320 foot deep well, completed n alluvial deposits consisting of medium to fine grained sands interbedded with silts. Well 3 is an irrigation well that provides water to a quarter-section center-pivot irrigation system. Completion details of Well 3 are shown on table C-3 and include the following

Total borehole depth	320 ft
Well depth	320 ft
Borehole diameter	28 in.
Casing diameter	16 in.
Total screen length	150 ft

Pump requirements for Well 3 were estimated from conversations with Bob Wilson of the Agricultural Extension in Ely, Nevada.[10] Mr. Wilson stated that most center-pivot irrigation systems in southern and eastern Nevada are fitted with 100 horsepower motors and pump against 150 ft of head. Flow rates from these wells is unknown. Theoretical calculations for flow rates indicate a 100 horsepower motor produces 2,637 gpm against 150 ft of static head. Depending on the size and make of the discharge pipe, this flow rate will be reduced by friction, but will likely remain above 2,400 gpm.

In accordance with irrigation practices in other parts of Nevada, Well 3 is outfitted with a 100 horsepower turbine shaft pump.

Well 4

Well 4 is a 600 foot deep well, completed in alluvial deposits consisting of coarse sand interbedded with gravel and silt. Well 4 is a domestic well, providing water to one or two dwellings. Completion details of Well 4 are shown on table C-4 and include the following

Total borehole depth	600 ft
Well depth	600 ft
Borehole diameter	19 in.
Casing diameter	8 in.
Total screen length	200 ft

Well 4 is outfitted with a five horsepower submersible pump, set at 450 ft below ground surface (bgs). The pump was sized to produce at least 10 gpm against a static head of 300 ft.

Well 5

Well 5 is a 1,500 foot deep well, completed in welded and bedded tuffs. Well 5 provides water to a stock tank and Well 5 is cased to a depth of 150 ft. Between 150 ft and 1,500 ft, Well 5 is completed as an open hole in the fractured tuffs. This well is designed to be drilled and completed in a single pass with minimal completion details. Completion details of Well 5 are shown on table C-5 and include the following

[10] R. Wilson personal communication, July, 1996.

Total borehole depth	1,500 ft
Well depth	1,500 ft
Borehole diameter	8 in.
Casing diameter	Not Applicable
Total screen length	Not Applicable

Well 5 is outfitted with a five horsepower submersible pump set at 1,250 ft bgs. The pump was sized to produce 2 gpm against a static head of 1,000 ft.

C.2 WELL COSTS

Costs for Wells 1 through 5 are included on tables C-1 through C-5.

C.3 OPTIONAL PUMP COSTS

Costs for two optional pumping systems were estimated. The two pumping systems include a windmill and a pump jack. Each optional pumping system was designed to produce two to three gallons per minute against a static head of 1,000 ft.

Windmill

Lifting a column of water 1,000 ft requires a 20 foot diameter windmill. The only available windmills of this size are reconditioned Aermotor windmills. The standard tower for these windmills is 40 ft high. The cost for buying this tower is unknown. Any other tower over 40 ft high would be custom built.

Costs for a 20 foot diameter windmill mounted on a 40 foot tower are included in table C-6. The total cost is estimated at $25,700.

Pump Jack

A pump jack capable of producing approximately 3 gpm against a head of 1,000 ft costs around $5,000. This cost does not include the electric motor for powering the pump jack.

Table C-1. Well 1 costs

Item	Units	Quantity	Unit Cost	Cost
Install 30" Conductor Casing	feet	50	$ 175.00	$ 8,750.00
Drill Pilot Hole	feet	3450	$ 45.00	$ 155,250.00
E-log	line item	1	$ 7,000.00	$ 7,000.00
Ream Pilot Hole to 26"	feet	3450	$ 60.00	$ 207,000.00
Caliper Log	line item	1	$ 4,000.00	$ 4,000.00
Install Blank Casing	feet	1223	$ 120.00	$ 146,760.00
Install Screen	feet	2162	$ 160.00	$ 345,920.00
Install Gravel Pack	feet	2515	$ 45.00	$ 113,175.00
Gravel Tube	feet	990	$ 6.00	$ 5,940.00
Grout Seal	feet	985	$ 55.00	$ 54,175.00
Plumbness & Alignment Test	line item	1	$ 5,500.00	$ 5,500.00
Surge/Airlift Development	hours	24	$ 275.00	$ 6,600.00
Pumping Development	hours	24	$ 150.00	$ 3,600.00
Step Test	hours	10	$ 150.00	$ 1,500.00
Constant Q Test	hours	40	$ 150.00	$ 6,000.00
Pump Cost	line item	1	$ 20,000.00	$ 20,000.00
Install Pump	line item	1	$ 6,500.00	$ 6,500.00
Elect. & Wellhead Finish	line item	1	$ 20,000.00	$ 20,000.00
TOTAL COST				$ 1,117,670.00

Table C-2. Well 2 costs

Item	Units	Quantity	Unit Cost	Cost
Install 22" Conductor Casing	feet	50	$ 125.00	$ 6,250.00
Drill Pilot Hole	feet	400	$ 40.00	$ 16,000.00
E-log	line item	1	$ 4,000.00	$ 4,000.00
Ream Pilot Hole to 22"	feet	900	$ 50.00	$ 45,000.00
Caliper Log	line item	1	$ 2,000.00	$ 2,000.00
Install Blank Casing	feet	812	$ 55.00	$ 44,660.00
Install Screen	feet	75	$ 75.00	$ 5,625.00
Install Gravel Pack	feet	117	$ 25.00	$ 2,925.00
Gravel Tube	feet	125	$ 6.00	$ 750.00
Grout Seal	feet	783	$ 45.00	$ 35,235.00
Plumbness & Alignment Test	line item	1	$ 2,500.00	$ 2,500.00
Surge/Airlift Development	hours	24	$ 275.00	$ 6,600.00
Pumping Development	hours	24	$ 150.00	$ 3,600.00
Step Test	hours	10	$ 150.00	$ 1,500.00
Constant Q Test	hours	40	$ 150.00	$ 6,000.00
Pump Cost	line item	1	$ 20,000.00	$ 20,000.00
Install Pump	line item	1	$ 6,500.00	$ 6,500.00
Elect. & Wellhead Finish	line item	1	$ 20,000.00	$ 20,000.00
TOTAL COST				$ 229,145.00

Table C–3. Well 3 costs

Item	Units	Quantity	Unit Cost	Cost
Install 30" Conductor Casing	feet	50	$ 175.00	$ 8,750.00
Drill Pilot Hole	feet	320	$ 40.00	$ 12,800.00
E-log	line item	1	$ 3,000.00	$ 3,000.00
Ream Pilot Hole to 28"	feet	320	$ 50.00	$ 16,000.00
Caliper Log	line item	1	$ 2,000.00	$ 2,000.00
Install Blank Casing	feet	175	$ 65.00	$ 11,375.00
Install Screen	feet	150	$ 85.00	$ 12,750.00
Install Gravel Pack	feet	180	$ 35.00	$ 6,300.00
Gravel Tube	feet	145	$ 6.00	$ 870.00
Grout Seal	feet	140	$ 55.00	$ 7,700.00
Plumbness & Alignment Test	line item	1	$ 2,500.00	$ 2,500.00
Surge/Airlift Development	hours	24	$ 275.00	$ 6,600.00
Pumping Development	hours	24	$ 150.00	$ 3,600.00
Step Test	hours	10	$ 150.00	$ 1,500.00
Constant Q Test	hours	40	$ 150.00	$ 6,000.00
Pump Cost	line item	1	$ 40,000.00	$ 40,000.00
Install Pump	line item	1	$ 6,000.00	$ 6,000.00
Elect. & Wellhead Finish	line item	1	$ 20,000.00	$ 20,000.00
TOTAL COST				$ 167,745.00

Table C–4. Well 4 costs

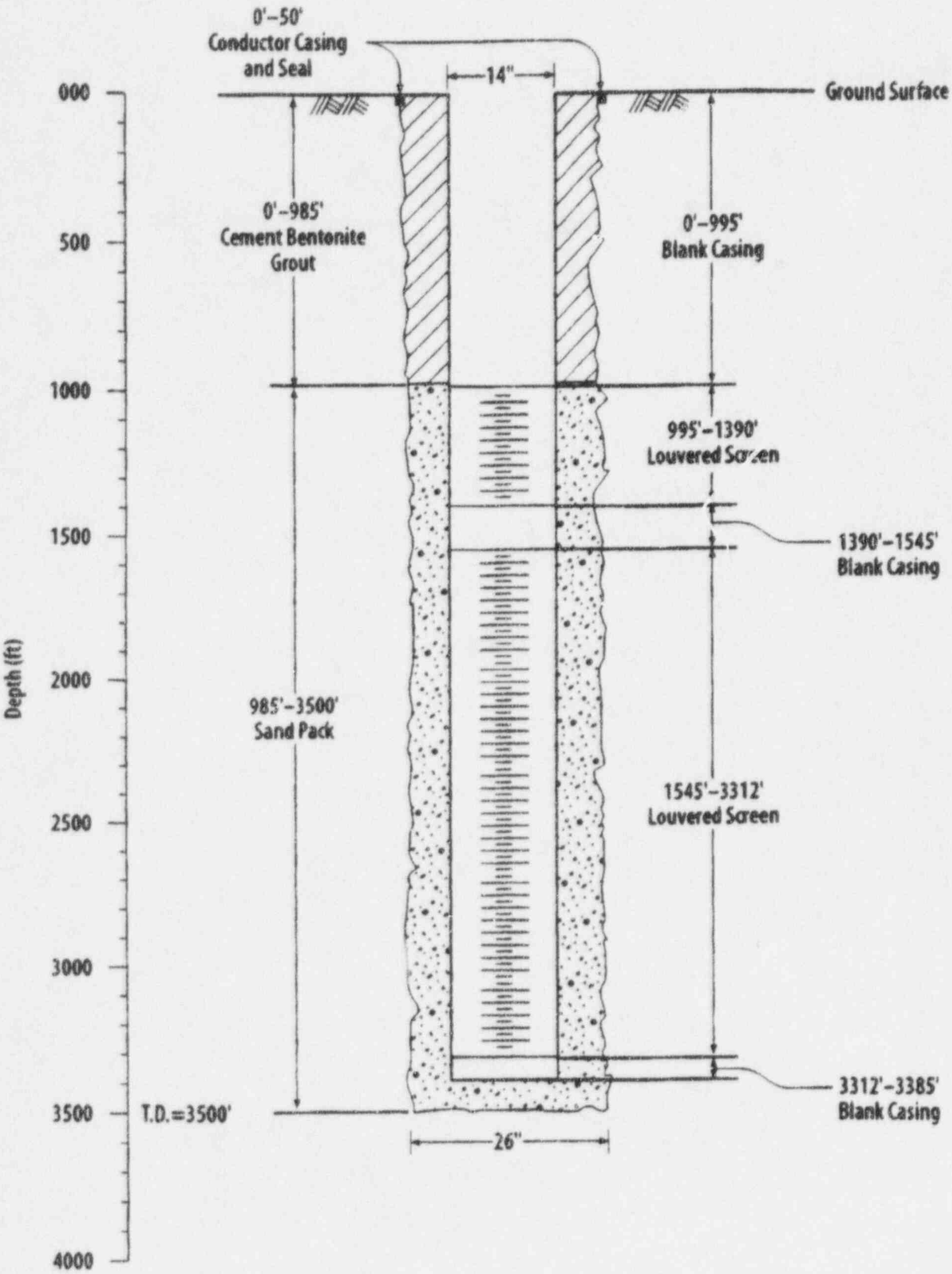
Item	Units	Quantity	Unit Cost	Cost
Install 16" Conductor Casing	feet	50	$ 100.00	$ 5,000.00
Drill Pilot Hole	feet	600	$ 35.00	$ 21,000.00
E-log	line item	1	$ 3,000.00	$ 3,000.00
Ream Pilot Hole to 19"	feet	600	$ 45.00	$ 27,000.00
Caliper Log	line item	1	$ 2,000.00	$ 2,000.00
Install Blank Casing	feet	400	$ 41.00	$ 16,400.00
Install Screen	feet	200	$ 60.00	$ 12,000.00
Install Gravel Pack	feet	260	$ 20.00	$ 5,200.00
Gravel Tube	feet	345	$ 6.00	$ 2,070.00
Grout Seal	feet	340	$ 40.00	$ 13,600.00
Plumbness & Alignment Test	line item	1	$ 2,500.00	$ 2,500.00
Surge/Airlift Development	hours	24	$ 275.00	$ 6,600.00
Pumping Development	hours	24	$ 150.00	$ 3,600.00
Step Test	hours	10	$ 150.00	$ 1,500.00
Constant Q Test	hours	40	$ 150.00	$ 6,000.00
Pump Cost	line item	1	$ 8,000.00	$ 8,000.00
Install Pump	line item	1	$ 6,000.00	$ 6,000.00
Elect. & Wellhead Finish	line item	1	$ 20,000.00	$ 20,000.00
TOTAL COST				$ 161,470.00

Table C-5. Well 5 costs

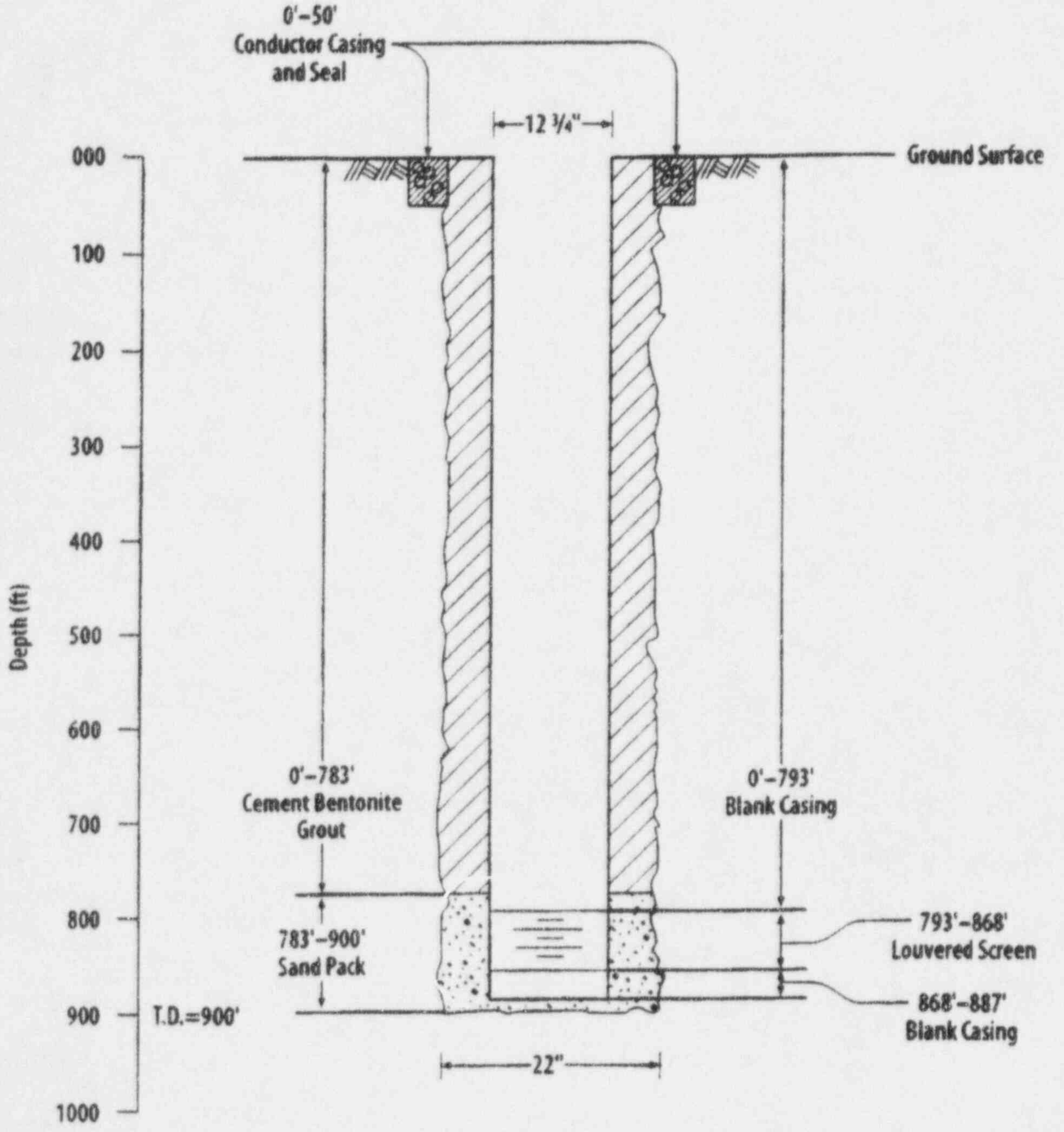
Item	Units	Quantity	Unit Cost	Cost
Install 16" Conductor Casing	feet	50	$ 100.00	$ 5,000.00
Drill Pilot Hole	feet	1500	$ 45.00	$ 67,500.00
E-log	line item	1	$ 5,000.00	$ 5,000.00
Ream Pilot Hole to 26"	feet		N/A	N/A
Caliper Log	line item	1	$ 3,000.00	$ 3,000.00
Install Blank Casing	feet	150	$ 41.00	$ 6,150.00
Install Screen	feet		N/A	N/A
Install Gravel Pack	feet		N/A	N/A
Gravel Tube	feet		N/A	N/A
Grout Seal	feet		N/A	N/A
Plumbness & Alignment Test	line item	1	N/A	N/A
Surge/Airlift Development	hours	24	$ 275.00	$ 6,600.00
Pumping Development	hours	24	$ 150.00	$ 3,600.00
Step Test	hours	10	$ 150.00	$ 1,500.00
Constant Q Test	hours	40	$ 150.00	$ 6,000.00
Pump Cost	line item	1	$ 15,000.00	$ 15,000.00
Install Pump	line item	1	$ 6,000.00	$ 6,000.00
Elect. & Wellhead Finish	line item	1	$ 20,000.00	$ 20,000.00
TOTAL COST				$ 145,350.00

Table C-6. Windmill costs

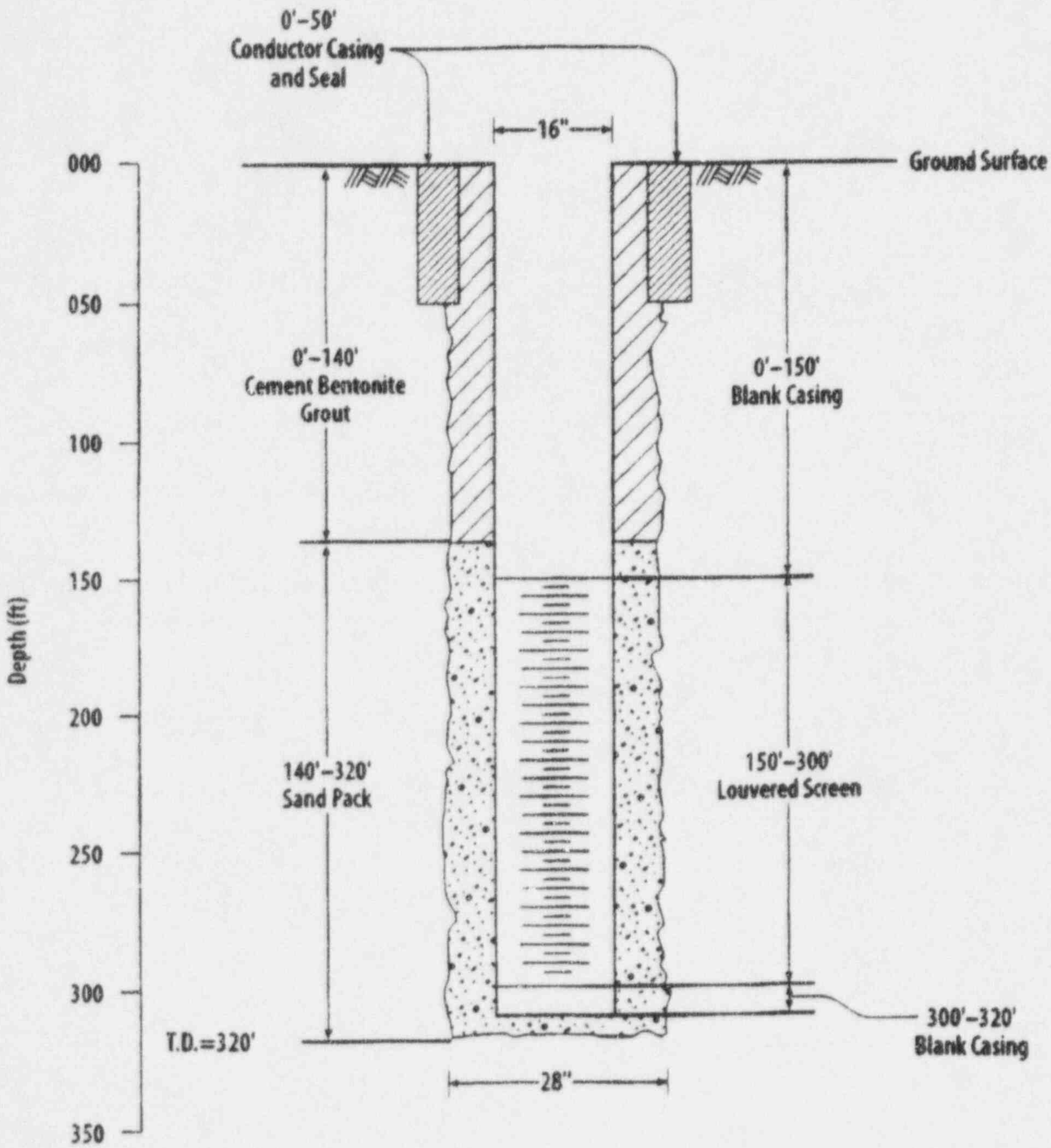
Item	Units	Quantity	Unit Cost	Cost
20' Diameter Windmill on a 40' Tower	Lump Sum	1	$ 18,000.00	$ 18,000.00
3/4" Sucker Rod	21' Rod	72	$ 65.94	$ 4,747.68
2" Threaded Black Steel Drop Pipe	21' Pipe	72	$ 37.99	$ 2,735.28
Pump Cylinder	Lump Sum	1	$ 225.00	$ 225.00
TOTAL COST				$ 25,707.96



derrik wi[illegible], r.g.	The Center for Nuclear Waste Regulatory Analyses	Figure 1 Well 1 Completion Details	August 1996



derrik wi[illegible], r.g.	The Center for Nuclear Waste Regulatory Analyses	Figure 2 Well 2 Completion Details	August 1996



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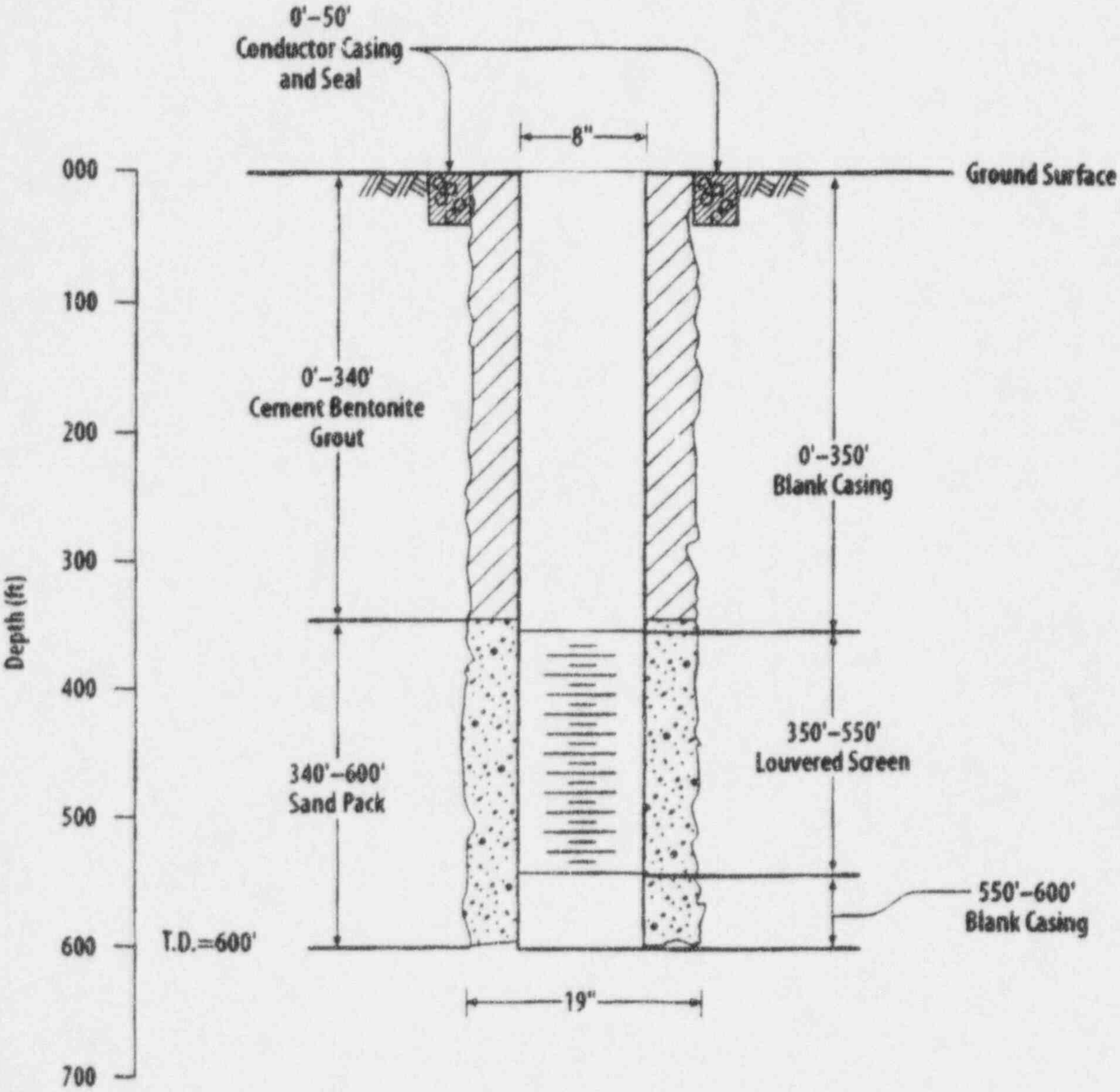

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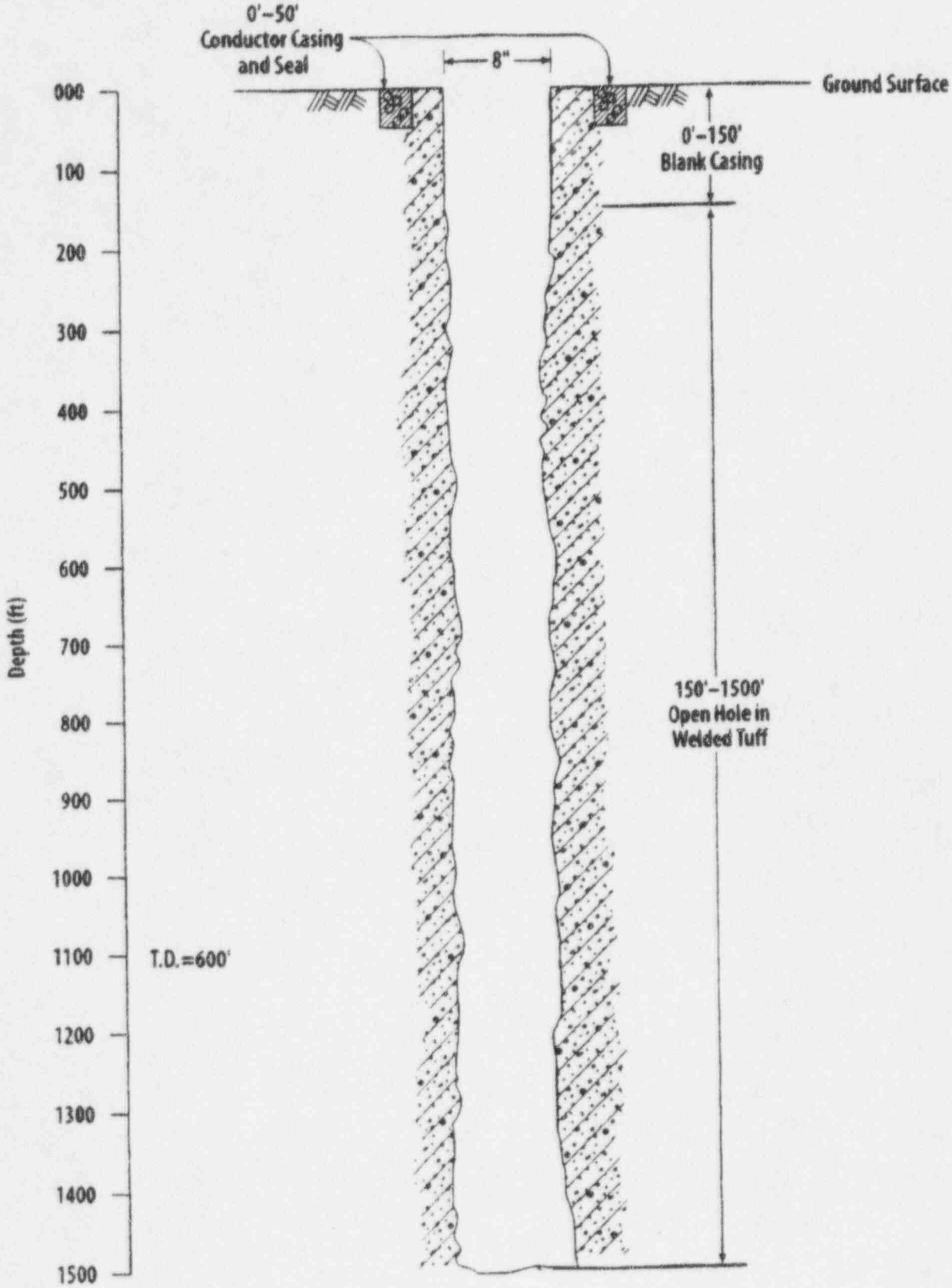

derrik wi[illegible], r.g.	The Center for Nuclear Waste Regulatory Analyses	Figure 5 Well 5 Completion Details	August 1996