Mapping of Pressure-Head Responses of a Fractured Rock Aquifer to Rainfall Events

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Abstract

Pressure-head response to rainfall was investigated in the Culebra Dolomite Member of the Rustler Formation in the vicinity of the Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico. The Culebra is a locally fractured dolomite with transmissivities ranging over six orders of magnitude. The variation in transmissivity has been linked to the degree of fracturing and fracture fill, as well as the presence of karst in Nash Draw, approximately 5 km west of the WIPP. Recent studies have shown that Nash Draw is a source of localized recharge to the Culebra after relatively large rainfall events. In this study, lag times between the onset of precipitation and Culebra water-level and pressure-head response were derived for two large rainfall events. The spatial distribution of lag times was mapped in an attempt to develop a better understanding of Culebra water-level response to rainfall events; this, in turn, provided additional insight into Culebra fracture distribution in the vicinity of the WIPP.

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Introduction

The Waste Isolation Pilot Plant (WIPP) is a U.S. Department of Energy (DOE) facility designed for the safe disposal of transuranic wastes generated by U.S. defense programs, located in southeastern New Mexico (Fig. 1). Groundwater monitoring is an integral part of the site compliance and licensing processes. The focus of the groundwater monitoring effort at the WIPP is the Culebra Dolomite Member of the Rustler Formation (Fig. 2), because it is the most transmissive, continuously saturated unit above the repository horizon and is the most probable groundwater transport pathway for radionuclides if the repository were ever to be breached (Beauheim and Holt, 1990). The Culebra flow model used in performance assessment (PA) calculations for the first licensing application was calibrated to groundwater heads assumed to be in steady-state. At the time of re-licensing (required every five years), ongoing monitoring of water levels had shown that the Culebra is not in steady-state and that heads were in excess of the range used in the original flow model calibrations. The U.S. Environmental Protection Agency (EPA), a regulator of WIPP, asked the DOE to address this issue. In response, Sandia National Laboratories (SNL), the scientific advisor to DOE for the WIPP, initiated a study to determine and model the causes of the continued Culebra water-level rise (Beauheim, 2003).

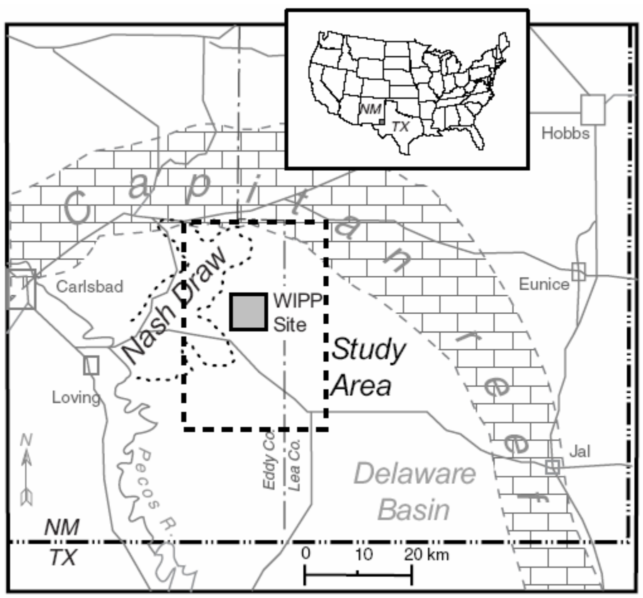

Figure 1. Location of the WIPP site.

Three scenarios were proposed that involved seepage of foreign waters into the Culebra through leaky boreholes (i.e., open boreholes, poorly plugged and abandoned, compromised casing, etc.). One scenario not addressed by the Beauheim (2003) study was recharge to the Culebra due to precipitation. The lack of attention for this scenario has largely been due to the uncertainty of where Culebra recharge occurs. In the past, recharge was commonly thought to occur somewhere north of the WIPP vicinity (Mercer, 1983), but more recent work by Lowry and Beauheim (2005) suggests that a possible source of recharge to the Culebra may be in an area south-southwest of the WIPP site (i.e., southern Nash Draw) where it is believed that the Culebra is unconfined. More recently, SNL studied the response of Culebra water level to a large rainfall event that occurred in late September 2004 (see Hillesheim et al., 2006; Powers et al., 2006). The study was able to link the rainfall event and other, smaller rainfall events to abrupt water-level increases in Culebra wells located in and near to Nash Draw. Only the large rainfall event caused noticeable though less pronounced responses in wells located nearer to the WIPP, these responses also lagged the event by weeks to months. The study concluded that Nash Draw is at least one area of recharge to the Culebra.

Additional high-resolution (i.e., hourly) data have been collected since 2004, which are reported and discussed in this paper. In addition, the new data were used to determine the lag-time between the onset of precipitation and an associated increase in Culebra water-level, if any. Finally, the lag-time response was mapped across the WIPP region in the hopes of providing additional insight into the nature of the Culebra flow system.

Hydrogeologic Setting

The WIPP is situated in the northern portion of the Delaware Basin, which underlies extreme southeastern New Mexico and portions of west Texas and is bounded by the Capitan Reef (Fig. 1; Bachman, 1985). The WIPP repository is excavated in bedded halite of the Salado Formation, approximately 655 m below ground surface (Fig. 2). At the center of the site, the Salado is about 600 m thick and is overlain by approximately 95 m of Rustler Formation and 150 m of Dewey Lake Formation, which is, in turn, overlain unconformably by ~15 m of eolian deposits. From the WIPP site to the east, the Dockum Group is present between the Dewey Lake and surficial deposits. Karst in the form of sinkholes, caves, and dolines is present ~5 km west of the site, in an area known as Nash Draw (Fig. 3). Nash Draw is a northeasterly trending depression, ~30 km long and from 8-16 km wide, thought to have formed by the coalescence of numerous karst features (Bachman, 1987).

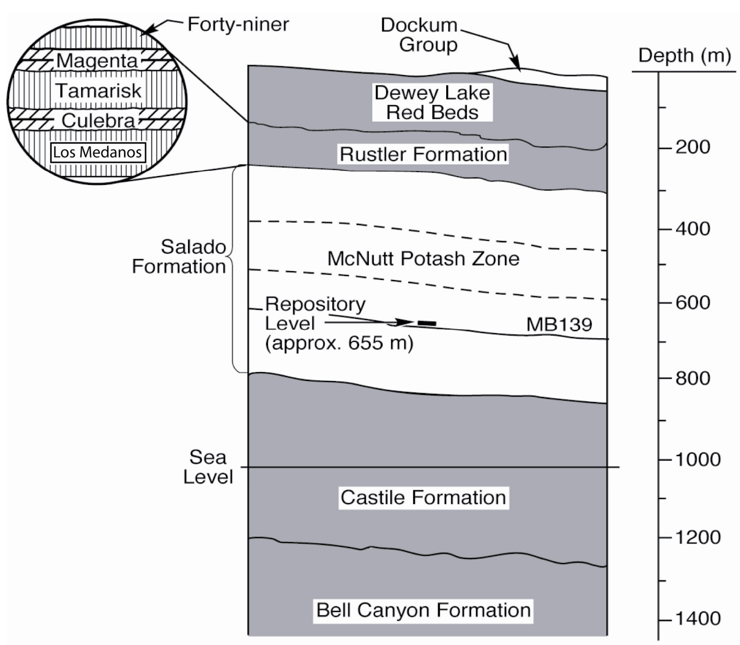

Figure 2. Stratigraphic column of the WIPP vicinity geology.

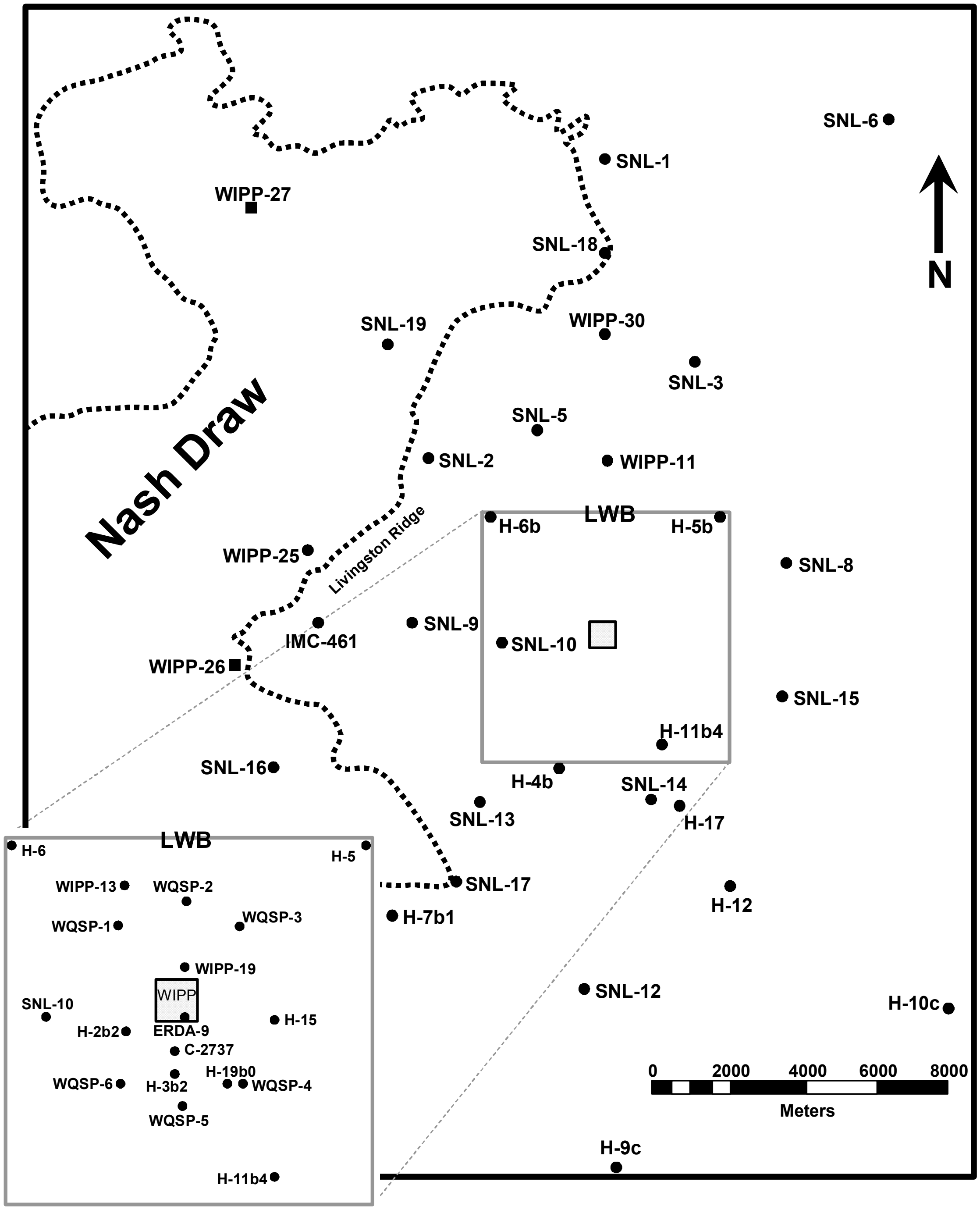

Figure 3. Map showing the location of Culebra wells. ● – denotes active wells and ■ – denotes recently plugged and abandoned wells; the dashed line marks the edge of Nash Draw; LWB is the WIPP land withdrawal boundary; and the gray-shaded area is the approximate location of the WIPP surface facility.

In the WIPP vicinity, naturally occurring groundwater is found in four principal horizons above the Salado; the Rustler-Salado contact, the Culebra and Magenta Dolomite Members of the Rustler Formation, and the lower portion of the Dewey Lake Formation

(Fig.2; Mercer, 1983). Water (actually brine) is found at the Rustler-Salado contact and is limited to the vicinity of Nash Draw (Mercer, 1983). The Dewey Lake only bears water to the south of the site (Beauheim and Ruskauff, 1998). The Magenta and Culebra are the most laterally continuous hydrologic units in the area, though the Magenta is less transmissive than the Culebra and bears no water southwest of the site (Mercer, 1983).

The Culebra is a locally fractured dolomite that is the most transmissive and continuously saturated hydrologic unit in the WIPP vicinity. Across the WIPP area, transmissivities range over six orders of magnitude (Beauheim and Ruskauff, 1998) and generally increase from east to west. The variation in transmissivity (T) has been linked to the degree of fracturing and fracture fill (Beauheim and Holt, 1990). Fracturing in the Culebra displays a high degree of variability and is controlled by dissolution of the underlying Salado Formation (halite), the presence of halite above or immediately below the Culebra (i.e., no observed fracturing), the erosion of overburden, and/or other factors (Holt et al., 2005). To the west of the WIPP, in Nash Draw, the presence of karst in Rustler evaporites has led to dissolution of the upper Salado Formation, which has increased fracturing in the Culebra. With the exception of Salado dissolution in and near Nash Draw, the primary control on Culebra T is thought to be fracturing due to erosion/unloading processes (Powers et al., 2003).

Methods

The groundwater monitoring network developed for the WIPP consists of more than 70 wells and piezometers completed to various water-bearing horizons. As of the end of calendar year 2006, fifty-one wells (seven of which are on the H-19 hydropad) were completed to the Culebra (Fig. 3). Water-level measurements are collected in these wells on a monthly basis (with the exception of six of the seven H-19 wells, which are monitored quarterly) by the WIPP managing and operating contractor (MOC). SNL collects additional water-level measurements as well as high-frequency pressure-head data in many of the Culebra wells.

Pressure-head measurements are taken using programmable memory gauges that are capable of measuring pressure at a variety of time intervals. The gauges are typically programmed to scan at five-minute intervals and to record readings on the hour, unless pressure-head changes by greater than 0.1 psi in a given scan interval, in which case an addition reading is recorded. High-frequency, low-magnitude changes in barometric pressure and earth tide can mask some changes in pressure-head; therefore, these effects were removed from the pressure-head measurements using the BETCO computer code (Toll and Rasmussen, 2007).

The WIPP MOC also collects weather data at a station located ~1 km north-northwest of the center of the WIPP site. Since January 2000, data (e.g., wind speed and direction, barometric pressure, temperature, and precipitation) have been collected at 15-minute intervals all-year round. Additionally, SNL has been collecting rainfall data at the SNL-9 drilling pad since March 2006.

Results and Discussion

Precipitation

Annual precipitation at the WIPP has averaged approximately 330 mm (Hillesheim et al., 2006), but can vary significantly from one year to the next. For example, in 2004 almost 600 mm of rain fell, which was preceded by a year of just over 200 mm and followed by a year of slightly above average rainfall of 360 mm (Fig. 4). Rainfall primarily falls during the summer monsoon (June to September) in the form of large convective rainstorms that can release large amounts of precipitation in a short period of time.

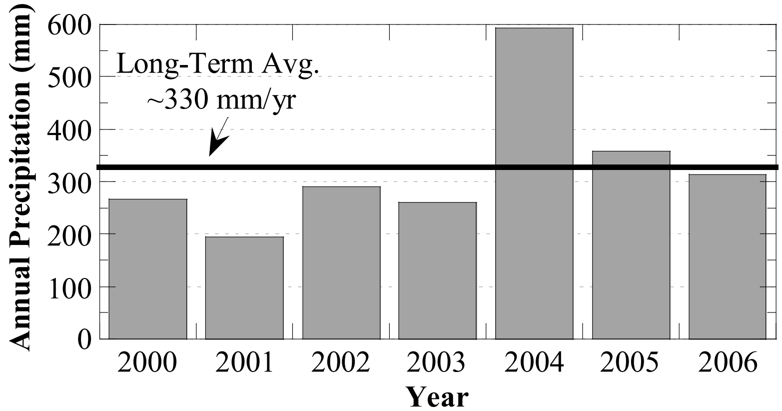

Figure 4. Annual rainfall totals recorded at the WIPP, 2000-2006.

Previous work by the authors comparing daily rainfall totals with Culebra hydrographs between 2000 and 2004 has shown that rainfall events, defined as >60 mm in less than 48 hrs, can be linked to abrupt water-level rise observed in wells located in and immediately adjacent to Nash Draw with limited response observed elsewhere. The exception is the large rainfall event of September 2004, which caused abrupt water-level rise in Nash Draw area wells followed by less pronounced and delayed response in wells nearer to the WIPP facility (Hillesheim et al., 2006). Since the time of that study, three additional rainfall events have occurred and are listed in Table 1 (bold).

Table 1. Rainfall events (E#) between June 2000 and December 2006. The September 2006 rainfall event (E7) is based on SNL data (1-30 Sept.; which has not been qualified) due to a malfunction at the WIPP weather station.

Rainfall Event	Date of Event	Event Total (mm)	Monthly Total (mm)	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	78.3
E5	Nov. 15-16, 2004	76.5	127.7	60.0
E6	Aug. 13-16, 2006	65.8	82.3	80.0
E7	Sept. 1-4, 2006	117.6	122.7	95.8

Rainfall events E5 and E6 are comparable in amount and duration (i.e., ~70 mm in less than 48 hr) to E1, E2, and E3, which caused limited observable water-level response outside of Nash Draw. E7, however, is more comparable to the large rainfall event E4 (i.e., >100 mm in less than 72 hr), which caused distinct responses in Culebra water level across the WIPP study area. Water-level response in well WIPP-26, located in southern Nash Draw, is a good indicator of Culebra water-level response to all the rainfall events as described in Hillesheim et al. (2006) and shown in Figure 5. Water-level rises after E1-E3 and E5 are of similar magnitude, but smaller than those observed for E4 and E6. It appears that the reason water-level rise after E6 is comparable to E4 is primarily due to the occurrence of E7 approximately two weeks after E6. For the remainder of this paper, E6 and E7 will be discussed as a single event, with the exception of wells located in Nash Draw, which show separate responses to both rainfall events (see discussion below). In addition, the scope of the paper will be limited to the analysis of water-level and pressure-head response to rainfall events E4 and E6/E7 due to their similar magnitude and impact on Culebra water levels (Figures 6 and 7).

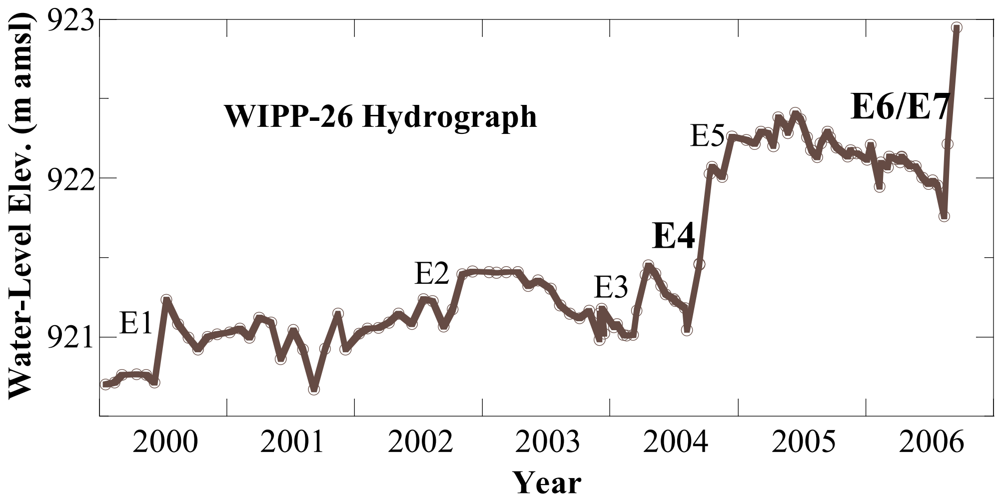

Figure 5. WIPP-26 hydrograph.

Culebra Water-Level and Pressure-Head Response to Rainfall Events

Comparison of Culebra water-level data with rainfall events E4 and E6/E7 shows that both events had similar effects on the Culebra (Figures 5 and 6). Water levels increased abruptly in wells located in and immediately adjacent to Nash Draw (hereafter referred to simply as Nash Draw vicinity, which include wells: WIPP-25, WIPP-26, WIPP-27, SNL-1, SNL-2, SNL-19, SNL-16). Two wells, SNL-9 and H-6b, located west of the WIPP facility, but not in the Nash Draw vicinity, also show somewhat rapid increases in water level. Wells situated to the south-southwest (e.g., H-7b1) and north (e.g., SNL-3) of the WIPP facility generally showed water-level rises that were more gradual. Wells located closer to the WIPP facility experienced very little increase in water level (e.g., WQSP-2), if any at all (e.g., C-2737). Wells situated in the eastern portion of the WIPP area showed no discernible response to either of the rainfall events.

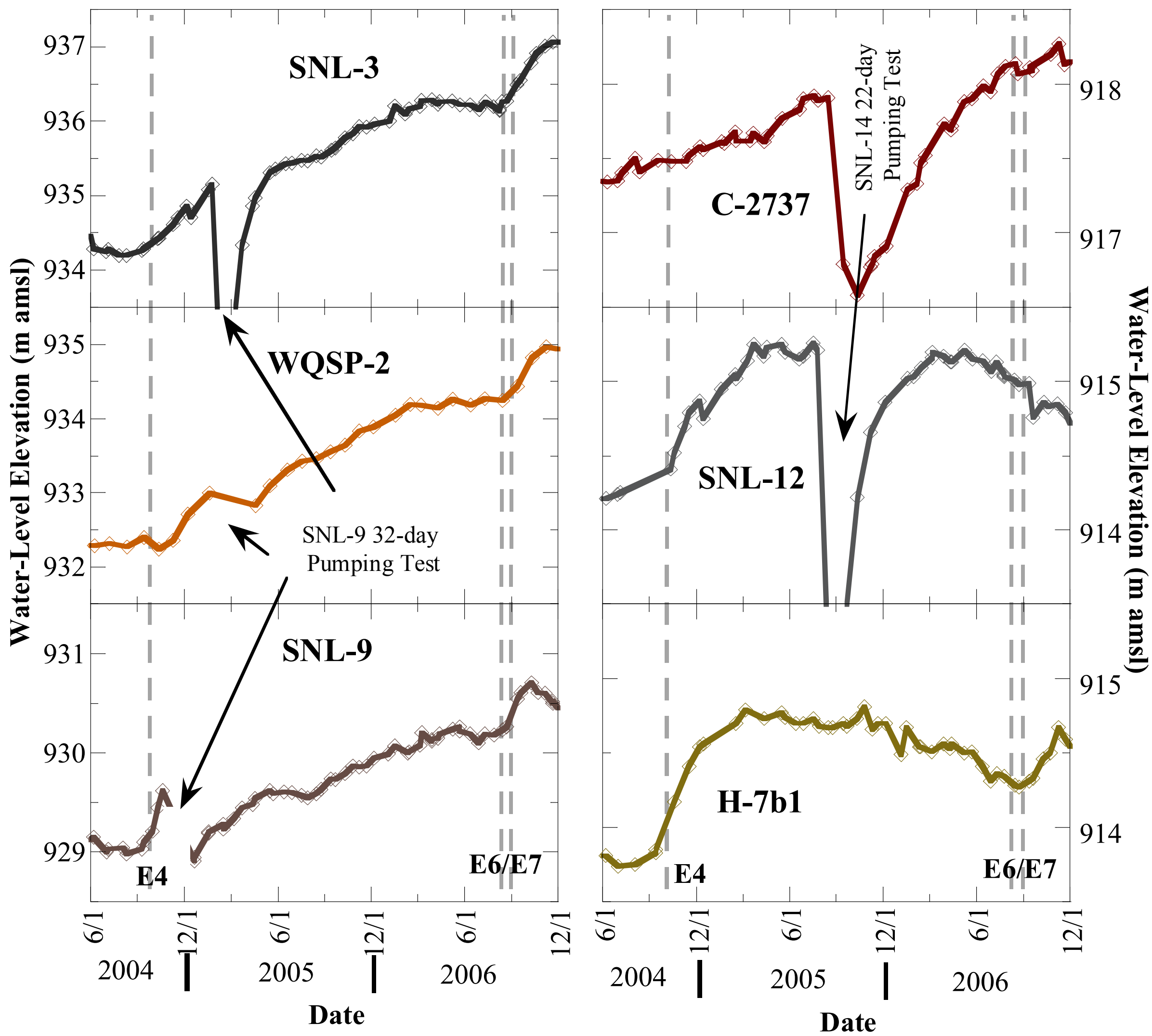

Figure 6. Hydrographs from selected Culebra wells (Note: water levels are not adjusted for density).

Hourly pressure-head data show slightly different responses in Culebra water level due to the nature of the two rainfall events (Fig.7). Wells located in the Nash Draw vicinity (e.g., WIPP-25 and SNL-2) responded abruptly and almost immediately to E4, but not as quickly to E6 (i.e., ~3 days), which is most likely due to E6 being less intense than E4. Pressure-head response in wells located east of Nash Draw and to the north and east of the WIPP facility (e.g., SNL-3, SNL-9, SNL-5, WIPP-30) was typically delayed and more gradual. In wells located immediately around of the WIPP facility and to the east, pressure-head response was limited and/or not observable. In most instances in wells near to the WIPP facility it was hard to discern if those wells responded to either rainfall event due to compliance water-quality sampling that occurs between October and November or other well testing activities conducted by SNL, particularly two 4-day pumping tests at SNL-18 (northern Nash Draw), from 14-18 August 2006, and SNL-17 (southern WIPP vicinity), from 11-15 September 2006.

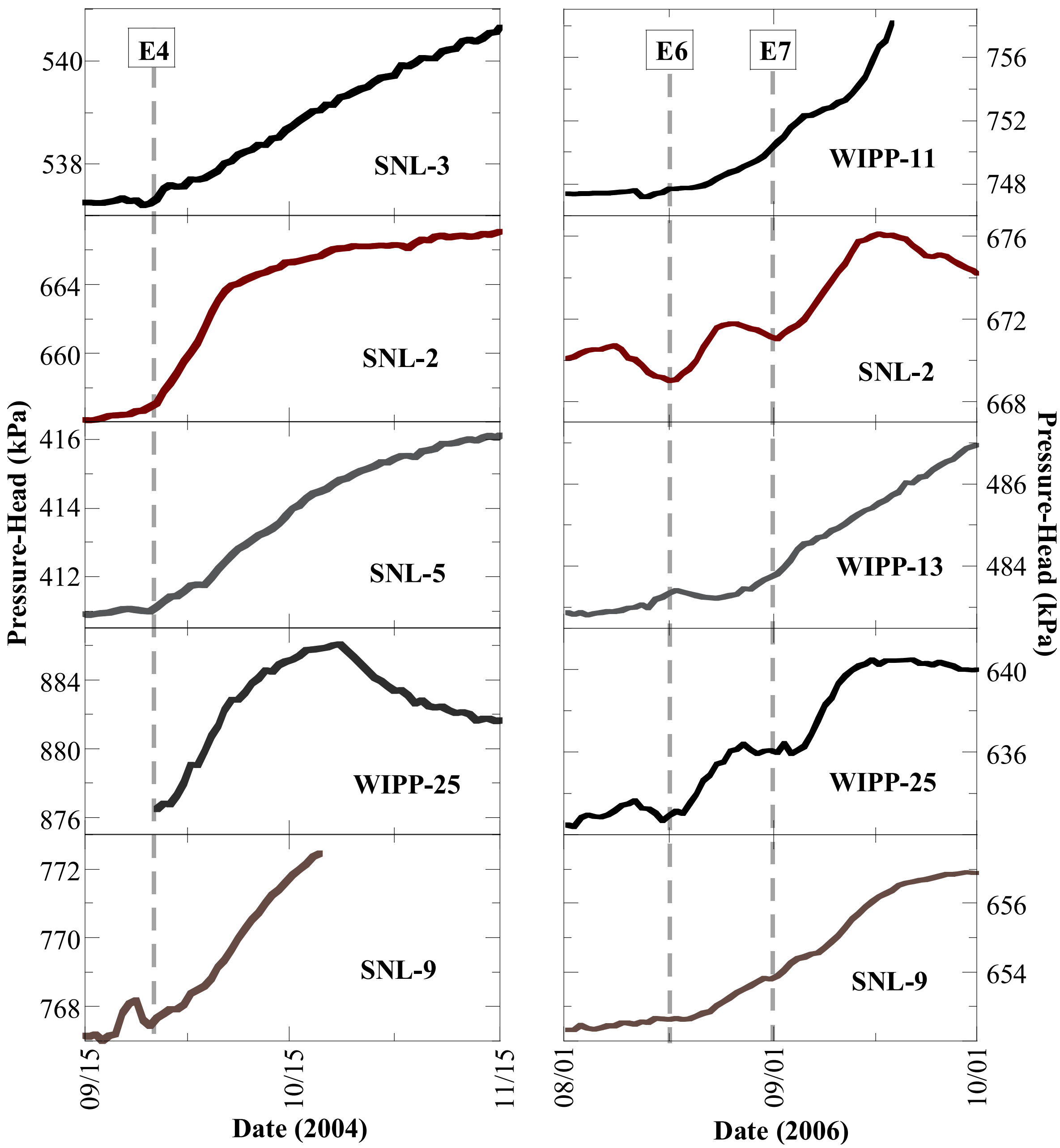

Figure 7. Pressure-head plots from a selection of Culebra wells (Note: heads reflect different gauge elevations that may have changed from E4 and E6/E7).

Worth mentioning is the observed double response many of the wells located in the Nash Draw vicinity experienced due to rainfall events E6 and E7 (Figures 7 and 8). Hourly time-series of pressure-head show two distinct increases in pressure as a result of each event. The structure of the response, however, was different from one well to the next. For example, pressure-head in SNL-19, located in northern Nash Draw, actually began to decrease after the initial increase caused by E6, while pressure-head at SNL-16, located in southern Nash Draw, continued to rise throughout but at an increased rate due to E7 (Fig. 8).

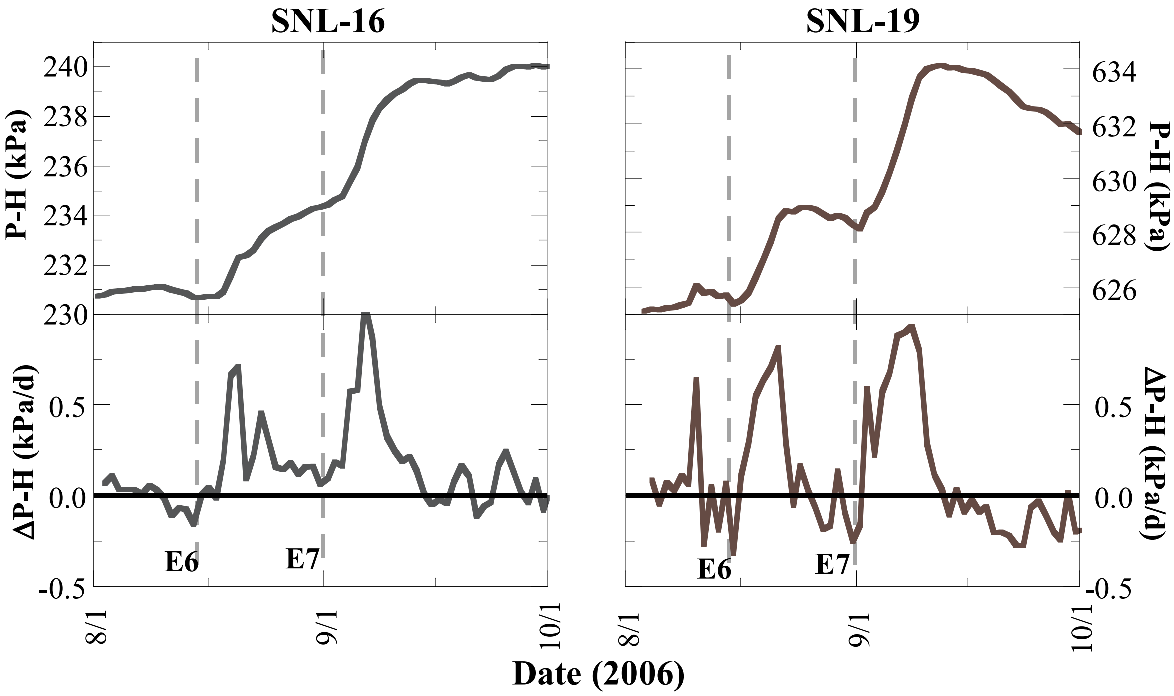

Figure 8. Pressure-head (P-H) response to E6 and E7 and change in pressure-head (ΔP-H) recorded in wells SNL-16 and SNL-19.

Culebra Lag-Time Response to Rainfall Events

The lag-time response of the Culebra to rainfall events E4 and E6/E7 was determined using water-level and, where available, pressure-head data, which we interpret here to reflect changes in water level. We interpret lag-time to be the difference in time between the onset of precipitation and the initial response at a given well. The onset of precipitation for E4 is 25 September 2004 and 15 August 2006 (the day of heaviest rainfall) for E6/E7. Culebra lag-time response to E4 was determined for 34 wells, of which 13 were determined using daily time-series of pressure-head. Lag-time response to E6/E7 was determined for 27 wells, of which 16 were determined using pressure-head data. It should be noted that not all the wells are the same for both determinations of lag-time. This is due to the addition of ten new wells and the plugging and abandonment of aging wells between 2004 and 2006. Many of the new wells drilled in 2006 (i.e., SNL-10, SNL-17, and SNL-18) and wells very near to them provided inconclusive determination of lag time due to well testing activities conducted after they were completed. Other wells provided inconclusive results due to compliance water-quality sampling in many of the WQSP-series wells that took place soon after the events (particularly E7). And finally, a long-term drawdown event (~2 m at H-9c), of unknown origin that began sometime in June 2006 and ended in December 2006, affected water-levels in wells located throughout the southern portion of the WIPP region (i.e., H-9c, SNL-12, H-17, H-11b4, SNL-14, H-4b), providing inconclusive results in that area for E6/E7. The Culebra lag-time responses to both rainfall events E4 and E6/E7 ranged from less than one day to no observable response and are summarized in Table 2.

Table 2. Lag-time response of water-level or pressure-head in WIPP wells to rainfall events E4 and E6/E7.

Well ID	E4 – Sept. 2004		E6/E7 – Aug./Sept. 2006	
	Lag-time (d)	Method	Lag-time (d)	Method
C-2737	NR	WL	NR	WL
ERDA-9	NR	WL	NR	WL
H-2b2	NR	WL	NR	WL
H-3b2	<75	WL	I	
H-4b	<45	WL	19	PH
H-5b	NR	WL	NR	WL
H-6b	6	PH	<29	WL
H-7b1	8	PH	<28	WL
H-9c	<73	WL	I	
H-10c	NR	WL	NR	WL
H-11b4	<17	WL	I	
H-12	ND		NR	WL
H-15	ND		I	
H-17	<17	WL	I	
H-19b0	<45	WL	I	
IMC-461	<9	PH	<4	PH
SNL-1	1	PH	<8	WL
SNL-2	1	PH	3	PH
SNL-3	6	PH	<28	WL
SNL-5	9	PH	<28	WL
SNL-6	ND		NR	PH
SNL-8	ND		NR	WL
SNL-9	6-9	PH	6	PH
SNL-10&14	ND		ND	
SNL-12	26	PH	I	
SNL-13	ND		18	PH
SNL-15	ND		NR	WL
SNL-16	ND		4	PH
SNL-17&18	ND		I	
SNL-19	ND		2	PH
WIPP-11	ND		I	
WIPP-13	<16	WL	10	PH
WIPP-19	45-74	WL	<57	WL
WIPP-25	2	PH	2	PH
WIPP-26	<8	PH	<5	PH
WIPP-27	<16	WL	ND	
WIPP-30	<16	WL	<6	PH
WQSP-1	18-74	WL	<29	WL
WQSP-2	18-74	WL	<29	WL
WQSP-4	<56	WL	<85	WL
WQSP-5	<74	WL	<85	WL
WQSP-3&6	I		I	

WL – water level PH – pressure-head
NR - no response or >75 days I - inconclusive results
ND – no data, well not drilled yet, or well plugged and abandoned

The time-lag responses for the two rainfall events were combined to make one data set to allow for more spatial coverage in the data. The lag-time responses, in days, were grouped into to intervals based on natural breaks. The interval values were then kriged to generate a map of the areal distribution of the lag-time response to a large rainfall event (Fig. 9).

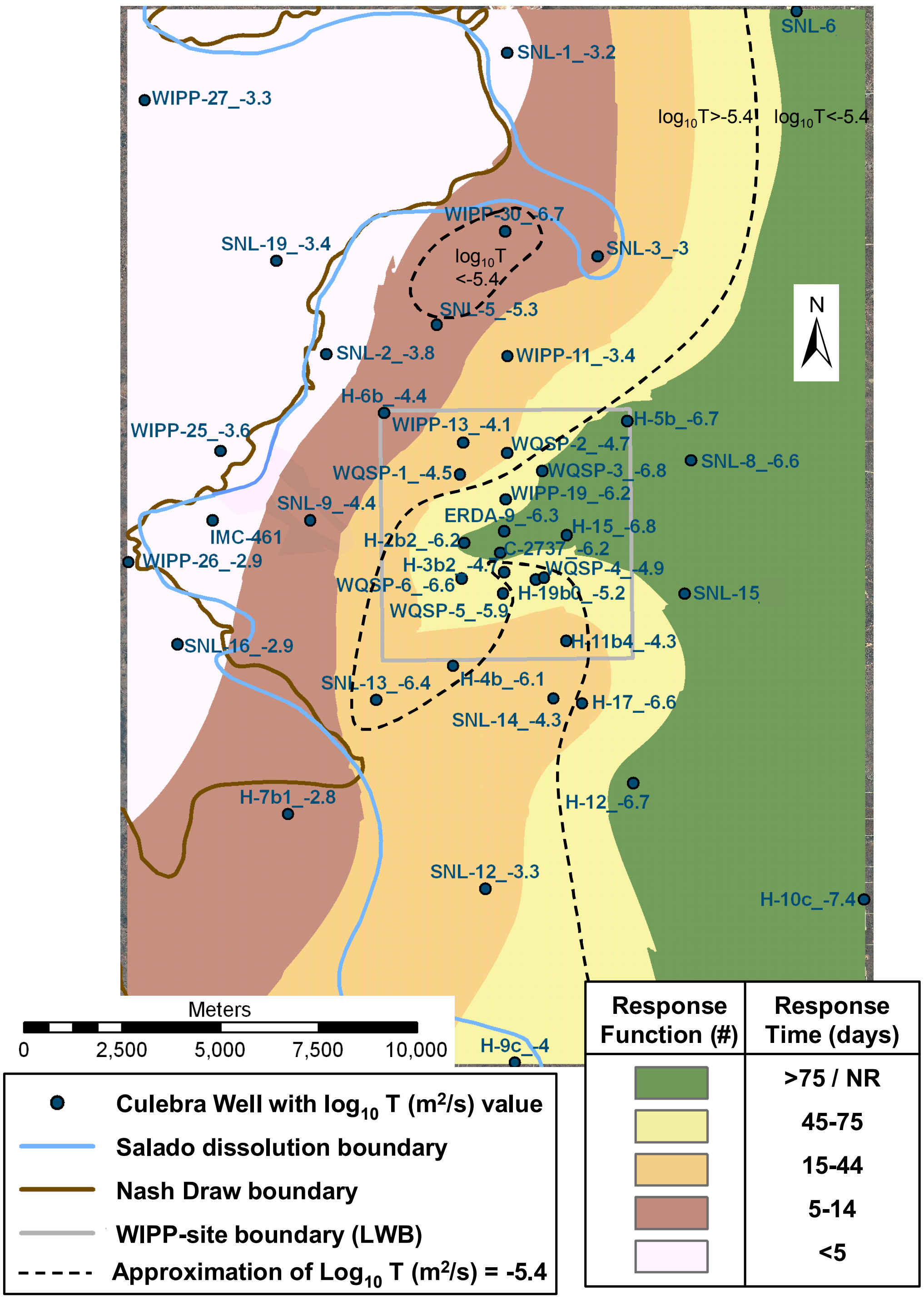

Figure 9. Map of Culebra lag-time response to major rainfall events.

In general, the lag-time increased from west to east away from Nash Draw, as would logically be assumed because Nash Draw is the recharge area. Recharge through Nash Draw is likely a result of the flooding that has been observed after large rainfall events (Powers et al., 2006). The flood waters either inundate low-lying areas where karst features such as sinkholes and caves may be found (Powers et al., 2006) or flow into fractures that run parallel to the base of Livingston Ridge (Powers et al., 2003). The karst features and fractures allow for the rapid delivery of water to lower units such as the Culebra. As the large volume of water rapidly enters the Culebra, pressure-head increases causing water levels to rise rapidly in and adjacent to Nash Draw. Outside of Nash Draw, water levels begin to rise in response to the diffusion of the increased pressure-head that, which can take days to months depending on the amount and connectivity of fracturing within the Culebra.

Inferences about Fracturing in the Culebra

Because Culebra T has shown good correlation to the degree of fracturing and fracture fill (Holt et al., 2005), comparison of Culebra T values with the lag-time distribution should provide additional insight into the fracture distribution in the Culebra. Figure 9 shows the $\log_{10}$ T (m^2/s) value of each Culebra well, where available, as well as an approximation of the $\log_{10}$ T = -5.4 contour, which is considered to be the high-T cutoff between fractured and unfractured Culebra (Holt et al., 2005). Log_{10} T values > -5.4 typically reflect zones of well-interconnected fractures as shown by the responses observed during multi-pad pumping tests. Log_{10} T values < -5.4 are found at wells that either show no evidence of fracturing or minor amounts of fracturing that are filled with cements, in addition void spaces (i.e., vugs) are also filled with cements in both instances (Powers et al., 2003).

In general, lag-time response compares well with Culebra T values for the entire WIPP area (Fig. 9). All Culebra wells with $\log_{10}$ T values >-5.4 (high T) responded to both rainfall events no matter what distance they were from Nash Draw, though the lag-time response was shorter than would be expected based on distance from Nash Draw for some wells. For example, wells H-6b and SNL-9, located within 2.5 km of Nash Draw, responded within 5 days of E4. Both wells may be linked to Nash Draw due to their possible proximity to a fracture or series of fractures that allow for the observed response. SNL-3 also responded within 5 days of E4, but the relatively repaid response is believed to be linked to the higher degree of fracturing caused by the dissolution of the upper Salado that has been observed there. A pronounced feature of the mapped lag-time response can be observed to the south of the WIPP site and is associated with a cluster of high T wells. It appears that this zone may be connected to Nash Draw through increased fracturing, which has been observed in cores form some of those wells.

Wells with $\log_{10}$ T values <-5.4 (low T) generally show little to no response, except for those located near to Nash Draw (i.e., WIPP-30, SNL-5 and SNL-13) and those situated adjacent to the zone of high T south of the WIPP site (i.e., H-17 and H-4b). The short lag-time response in wells near to Nash Draw is due to their close proximity to the source of recharge and possibly due to their proximity to dissolution extending from Nash Draw. The relatively rapid lag-time response in wells H-17 and H-4b is most likely due to their proximity to the increased fracturing associated with the zone of higher T mentioned above.

Summary

Lag-time responses to two large rainfall events that occurred in the WIPP vicinity during 2004 and 2006 were determined using water-level and pressure-head data collected in wells completed to the Culebra Dolomite. Lag-time responses for the two events were combined into one data set and mapped. The distribution of lag-time further confirmed that Nash Draw is an area of recharge to the Culebra. Lag-time matched well with measured T values of the Culebra, which combined with the spatial distribution of lag-time response, provides further insight into the Culebra fracture distribution in the vicinity of WIPP.

Future work to further this study includes: collection of additional precipitation data at different locations (i.e., northern and southern Nash Draw) throughout the WIPP region, continued monitoring of the Culebra (currently SNL has transducers in 37 of the 45 Culebra well locations), a more robust statistical approach (i.e., cross-correlation between rainfall and water-level) in determining lag-time, and modeling of the evolution of the water-level response to rainfall events using the Culebra flow model used in PA calculations.

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