OVERVIEW OF THE WIPP GROUNDWATER MONITORING PROGRAMS WITH INFERENCES ABOUT KARST IN THE WIPP VICINITY

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ABSTRACT.—The Waste Isolation Pilot Plant (WIPP), located in southeast New Mexico, is a U.S. Department of Energy (DOE) facility designed for the safe disposal of transuranic wastes resulting from U.S. defense programs. As part of the compliance certification process with the U.S. Environmental Protection Agency (EPA), groundwater monitoring programs have been established to measure changes in water level as well as chemical and physical properties of the water. The monitoring network currently consists of 63 wells situated in and around the WIPP vicinity. Of these, 49 are completed to the Culebra Dolomite Member of the Permian Rustler Formation, the most transmissive hydrologic unit in the WIPP vicinity. Comparison of Culebra water-level records with precipitation records indicates that there is a local area of recharge in the vicinity of WIPP, namely Nash Draw (~8 km west of WIPP). Recharge, in turn, appears to be driven by intense rainfall events (>60 mm) of short duration (<48 hrs). The limited response observed in Culebra wells spread over the WIPP site to such rainfall events does not support the suggestion that karst exists in the vicinity of WIPP, except in Nash Draw.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is a U.S. Department of Energy (DOE) facility designed for the safe disposal of transuranic waste resulting from U.S. defense programs. As early as 1957, the National Academy of Sciences (NAS) recommended natural rock salt as an appropriate medium for disposal of radioactive waste (NAS, 1957). Following this recommendation, the DOE through its predecessor agencies, the Atomic Energy Commission (AEC) and later the Energy Research and Development Administration (ERDA), identified the Delaware Basin of southeastern New Mexico as a candidate site based on the presence of the thick salt beds of the Permian Salado Formation. In 1972 site selection and characterization began.

It was well known during the site characterization for WIPP that karst (i.e., caves, sinkholes, dolines, etc.) was present ~8 km to the west, in an area known as Nash Draw. Nash Draw is a northeasterly trending depression, ~30 km long and ranging from 8-16 km wide, thought to be formed by the coalescence of numerous karst features (Bachman, 1987). The topic of karst at WIPP is controversial and highly debated, as can be seen in numerous reports and articles (see references in Hill, 2003; Lorenz, 2006). Here we do not review the arguments about whether karst is present at WIPP. Instead, we focus on describing the history, methods, and results of WIPP groundwater monitoring programs. Using this information, we then draw some inferences about WIPP hydrology that may aid in the resolution of the karst debate.

Geologic Setting

The WIPP site is situated in the northern portion of the Delaware Basin, ~40 km east of Carlsbad, Eddy County, NM (Fig. 1). The Delaware Basin underlies extreme southeastern New Mexico and portions of west Texas, and is bounded by the Capitan Reef on the west, north, and east sides (Bachman, 1985). Near WIPP, the stratigraphy pertinent to this paper includes: the Castile, Salado, and Rustler Formations and Dewey Lake Red Beds of Late Permian age; the Triassic-age Dockum Group; and Quaternary sedimentary/eolian deposits (Fig. 2).

The WIPP repository is excavated in bedded halite of the Salado, approximately 655 m below ground surface (Fig. 2). At the center of the WIPP site, the Salado is ~600 m thick and is overlain by ~95 m of Rustler and ~150 m of Dewey Lake. The Dewey Lake is, in turn, overlain unconformably by ~15 m of

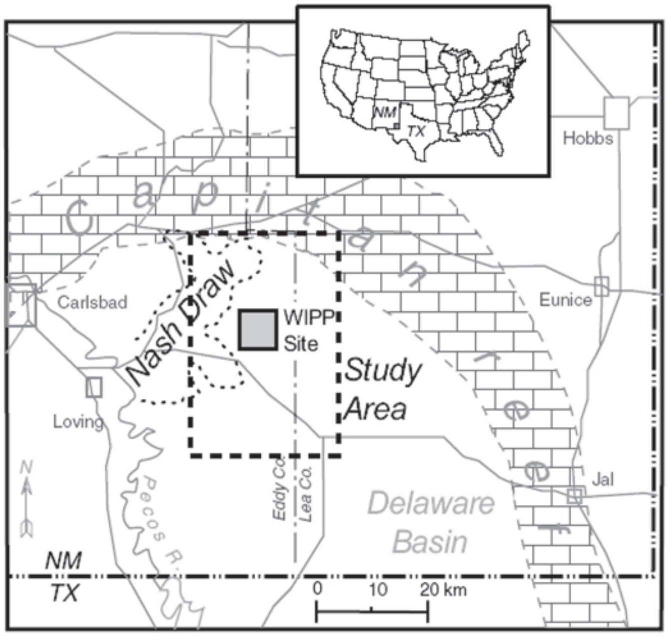

FIGURE 1. Location of the WIPP site and principal study area.

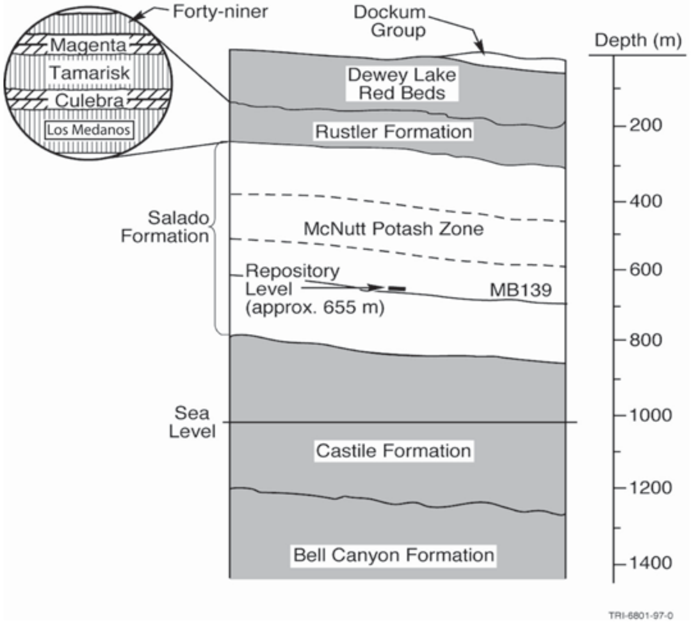

FIGURE 2. WIPP stratigraphic column.

surficial sedimentary and eolian deposits. From the approximate center of the WIPP site to the east, the Dockum Group is present between the Dewey Lake and surficial deposits.

WIPP Site Hydrology

Naturally occurring groundwater is found, at least locally, in four principal horizons above the Salado: the Rustler-Salado contact, the Culebra and Magenta Dolomite Members of the Rustler, and the Dewey Lake (Fig. 2; Mercer, 1983). Water (actually brine) found at the Rustler-Salado contact is localized to the Nash Draw area (Mercer, 1983) and the Dewey Lake yields water to wells only in the southern part of the WIPP site and farther south (Beauheim and Ruskauff, 1998). The Magenta and Culebra are the most laterally continuous hydrologic units in the WIPP vicinity (Mercer, 1983). The Magenta is less transmissive than the Culebra, and bears no water southwest of the WIPP site (i.e., southern Nash Draw). The Culebra is the primary focus of groundwater monitoring efforts at WIPP because it is the most transmissive and continuously saturated hydrologic unit at the site. Thus, it is considered one of the possible pathways for radionuclide release to the environment if the repository were ever to be breached (Beauheim and Holt, 1990).

GROUNDWATER MONITORING AT WIPP

Groundwater monitoring of the various water-bearing units at WIPP has been conducted since site characterization began. At present, groundwater-monitoring activities are overseen by the Integrated Groundwater Team which comprises members from the DOE; Sandia National Laboratories (SNL), in the role of Scientific Advisor to the DOE; and Washington Regulatory and Environmental Services (WRES) an affiliate of Washington TRU Solutions (WTS), the WIPP site Management and Operating Contractor.

Evolution of the Groundwater Monitoring Network

Site selection for WIPP commenced in 1972 when Oak Ridge National Laboratory and the U.S. Geological Survey (USGS) drilled two exploratory boreholes ~8 km northeast of the current WIPP site (near the AEC-7 borehole; Fig. 3). In 1975, SNL became the lead for scientific investigations of the WIPP site. Soon thereafter, the discovery of less than ideal geology caused the WIPP site to be moved to its current location (Fig. 3) marking the initiation of the Site Characterization Program (SCP; Powers et al., 1978). With the launching of the SCP in 1976, a significant number of new boreholes were drilled over the next decade (Fig. 3) to evaluate potash resources (P-series; Jones, 1978), characterize geology and stratigraphy (WIPP-series; see Hill et al., 1997), and conduct hydrology studies (H-series; e.g., Beauheim et al., 1991; Beauheim and Ruskauff, 1998). In 1979, the focus of the SCP shifted from geologic to hydrologic investigations, and an extensive well testing program was initiated. In the following years, fifteen more H-series wells were added and many of the P- and WIPP-series boreholes were converted to hydrologic monitoring wells in order to acquire data needed to evaluate important hydrologic (e.g., transmissivity, storativity, porosity, etc.), geo-

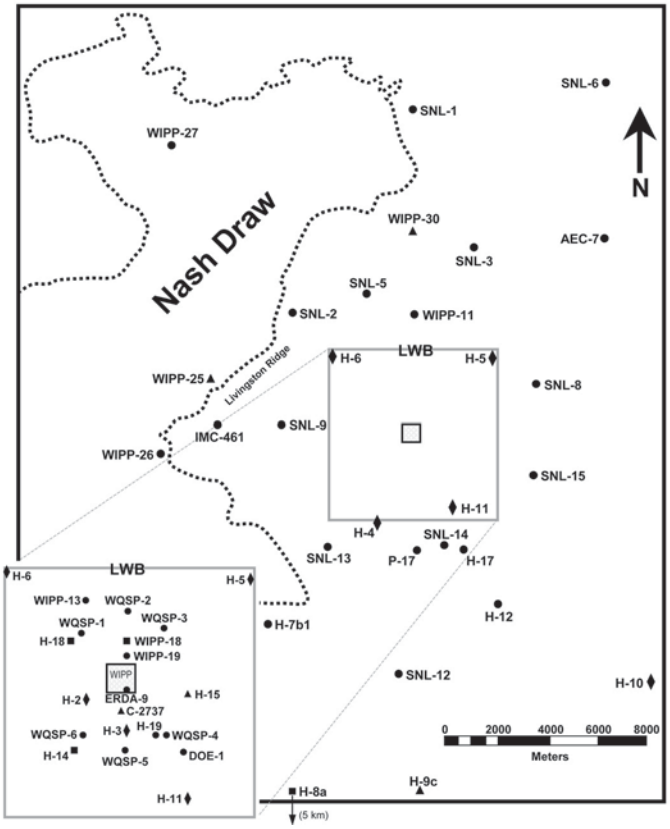

FIGURE 3. Map showing the locations of the WIPP groundwater monitoring network wells. Well completion horizons are as follows: Culebra – circle (●); Magenta – square (■); dual-completion Culebra/Magenta – triangle (▲); pad cluster Culebra/Magenta – diamond (♦). The dashed line demarks the edge of Nash Draw.

chemical, and transport properties of the various water-bearing units at WIPP. Testing and monitoring activities were conducted on all water-bearing horizons; however, most of the effort was focused on the Magenta and Culebra Dolomite Members of the Rustler Formation. Also during this period, the WIPP site preparation and construction activities were initiated, and between 1981 and 1988 four large-diameter shafts were constructed to provide access to the repository horizon.

In 1985, the first formal test plans governing groundwater-monitoring activities were developed. The monitoring activities generated defensible data for meeting the requirements of site characterization, performance assessment, regulatory compliance, and permitting. In 1988, the groundwater-monitoring program was incorporated into the site Environmental Monitoring Program (DOE, 1994), and is now overseen by WRES.

In 1992, the U.S. Congress enacted the Land Withdrawal Act (PL 102-579, 1992) establishing a boundary around the WIPP site, which prevents potash and oil/gas exploration from being conducted too close to the WIPP repository. At this time, the DOE shifted focus from site characterization and validation studies to surveillance monitoring to establish appropriate background (baseline) conditions in anticipation of receiving certification/permit approval. The only wells drilled in the 1990's were the seven WQSP-series wells, in 1994, for the sole purpose of compliance water-quality sampling (DOE, 1995) and a cluster of seven wells completed on the H-19 pad, in 1995, to address conceptual model concerns via a tracer test (Meigs et al., 2000).

In 1996, partly based on the results obtained from the extensive testing, monitoring, and modeling of WIPP parameters, the DOE submitted the WIPP Compliance Certification Application (DOE, 1996) to the EPA, as well as an application for a Hazardous Waste Facility Permit (HWFP) to the New Mexico Environmental Department (NMED). In 1998, the EPA issued certification to WIPP (EPA, 1998) for disposal of nuclear waste, followed in 1999 by NMED issuing an HWFP (NMED, 1999). The first waste was subsequently emplaced in March 1999, marking the initiation of the compliance-monitoring phase for WIPP, which will span the planned 35-yr operational period and is expected to continue for up to 100 years after closure of the facility.

The fourteen wells drilled in 1994 were cased with fiberglass-reinforced plastic. This was done because many of the wells drilled during site characterization for WIPP (most of which were 20+ yrs old) were in poor condition due to the deterioration of the steel casings. To address this issue, the DOE launched a program in 2002 to optimize the existing groundwater monitoring network by either replacing the old, deteriorating wells on existing pads or relocating new wells to more strategic locations (McKenna, 2004). This program called for all new wells (SNL-series) to be constructed with fiberglass-reinforced plastic casing and gravel-pack behind the screens according to EPA (1986) recommended standards and all steel-cased wells to be plugged and abandoned over the next 5-10 yrs.

As of December 2005, the WIPP groundwater-monitoring network consisted of 63 wells located within and around the WIPP boundary (Fig. 3). The wells are typically configured to monitor one particular hydrologic unit, though there are some dual-completion wells. The majority of wells are completed either to the Culebra (44), Magenta (11), or both (5); two wells are completed to the Bell Canyon and one to the Dewey Lake. As called for by DOE (2003), new wells are being added to the network yearly, replacing the older, steel-cased wells prior to their being plugged and abandoned. The total number of wells will decrease slightly over the next five years, as the well network is optimized and unneeded wells are plugged and abandoned without being replaced.

Groundwater Monitoring Programs

Monitoring of Culebra water quality and water levels at and near the WIPP site is a requirement of both Compliance Certification and the HWFP. It is an integral part of the DOE's broader requirements to demonstrate WIPP operations are performed in a manner that ensures protection of the environment, the health and safety of workers and the public, proper characterization of the disposal system, and compliance of WIPP with current and future applicable regulations.

The Integrated Groundwater Team has developed program plans focused on collecting high-quality data needed to address various compliance issues, regulator/stakeholder concerns, and operational and safety concerns that may arise during the monitoring period (SNL, 2003; DOE, 2003). As directed by the DOE, WRES oversees groundwater-monitoring activities and SNL analyzes the data collected, both by WRES and from well testing, in order to meet compliance requirements and resolve any regulator/stakeholder issues. These organizations work together to ensure that operational and safety standards are met.

WRES has established the Groundwater Monitoring Program (GMP) to meet their obligations to DOE. The GMP comprises two main subprograms: the Water Quality Sampling Program (WQSP) and Water Level Monitoring Program (WLMP). The WQSP was first developed to establish background (baseline) water-quality values for Culebra groundwater prior to WIPP receiving its first waste shipment. After WIPP began receiving shipments in 1999, the seven WQSP wells became the sole locations for water-quality monitoring, as specified in EPA (1998) and NMED (1999). Twice per year the wells are sampled and the water analyzed for chemical and physical properties, as well as for specific radionuclides. The WLMP includes water-level measurements in all wells in the current WIPP groundwater-monitoring network. Monthly measurements are taken at locations containing a single well (including dual-completion wells) or multiple wells (on the same pad) completed to different hydrologic units, while quarterly measurements are taken in redundant wells (i.e., wells on same pad completed to same unit).

SNL has developed test plans that call for additional water-level monitoring activities at WIPP (e.g., Hillesheim, 2006). The primary focus of their groundwater-monitoring program is to investigate both low- and high-frequency water-level fluctuations. This is accomplished by augmenting data collected by WRES with programmable pressure-temperature memory gauges placed in many of the WIPP wells. The gauges are installed at a fixed position in the well and measure pressure-head. They are capable of taking readings on a continuous basis at intervals ranging from seconds to days and can be set to take off-programmed readings if pressure-head begins to change rapidly due to stress applied (i.e., well testing, barometric pressure, earth tides, etc.) to the hydrologic unit. High-frequency, low-magnitude fluctuations in barometric pressure and earth tide, however, can mask responses to stresses applied to the hydrologic unit. Fortunately, noise created by these two effects can be removed using the computer code BETCO (Toll and Rasmussen, 2005). In sum, pressure gauges allow for the study of high-frequency events not resolvable using the monthly water-level measurements collected by WRES (Fig. 4).

RESULTS AND DISCUSSION

The hydrologic focus of regulatory compliance is on the Culebra; therefore we will focus the remainder of this paper on Culebra water-level data collected between 1977 and 2004. Culebra water levels have been measured and reported by several different organizations and contractors since the inception of the WIPP project. Data collected by the USGS have been reported by Mercer and Orr (1979) and Richey (1986; 1987a, b). Data collected by, or on behalf of, SNL are reported in Hydro Geo Chem (1985), Intera Technologies and Hydro Geo Chem (1985), Intera Technologies (1986), Saulnier et al. (1987), and Stensrud et al. (1987; 1988a,b; 1990). Data collected by WRES are reported in Kehrman (2002a) and DOE (2004; 2005).

Long-Term Water Level Changes

Water-level records (hydrographs) from some WIPP wells date back to 1977 and show myriad changes since monitoring began (Fig. 5). The observed variability can be attributed to anthropogenic (e.g., pumping tests, mining operations, etc.) or natural (e.g., changes in recharge rate) influences, or both, but separating these two influences can be difficult.

1977-1989

Much of the variation observed in wells near WIPP (e.g., H-6b and P-17), prior to 1989, is in response to well testing (e.g., pumping, slug, drill-stem tests, etc.) and shaft construction, which caused the hydraulic heads and gradients in the various water-bearing units at WIPP to be altered significantly. Hydrographs for wells several kilometers from WIPP (e.g., WIPP-26) show no response to well testing and shaft construction. Nevertheless, all wells show broad rising and falling trends over periods of several years.

1989 to 2004

Beginning in late 1988, a general long-term rise in Culebra water-level (Fig. 6) has been observed over much of the WIPP region, including Nash Draw. At the time of the Compliance Certification Application (i.e., 1996), this long-term rise was recog-

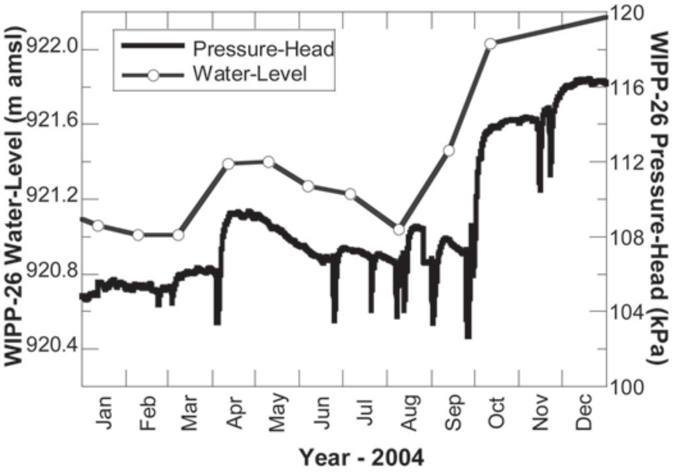

FIGURE 4. Comparison of monthly water-level (W-L) data collected at WIPP-26 with hourly pressure-temperature gauge measurements of pressure-head. The pressure-head record was corrected for barometric pressure and earth tide effects using BETCO (Toll and Rasmussen, 2005), but not for density effects of the water.

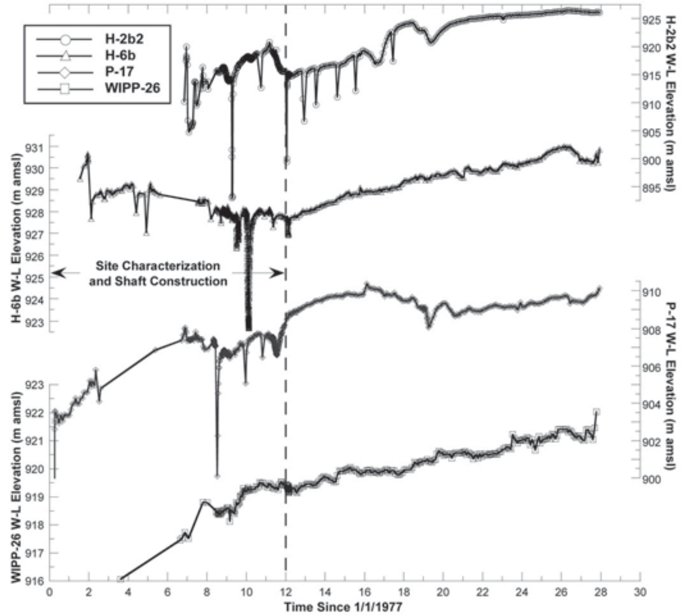

FIGURE 5. Hydrographs, 1977 to 2004, of WIPP-26 located in southern Nash Draw, P-17 south of the WIPP site, H-6b north of the WIPP site, and H-2b2 close to the center of the WIPP site. Water level (W-L) is not corrected for density variations and is plotted as an elevation in meters above mean sea level (m amsl).

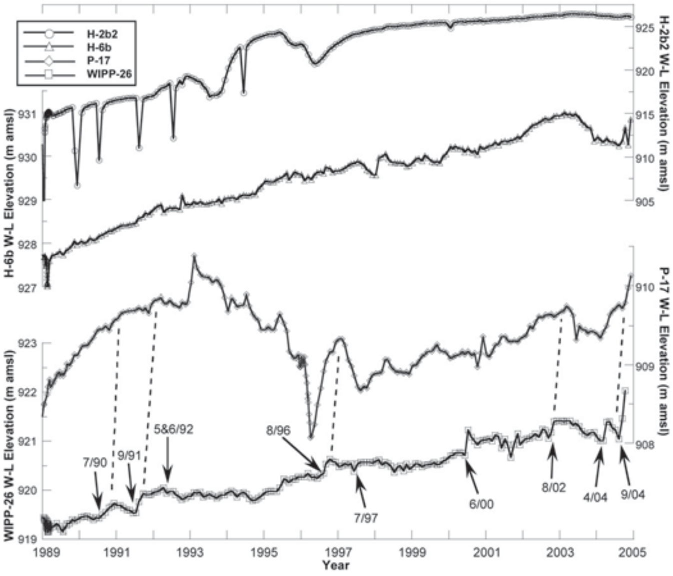

FIGURE 6. Hydrographs, 1989 to 2004, of WIPP-26 located in southern Nash Draw, P-17 south of the WIPP site and H-6b north of the WIPP site, H-2b2 close to the center of the WIPP site. Arrows point to months of >115 mm total rainfall (bolded entries in Table 1). Dashed lines indicate possible correlation of events. Water level (W-L) is not corrected for density variations and is plotted as an elevation in meters above mean sea level (m amsl).

nized, but was thought to represent recovery from the accumulation of tests and shaft leakage that had occurred at the WIPP site since the late 1970's. In addition, changes in the amount of potash effluent discharged onto tailings piles in or near Nash Draw were considered likely causes of water-level changes observed in wells located in or near Nash Draw (e.g., Silva, 1996). (We note that Magenta water levels have similar trends, but we do not analyze them further here.)

Since January 1989, wells closest to the WIPP shafts (near-field) have experienced significant water-level increases (as much as 23 m), mostly due to shaft completion and sealing. In general, water levels in wells located more than a few kilometers from the shafts (far-field) have risen on the order of 2-5 m over the past 15 yrs (1989 to 2004; Fig. 6), but there have been intervals of both decreasing and stagnant (i.e., little change) water levels during this span.

By 2003, it was clear that the water-level rise occurring since 1989 was probably not solely due to recovery from testing and shaft construction and was potentially related to other factors (Beauheim, 2003). Three scenarios were proposed to account for the observed long-term water-level rise, including: 1) leakage into the Culebra of refining process water discharged onto potash tailings piles, probably through subsidence-induced fractures and/or leaky boreholes; 2) leakage into the Culebra of water from overlying or underlying hydrologic units through poorly plugged and abandoned boreholes; and 3) leakage into the Culebra via compromised casing of injection (or nearby) wells used for brine disposal and secondary hydrocarbon recovery. Results from modeling studies by Lowry and Beauheim (2004; 2005) show that Scenarios 1 and 2 could plausibly account for, or at least contribute to, the observed rise in water levels around WIPP (Scenario 3 is still under investigation), but neither scenario can be definitively proven.

Short-Term Water-Level Fluctuations

Water-level rise in the WIPP groundwater-monitoring network wells has not been linear, and short-term (<1 yr) fluctuations are superimposed on the long-term trend (Fig. 6). Many of these observed changes, prior to 1989, can be explained by shaft construction and/or extensive well testing at the WIPP site. Almost all of the sharp drawdowns and increases in water level observed in the hydrographs between 1989 and 1996 can be attributed to well testing and maintenance. From 1997 to 2002, no well testing was performed. During this time, many wells received routine maintenance (i.e., bailing, swabbing, scraping, etc.) and one new well (C-2737) was drilled as a replacement for H-1. Well testing began again in 2003 as new wells were being installed to replace old, failing wells in an effort to optimize the WIPP groundwater-monitoring network for future compliance monitoring.

Not all short-term variations in Culebra water levels since shaft completion can be completely accounted for by well testing and maintenance activities in the WIPP vicinity. Scenario 3 of Beauheim (2003) is better suited to explain some of the observed short-term fluctuations. Scenario 3 hypothesizes that some injection wells used for brine disposal and secondary oil and gas recovery, or nearby wells, may have leaky casing. This could cause water levels in the Culebra, if the leaks were at the Culebra level, to increase and subsequently decrease rapidly if water was not injected at a constant rate over time. A second possibility is nearby drilling disturbance, due to the significant increase in oil and gas exploration in the Delaware Basin over the past two decades. Target geologic units for oil and gas wells are below the Castile Formation (Fig. 2), and drilling can disturb water levels of the various hydrologic units the borehole passes through. For example, in early 2005, an oil well was drilled ~150 m away from the H-10 pad causing water-level increases in both the Culebra and Magenta of approximately 2.5 and 1 m, respectively. Short-term drawdowns of water levels have also been observed in several wells that are consistent with pumping events in the area for periods of a few hours; however, no source has been identified as the causal mechanism for these drawdown events. These possible explanations could account for short-lived, rapid increases and/or drawdowns observed in the WIPP groundwater-monitoring network wells, but not long-term water-level rise or rapid, sustained water-level increases that are observed.

One possible explanation for Culebra water-level rise that has received little attention is recharge via precipitation. The lack of attention has largely been due to uncertainty about where recharge to the Culebra occurs, and absence of clear, consistent correlation between precipitation and monthly water levels. Recharge was commonly thought to occur somewhere north of WIPP (Mercer, 1983). More recently, Lowry and Beauheim (2005) have suggested that another source of recharge to the Culebra may be from an area south of the WIPP site, possibly southern Nash Draw, where it is believed that the Culebra is unconfined. Recharge in northern and central Nash Draw may also contribute, especially to wells on or near to Livingston Ridge, which forms the eastern boundary of Nash Draw.

Precipitation at WIPP

WIPP is located in a semi-arid region on the northern edge of the Chihuahuan Desert. Rainfall at WIPP averages ~330 mm/yr (DOE, 2005), approximately 50% of which falls during major rainstorms associated with the summer monsoon season (late May to early September). The rainfall pattern of the region is also spatially heterogeneous, and a large rainfall event in nearby Carlsbad may register only half as much or none at all at the WIPP site, or vice versa.

Weather data, including rainfall totals, have been collected at WIPP by WTS since 1986 (DOE, 1994). Rainfall has varied drastically from one year to the next (Fig. 7); in 1997, >500 mm of rain fell compared to ~150 mm the following year. Between 1988 and 1992, rainfall totals were predominantly above average (averaging ~400 mm/yr), while the years from 1993 to 2003 (with the exception of 1997) were dominated by below average precipitation (averaging ~240 mm/yr). A monthly breakdown of rainfall totals shows that approximately 13% (28) of the 219 months spanning September 1986 to December 2004 had rainfall totals greater than 60 mm and that only 4% (8) had rainfall totals over 115 mm (Table 1).

TABLE 1. Months, from 1986 to 2004, with rainfall totals greater than 60mm (>100 mm in bold).

Year	Month	Monthly Total (mm)
1986	9	96.5
1986	10	63.8
1986	12	72.9
1987	5	89.9
1988	5	72.1
1988	7	87.1
1988	8	86.1
1988	9	70.9
1989	6	82.3
1989	8	66.0
1990	**7**	**142.7**
1990	8	69.9
1990	9	73.7
1991	7	86.4
1991	**9**	**158.0**
1991	12	71.4
1992	**5**	**126.5**
1992	**6**	**126.7**
1993	7	91.2
1995	9	85.1
1996	6	67.6
1996	**8**	**130.0**
1997	**7**	**135.6**
1997	9	76.5
2000	**6**	**152.9**
2002	8	83.1
2004	4	82.6
2004	**9**	**170.9**

Beginning in January 2000, high-resolution rainfall data have been recorded at 15-minute intervals at WIPP. Daily rainfall totals show that as rainstorms move across the region, they can release large amounts of precipitation in a short period of time. For example, approximately 70 mm of rain fell over a 24-hour period at WIPP in early August 2002, accounting for greater than 80% of that month's cumulative total (Table 2). By comparing monthly and daily rainfall totals with hydrographs generated from the WIPP monitoring wells, we should be able to determine the impact, if any, that precipitation has on Culebra water levels.

TABLE 2. Rainfall Events (E1-E4), between 2000 and 2004, of >60 mm in less than a 48-hr period.

Rainfall Event	Date of Event	Event Total (mm)	Monthly Total (mm)	Event Percent of Monthly Total
E1	**June 19, 2000**	66.5	152.9	43.5
E2	**Aug. 2, 2002**	69.1	83.1	83.2
E3	**Apr. 2-4, 2004**	65.8	82.6	79.7
E4	**Sept. 25-26, 2004**	133.9	170.9	95.2
	Sept. 29-30, 2004	29.0		

Comparison of Precipitation Records with Well Hydrographs

Between 1988 and 2004, a handful of relatively rapid (few months or less) water-level increases were observed in hydrographs from various Culebra monitoring wells that cannot be correlated with known WIPP or non-WIPP field activities. In this section, we seek to compare: first, monthly rainfall totals and, second, daily rainfall totals with hydrographs from wells spread across the WIPP site.

Monthly Rainfall Records

Comparison of WIPP well hydrographs with monthly rainfall totals should allow us to determine, or at least narrow, the candidate list of causes for observed abrupt water-level rises at WIPP. Comparing months of high rainfall (>60 mm; Table 1) with hydrographs gives us a first-cut approach to the problem. The WIPP-26 hydrograph shows that there is a water-level response to months of high precipitation totals (Fig. 6). This response typically occurs either during or soon after months (or successive months) with very high rainfall (i.e., >115 mm). There is evidence, however, that water-level rise may occur during months when precipitation is as little as 80 mm (e.g., August 1989 and 2002, and April 2004), suggesting the minimum threshold value of 115 mm per month is not always valid. It is also evident that not all months with >115 mm of rainfall cause a rise in Culebra water level at WIPP-26. For instance, water level appears to decline in WIPP-26 after two consecutive months of >115 mm rainfall totals in mid-1992. Water levels at WIPP-26 remained generally constant during 1997 (Fig. 6) even though 1997 was the wettest year on record at WIPP (Fig. 7) and rainfall was ~135 mm during July 1997 alone.

Water-level rises at WIPP-26 associated with heavy rainfall months correlate well with rises observed in other wells located across the southern portion of the WIPP site (e.g., P-17; Fig. 6), though the other responses lag the WIPP-26 response. There is little correlation between these same rises in WIPP-26 and records from wells located near the WIPP facility (e.g., H-2b2) or in the northern portion of the site (e.g., H-6b), with one exception, a water-level rise near the end of 2004. This evidence (that southern wells correlate better with larger rainfall events) suggests that precipitation in southern and southeastern Nash Draw affects water levels more than precipitation in other areas around the WIPP site.

Rainfall is indeed contributing to some of the observed water-level rise since 1989, but monthly rainfall totals only give a general picture of cause (i.e., precipitation) and effect (i.e., water-level rise). To establish a better understanding of this cause and effect relationship, we compare daily rainfall totals with the hydrographs. By doing this, the threshold amount of precipitation needed to generate a detectable response in water level can be estimated as well as the response time (i.e., lag) between rainfall and water-level rise.

Daily Rainfall Records

Daily rainfall totals available since January 2000 show the relationship between daily rainfall and water-level rise. From January 2000 through 2004, there have been four rainfall events (E1-E4), in which >60 mm of precipitation fell in less than 48 hours (Table 2). Comparing these events with the WIPP-26 hydrograph shows that water level rose abruptly soon after each event (Fig. 8). For instance, within a month of the June 2000 event (E1; ~66 mm in <24 hrs) water level rose ~0.5 m and in August 2002 (E2; ~69 mm in <24 hrs) water level rose more than 0.2 m. Two events (E3 and E4) occurred in 2004. E3, in early April, caused water level to rise ~0.2 m. E4, in late September, is the largest rainfall event recorded at WIPP since January 2000, producing ~160 mm of rain over two 2-day periods with 82% of that falling during the first 2-day period. Less than one month later, water level had risen greater than 0.6 m at WIPP-26.

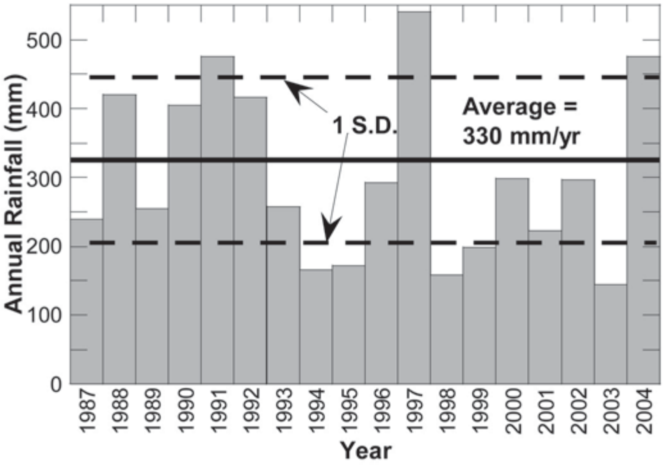

FIGURE 7. Annual rainfall totals recorded at WIPP, 1987-2004. The solid line represents the annual average and the dashed lines represent one standard deviation (1 S.D.) from the average.

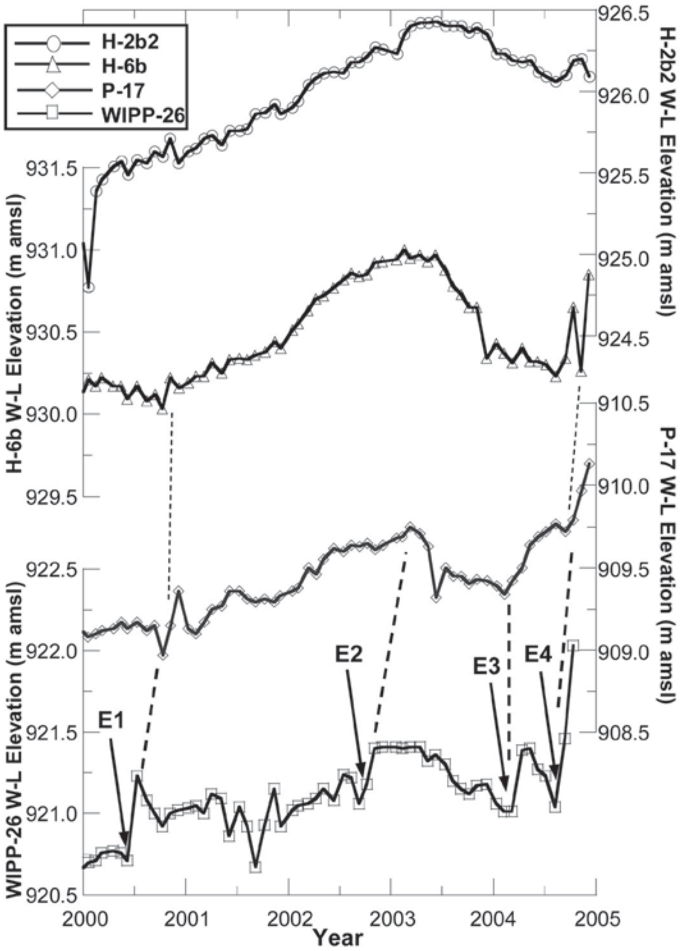

FIGURE 8. Hydrographs, 2000 to 2004, of WIPP-26 located in southern Nash Draw, P-17 south of the WIPP site, H-6b north of the WIPP site, and H-2b2 close to the center of the WIPP site. E# denotes rainfall events listed in Table 2. Dashed lines indicate possible correlation of events. Water level (W-L) is not corrected for density variations and is plotted as an elevation in meters above mean sea level (m amsl).

These events as observed on the WIPP-26 hydrograph show some correlation with other hydrographs from across the WIPP site (Fig. 8). For instance, E1 may have caused small (<0.5 m) water-level increases in both P-17 and H-6b, both of which lag the rise in WIPP-26 by several months. Neither E2 nor E3, however, are recognized as an abrupt/rapid increase in water level at wells outside of Nash Draw or in the immediate vicinity of

Livingston Ridge. E4, on the other hand, can be observed to some extent in a number of wells at WIPP.

Hourly Versus Monthly Water-Level Measurements

How abrupt were the water-level increases associated with E4? To answer this question, higher resolution data are needed. Programmable pressure and temperature transducers installed in many WIPP wells collect hourly measurements, capturing much more detail about water-level changes relative to the monthly measurements. For instance, one would not see the short-term drawdown responses to apparent pumping events that occur in WIPP-26 from the monthly water-level measurements, but they are quite obvious in the hourly pressure-head readings (Fig. 4). Hourly readings also allow us to determine the timing and rate of water-level rise (or drawdown) observed in WIPP wells more precisely.

Continuous measurement of pressure-head in wells is relatively new to groundwater monitoring at WIPP. Beginning in late 2002, pressure-temperature transducers were installed in several wells to monitor responses to pumping tests. These transducers were distributed well enough by early 2004 to compare water-level fluctuations in wells from across the WIPP site. Pressure-head data from various wells show that the responses to both 2004 rainfall events (E3 and E4) are spatially different (Fig. 9). E3 appears as a distinct, abrupt increase in pressure-head at WIPP-26 (2.7 kPa) and only a very slight (<0.7 kPa) increase at WIPP-25, which is located in northern Nash Draw (~4 km northeast of WIPP-26). E4, on the other hand, appears as a distinct, rapid rise in pressure-head at both WIPP-25 and WIPP-26 of 5.0 kPa and 6.2 kPa, respectively, in the 10 days after the onset of E4. Also, within 10 days of E4, pressure-head at SNL-5 (located ~3 km northeast of H-6b) and P-17 gradually increased 1.4 kPa and 1.0 kPa, respectively. From this information, we infer that the Culebra is less sensitive to rainfall in northern Nash Draw relative to southern Nash Draw, possibly because of differing degrees of Culebra confinement. It can also be surmised that Culebra water levels in Nash Draw are sensitive to short-duration, intense rainstorms.

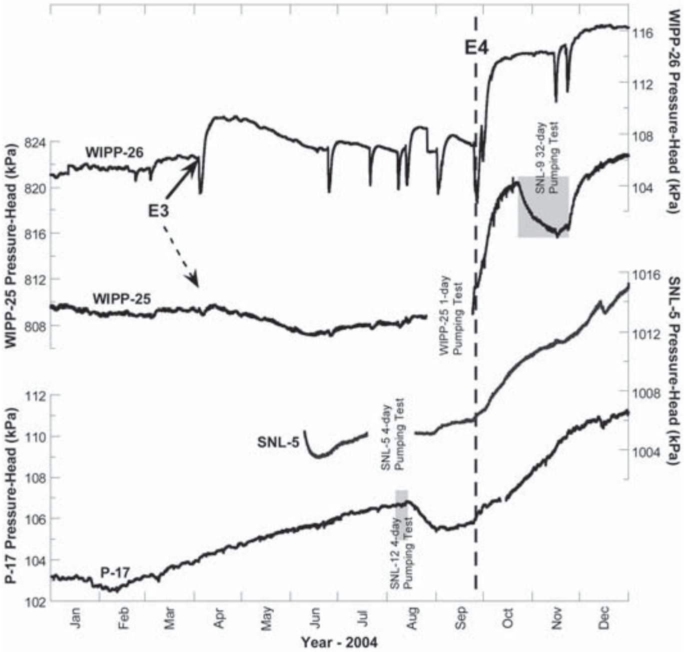

FIGURE 9. Comparison of pressure-temperature gauge records of pressure-head from SNL-5 (completed May 2004), P-17, WIPP-26, and WIPP-25. WIPP-26 and WIPP-25 are located in Nash Draw, P-17 is south of the WIPP site, and SNL-5 is north of the WIPP site (~3 km northeast of H-6b). The pressure-head records were corrected for barometric pressure and earth tide effects using BETCO (Toll and Rasmussen, 2005), but not for density effects of the water. Note: The SNL-5 pressure record was used in lieu of the H-6b record as it was the closest well that did not respond to pumping tests and drilling activities in the area at the time of E4.

Inferences about Karst in WIPP vicinity

WIPP-26 shows almost instantaneous response to large rainfall events (E1-E4), but WIPP-26 water level does not respond to every rainstorm. It appears that a certain amount of precipitation must fall over a short period of time to induce a water-level rise. This threshold is probably due to the nature of Nash Draw, which is characterized by many sinkholes and caves that create small basins that are intermittently inundated after rainfall events of sufficient magnitude. It is intuitive to assume that the Nash Draw drainage system can handle a limited amount of rainfall before flooding occurs. This flooding inundates low-lying areas and recharges underlying units through caves and sinkholes. This process is supported by evidence in Powers et al. (2006) of a flooding event in southern Nash Draw at the time of E4. Where the Culebra is recharged within Nash Draw, however, is not yet determined.

The evidence of Culebra water-level rise in Nash Draw linked to large rainfall events suggests that WIPP-26 and WIPP-25 are located where the Culebra is either unconfined or is affected by nearby karst, or both. Outside of Nash Draw, with the exception of wells located very near to Livingston Ridge, water-level rise associated with rainfall events is not as abrupt or of the magnitude as that observed at WIPP-26 or WIPP-25.

This leads us to infer that similar recharge is not occurring closer to WIPP. If similar karst were present near WIPP, one would expect to see a similar response (i.e., abrupt) in water levels as those observed in the Nash Draw wells. This, however, is not the case, as at P-17 and SNL-5 water levels rose much more gradually after E4 relative to WIPP-25 and WIPP-26, and many wells showed little discernable response at all. We suggest that the water-level rise observed in non-Nash Draw wells is due to pressure-head diffusion away from Nash Draw. This is because when a large recharge event occurs, such as E4, the Culebra cannot immediately dissipate/discharge the larger volume of water rapidly entering the system, causing water levels to rise in areas adjacent to Nash Draw.

SUMMARY AND CONCLUSION

Groundwater monitoring and testing have been an integral part of site characterization and now compliance monitoring for WIPP. Monitoring activities are conducted in 63 wells completed to various water-bearing horizons, with the main focus of the groundwater monitoring programs being the Culebra Dolomite Member of the Rustler Formation, the most laterally continuous and transmissive water-bearing unit at the WIPP site. Water-level data on the Culebra since 1977 show myriad changes, most of which can be attributed to human-induced stresses (i.e., well testing, shaft construction, hydrocarbon production, etc.), but not all water-level rises can be accounted for by known field activities.

Abrupt water-level rises lasting several months of previously unknown origin in Nash Draw can now be attributed to large intense rainfall events (i.e. greater than 60 mm in less than 48 hours). Culebra water-level responses to these rainfall events vary depending upon the magnitude and duration of the storm as well as the distance of the well from the recharge area (i.e., Nash Draw). Small, localized water-level increases are linked to rainfall events of ~65 mm over a 24-48 hour period, while a relatively large, wide-spread water-level rise is attributed to a rainfall event that produced ~160 mm over two 2-day periods in late September 2004. The limited response observed in Culebra wells spread over the WIPP site to large rainfall events does not support the suggestion that karst exists in the vicinity of WIPP, except in Nash Draw. The relatively infrequent major rainfall events that affect the Culebra in Nash Draw cannot, however, explain the decades-long water-level rises observed in the WIPP region. Those rises must have a different cause.

ACKNOWLEDGEMENTS

The authors would like to thank Dennis W. Powers and Nathaniel J. Toll for reviews of an earlier version of this manuscript. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin company, for the United States Department of Energy's National Nuclear Security Administration (NNSA) under Contract DE-AC04-95AL85000. This research is funded by WIPP programs administered by the Office of Environmental Management (EM) of the U.S. Department of Energy.

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