WIPP Geohydrology – The Implications of Karst

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Introduction

Karst refers to a particular type of surface morphology and groundwater hydrology that results from the dissolution or corrosion of rock. The most spectacular and best studied karstlands are in carbonate rocks, but karst also forms in gypsum, anhydrite, and salt.

The WIPP is in one of the largest karstlands of the United States. Karst morphology has been extensively studied by G. O. Bachman and others. The implications of karst hydrology have not yet been considered.

The problem with karst is that shallow groundwater flow is highly irregular in both time and space, through open conduits with a minimum of filtration, and (under the right weather conditions) extremely fast. The Rustler Formation is both the principal aquifer in the region and the principal karst horizon. The Rustler Formation is not a reliable barrier to the migration of contaminated water.

This report results from a review of literature on karst hydrology, inspection of karst features in the field, and discussions with an experienced consultant. The conclusions are based on the referenced literature and should not be judged without a thorough understanding of that material. For minimum background information, the reader is referred to Bachman (1980) and Bogli (1980).

Evidence of Karst

A literature review places the WIPP site within one of the largest karstlands of the United States. Davies and LeGrand (1972) and LeGrand, Stringfield and LaMoreaux (1976) both summarize the important karstlands of the U.S. and include the Pecos Valley of southern New Mexico in their discussions. The maps in these articles (p 470 and p 36, respectively) indicate the WIPP site lies within an extensive karstland. A similar map is reproduced in Milanovic (1981, p 15) and in slightly more detail in Davies (1970, p. 77).

Relevant articles on a more local scale include (Morgan (1941), Olive (1967), Gustavson, Hoadley and Simpkins (1981), Vine (1963), and Bachman (1974, 1980, 1981).

Morgan (1941) noted that in the Pecos River drainage basin solution of halite, gypsum, and limestone has controlled the position and efficacy of surface streams and accomplished much of the actual basin excavation. He also notes that over large areas the surface drainage systems have been completely disrupted by development of subterranean drainage through solution channels. The WIPP site is indicated by his map (Fig. 1, p 28) as lying in one of these areas.

More recently Gustavson, Hoadley, and Simpkins (1981) identified rapid karstification of land surfaces overlying areas of active salt dissolution. Their studies are largely conducted in the Texas Panhandle, but simple extrapolations of their regional maps place the WIPP in a karstland.

Olive (1967) discussed solution-subsidence troughs in the outcrop area of the Castile Formation. He attributed the troughs to collapse of solution conduits initially developed along east-trending joints. Although this karstified formation differs from that at the WIPP, the article demonstrates karst development in gypsum in the same semi-arid climate.

G. O. Bachman has conducted extensive investigations of the surface geology of the Los Medanos area to support geologic feasibility studies of the WIPP. The results of this field work and his present interpretation of the Cenozoic history are in Bachman (1980). This report describes dissolution and karst development in the Permian evaporites of the Pecos drainage in the Delaware Basin (including the WIPP site). The affected evaporites include anhydrite, gypsum, halite, and related minerals, and the karst features include collapse sinks, breccia pipes, domes, mounds, caves, and intricate solution passages. Here, and in Bachman (1974), it is suggested that the rate of karstification is dependent on climate with more rapid dissolution and collapse during humid intervals and active fields of windblown sand during arid intervals. The result is an extensive, partially-buried karst plain.

Nash Draw is the most impressive topographic feature in the vicinity of the WIPP site. It is described by Vine (1963) and mapped in detail by Bachman (1981). Processes identified in its formation include near surface dissolution and the related in-filling of solution cavities by surficial sediments. Presently active dissolution of gypsum from the Rustler Formation has resulted in numerous collapse sinks, caves, and tunnels, in a complex karst topography. Caves near the Ken Smith Ranch, near WIPP-26, and near the turn-off from NM

Route 28 to ERDA-10, are large enough to enter (J. Mercer, pers. comm.). Deep-seated dissolution and subsequent collapse of the overlying evaporite section has not been identified.

Karst springs are usually large, few in number, and very irregular in flow. Surprise Spring at the north end of Laguna Grande de la Sal and the brine springs at Malaga Bend are probably karst, although Surprise Spring is affected by waste water from potash refining. The brine springs at Malaga Bend have been studied as part of a salinity alleviation project. The flow is estimated at 0.5 cubic ft/sec, but (more pertinent to karst) it is irregular. Hale, Hughes and Cox (1954, p 26) noted that short period (hours - few days) water level changes in wells in the spring aquifer accompanied local rain storms. Similar conclusions are indicated from the monthly precipitation table (p 26) and hydrographs in Havens and Wilkins (1979). Particularly notable are the very abrupt changes in all their wells accompanying 6-1/2 in. of rain during August 1966. The significance of such rainfall-related short-period well level oscillations near a karst spring is discussed in Milanovic (1976).

The evidence for regional karstification is extensive, and there is no reason to preclude karst conditions from the immediate vicinity of the WIPP site. The following observations indicate that karst conditions do exist at the site:

- the Rustler Formation isopach
- solution-controlled anisotropic heterogeneous vugular porosity
- closed topographic depressions
- the WIPP 33 cavities
- the gravity field
- lack of surface runoff
- the water balance

An isopach of the Rustler Formation is given in Powers and others (1978, Figure 4.3-8) and more recently in the USGS contribution to Barrows and others (in preparation). These maps show the isopach thinning from 450 feet in the southeast corner of WIPP site Zone IV to 275-300 feet in the northwest corner. There is a strong correlation between the isopach thinning and downward progression of surface defined by borehole encounters of the uppermost halite, the uppermost anhydrite, and the lowermost gypsum. These relations have been attributed to the downward and eastward progression of dissolution in the formation by Powers and others (1978, p. 4-41) and by Snyder in Barrows and others (in preparation). The Rustler Formation thinning is an example of a complex interstratal blanket karst involving halite, anhydrite-gypsum, and, to a lesser extent, dolomite.

The interpretation that dissolution progresses downward and eastward is inconsistent with confined southwesterly flow in the Rustler Formation. If the flow were confined, then dissolution should proceed from the recharge area where fresh water first enters the formation. This is demonstrated by a laboratory model of halite karst development described by Bogli (1980, p 210). A more likely process involves easterly progressing karst development with downward infiltration of fresh water through feeders in the overlying Dewey Lake Formation to karst channels in the Rustler Formation.

The borehole measured hydraulic characteristics reported by Gonzalez (1982) are consistent with an interstratal phreatic karst. The measured transmissivities vary over five orders of magnitude within the site (0.001-100 ft^2/day) and up to 1250 ft^2/day in Nash Draw. Transmissivity and the isopach thinning of the Rustler Formation generally increase from east to west. Where measured, the transmissivities are anisotropic with reported ratios of 2.1:1 and 2.7:1. The potentiometric gradient is well below the ground surface, of low average gradient, and irregular. The core descriptions of the aquifer (Schreiber, 1982) indicate primarily vugular porosity.

There are a large number of closed topographic depressions at the WIPP site. These are best seen with stereoscopic viewing of the site aerial photographics or by inspection of the site topographic maps (2 ft. contour interval) (Bechtel, 1981). The largest of the depressions are: in sec. 9, R31E, T22S; at WIPP 14; and at WIPP 33. The one in section 9 is briefly discussed in Powers and others (p 4-7, Fig. 4-2-1b) and by Griswold (1977, p 13, Fig. 34). The depression at WIPP 33 is discussed in the WIPP 33 Basic Data Report (SNLA and USGS, 1981).

The smaller depressions may be windblown. However, the larger depressions are not reasonably attributed to the wind. They are generally round instead of elongate in the prevailing wind direction, symmetric instead of having wind-blown and leeward sides, and have hummocky sandy bottoms instead of a pebble-strewn wind scour. They are also partially coincident with the negative gravity anomalies and one (WIPP 33) was found to be underlain by cavities.

The larger of the depressions are reasonably interpreted as alluvial dolines. Following M. Sweeting (1973, p 46) or A. Bogli (1980, p 61) alluvial dolines form when loose surficial material is washed into solution cavities in the underlying rocks.

Borehole WIPP 33 (SNLA and USGS, 1981) encountered four cavities totaling slightly over 20 feet in the Forty-niner and Magenta Dolomite Members of the Rustler Formation. These cavities are direct evidence of karst. They demonstrate the relation between alluvial dolines, negative gravity anomalies and karst channels in the Rustler Formation.

The surface of the doline at WIPP-33 is floored with loose sand. There are matted leaves and debris indicative of shallow flooding but no evaporite crust. One of the few small arroyos at the site drains into the depression.

A negative gravity anomaly at WIPP 33 was indicated by the regional gravity survey. Additional reconnaissance high-precision gravity profiles resolved a 0.6 milligal negative anomaly with a double galf width of 900 ft. This anomaly cannot be reasonably attributed to the 44 ft of Holocene fill encountered in WIPP 33. The top of the causative body should be at or above 450 ft, and the anomaly is too large to be attributed directly to the cavities.

The WIPP gravity survey is a classic demonstration of the utility of microgravity in karstlands. The field parameters were initially selected to resolve low-amplitude, broad-wavelength anomalies originating from structures within the Castile Formation. Instead of the anticipated signals, the survey revealed a complex pattern of high-amplitude, and short-wavelength negative anomalies. These are presently interpreted as resulting from density (and acoustic velocity) alternations in the vicinity of karst channels. The interpretation and preliminary data are in Barrows and others (in preparation, section 3.3). It consists of the following elements:

Borehole WIPP 34 is in a normal gravity field. WIPP 13, WIPP 14, and WIPP 33 are in negative gravity anomalies. The depths to shallow stratigraphic horizons in all the boreholes are normal.

One of the negative gravity anomalies is coincident with a time-structure syncline at the reflection time of the Rustler Formation (seismic line 77x2). Assuming stratigraphic depths are normal, the seismic time-structure syncline can be produced by lateral velocity variations in the overlying Dewey Lake Formation. The magnitude of the required velocity variation is comparable to that indicated by measurements in uphole velocity surveys at WIPP 13 and WIPP 34. The density variation implied by this measured velocity variation is, along with the thickness of the Dewey Lake Formation, sufficient to account for the negative gravity anomaly.

Boreholes WIPP 14 and WIPP 33 are in alluvial dolines. The two dolines are coincident with negative gravity anomalies.

Gravity interpretations are inherently ambiguous. However, the anomalies are large, real, and must originate at shallow depths. The boreholes did not encounter stratigraphic features which could cause such anomalies, and alteration in the vicinity of karst channels is the simplest interpretation yet proposed. Microgravity surveys in other karst areas (Aczi, 1977, and Omnes, 1977) have also detected negative anomalies which are too large to be entirely due to the cavities. These are interpreted as partially resulting from rock alteration near to the channels.

The morphology of semi-arid environments is normally the product of intermittently running water. Arroyos, piedmonts, and playas are characteristic features. The WIPP site has almost no surface runoff and is characterized by a gently-sloping, slightly hummocky plain blanketed with partially stabilized windblown sand and sand dunes. This morphology is evident on the detailed WIPP topographic maps (Bechtel, 1981). The maps show numerous small closed topographic depressions scattered over the site.

This lack of erosional morphology is not due to inadequate precipitation. There are about 12 inches of annual rainfall most of which falls between May and October. Ed. L. Reed and Associates (1977) provided a study of the surface hydrology in the Los Medanos Area. They indicated an intensity distribution of 1.6 inches and 4 inches for the 2 year and 100 year (resp.) recurring 6 hour storms; and 2 inches and 5 inches for the 2 year and 100 year (resp.) recurring 24 hour storms. They also calculated anticipated runoff using criteria established by the U.S. Soil Conservation Service. The 100 year, 24 hour storm should cause 990 acre feet of runoff from the 30 sq. mile WIPP site. Instead of running off, the precipitation collects in the small topographic depressions and rapidly soaks into the ground.

The absence of surface runoff is characteristic of a karstland. "Mature karst" has been defined as the stage when subsurface drainage is sufficiently developed to accommodate nearly all surface runoff (Bogli 1980, p. 47).

Further karst indications can be inferred from the steady-state water balance equation

$$\text{Inflow} = \text{Outflow}$$

Despite its simplicity, this expression is fundamental to hydrology and must be satisfied by any model or any part of a model (Ward, 1967, p. 19).

Consider the soil at the WIPP site. The inflow is simply 1 foot of precipitation per year (Powers and others, 1978, p. 6-4). Outflow is split between percolation to the groundwater system and evapotranspiration.

Insufficient information exists to establish the division between evapotranspiration and downward percolation. Efficient evapotranspiration should be favored by the semi-arid climate, deep water table and generally dry precursory conditions. Percolation to the ground water system should be favored by sparse vegetation, intense rainstorms, and transmissive soils. The soils are at least transmissive enough to allow infiltration of the larger storms.

Geohydrology Associates, Inc. (1978, p. 48) discussed various studies pertinent to establishing the percentage of total precipitation that is evapotranspirated. They needed the value to calculate the water budget at the potash mines and concluded that 96% evapotranspiration is reasonable. Their report describes many surficial karst features in the area. However, they did not assume karst hydrology in modeling the groundwater movement.

Assuming 96% evapotranspiration, then 0.04 foot of water per year is added to the groundwater system. Further assuming the Rustler aquifers are fifty feet thick with an average effective porosity of 10% (Powers and others, 1978, p. 6-22), then enough water is added to completely refill the aquifer every 125 years.

It follows that the groundwater must be removed from the system on an average of 125 years (some faster, some slower). Calculations based on borehole-measured parameters and a particle-tracking model for a nonabsorbing tracer yield extremely long travel times around 40,000 years (Gonzalez, 1982). There is a basic inconsistency between the two approaches. Appealing to an evapotranspiration efficiency approaching 100% is both unsubstantiated and unnecessary. It is subsequently shown that in a karstland boreholes are expected to indicate values which are not representative of the area. The calculated very long travel times are then both understandable and wrong.

Implications

The WIPP site is reasonably described as a karstland. Regional karst is evident in the surface morphology and has been so identified by Morgan (1941), Olive (1957), Davies and LeGrand (1972), LeGrand, Stringfield and LaMoreaux (1976), G.O. Bachman (1974, 1980, 1981), Powers and others (1978, section 6.3.6) and Gustavson, Hoadley and Simpkins (1981, p 130-137). Locally the Rustler Formation is an example of a complex, interstratal, blanket karst involving halite, gypsum-anhydrite, and dolomite. Karstification of the Rustler Formation is evident from the Rustler isopach, solution-controlled anisotropic heterogeneous vugular permeability, the gravity field, the WIPP 33 cavities, closed topographic depressions, lack of surface run-off, and considerations of a reasonable water balance.

Implications to WIPP follow from the characteristics of karst hydrology. The English literature on karst hydrology is limited but adequate to form some general conclusions. This literature includes two text books (Bogli, 1980 and Milanovic, 1981), a couple of published symposia (Yevjevich, 1976, and Tolson and Doyle, 1977) and several articles. It should be noted that karst hydrology is a newly developed area of research and not much was published in English before the last half decade.

The hydraulic characteristics of a karstland result primarily from the dissolution or corrosion of rock. Secondary processes include the transport of insoluble material through solution conduits and the incasion or collapse of underground cavities. The processes are discussed at length in Chapter 14 of Bogli (1980).

Karstlands develop in phases. During the initial phase a hydraulic gradient forms in a corrodible but unaltered country rock. Water flows slowly through interstices and open joints and corrodes or dissolves the rock. One or two of the pathways will be slightly more permeable, carry slightly more water, and grow faster than the other pathways. As they grow, the hydraulic gradient decreases and alternate pathways become increasingly inactive. The end result is a highly irregular regional network of primary solution conduits within a larger volume containing generally inactive stagnated secondary pathways. Average transmissivities should be highly anisotropic in the direction of the original gradient (Mandel, 1966, p 5).

The initial stage of karstification lasts until the subsurface drainage is sufficiently developed to accommodate all of the surface run-off. The karstland is then defined as "mature" (Bogli, 1980, p 47). During maturity, corrosion enlarges the conduits, the water table drops towards the level of the drainage springs, and the number of springs decreases as the more aggressive conduits capture increasingly larger proportions of the total flow. Finally in old age the cavities collapse. In this sense, karst development at the WIPP site should be regarded as mature.

The preceding discussion is independent of the size of the volume considered. In a karstland, flow through any representative volume is expected to be dominated by a few throughgoing conduits and there should be no spatial scale at which the average hydraulic properties vary gradationally. Because of this inherent heterogeneity, continuum models should not apply. This includes the use of an anisotropic continuum for a "fracture flow" model. For further discussion of the physical conditions necessary to use the anisotropic continuum approximation see Maini, Noorishad, and Sharp (1972, paper I1-E. 8p.).

Another implication of the karstification process is that borehole-measured transmissivities and storativities should not be representative of the area. A borehole which misses one of the active corrosion conduits should show values which are much less than the average. This applies to almost all boreholes in a karst terrain because the area of active conduits is only a small part of the total area. Conventional borehole measurement can still be made in a karstland. Mandel (1966, p 6) notes that even in well developed karstlands there can be a regular distribution of groundwater potentials and a "cone of depression" around pumping wells. In this sense, karst may be indistinguishable from classical porous aquifers.

A karstland can normally, but not always, be subdivided into three hydrological zones based on the position of the water table (Bogli, 1980, Ch 6). The largely inactive vadose zone includes feeders in which groundwater flows downward towards collecting channels. The high-water zone is that region which is alternately flooded and empty, and the phreatic zone remains completely flooded. All three zones should be present where corrodible rocks extend from depth to the surface (e.g., Nash Draw). At the WIPP site the corrodible Rustler Formation is beneath the Dewey Lake Formation and entirely saturated with water (interstratal phreatic karst). When penetrated by wells, water rises several hundred feet into the relatively impermeable Dewey Lake Formation (i.e., an artesian aquifer). Other karstlands in which saturated corrodible rocks are covered by non-soluble formations include the Athabasca carbonate and evaporite karst in Alberta, Canada (Ozoray, 1977, p 85-98), the partially covered Silver Springs basin in Florida (Faulkner, 1976, p 137-164) and the Santa Rosa area of New Mexico (M. Sweeting, 1973, p 299). Artesian conditions in karstlands have been noted along the northern coast of Puerto Rico (Giusti, 1977, p 149-167), in Yugoslavia (Milanovic 1976, p 165-191 and 1977, p 357-358), in portions of the Silver Springs basin (Davies and LeGrand, 1972, p. 477), and the Roswell Artesian Basin of New Mexico (Davies and LeGrand, 1972, p 502; Bean, 1942).

The velocity of groundwater in a karstland is very irregular. Milanovic (1981 ch 5) reviews the background and present concepts of karst water and its zonation by velocity. At one extreme are the old and nearly stagnant waters occupying pores in the remaining unaltered country rock and in abandoned pathways which are no longer part of the primary system. Bogli (1980, p 82) notes several occurrences of stagnated karst waters, one of which was dated at 3400 ±400 yrs. At the other extreme are the waters in the primary system. A few direct velocity observations have been made by speleologists observing the flow of water along cavern floors. Most velocity measurements are made indirectly by injecting a tracer into the karst watercourse, usually at a swallow hole, and observing the arrival at a spring. This "velocity" is the linear distance divided by travel time and does not account for irregularities in the flow path.

The measured tracer velocities are, by groundwater standards, very fast. Milanovic (1981, p 135) gives a histogram and discussion of 281 tests conducted in the Dinaric Karst of Yugoslavia. The measured velocities ranged from 0.002 to 55.2 cm/sec with an average of 5 cm/sec. The linear travel distances are 10 to 15 or more kilometers. Bogli (1980, p 78-79) reports flow velocities ranging between a few meters per hour and 1/2 km/hour (0.08 to 14 cm/sec). Comparable velocities were discussed by the participants in the 1975 U.S.-Yugoslavian symposium on karst hydrology and water resources (Yevjevich, 1976, pp 170, 176, 186-187, 240). At a reasonable karst velocity of 1 cm/sec water in the primary system can move 30 km in about one month.

The observed character of karst flow also differs significantly from more conventional groundwater. First, velocity is not proportional to the potentiometric gradient. Milanovic (1981, p 138) gives a plot of the measured tracer velocities versus the gradient between the end points. There is no detectable relation on the plot despite the wide range of both variables. Bogli (1980, Ch 5) notes that there is no direct relationship between the velocity of flow and the gradient. It follows that models based on a linear or Darcy relation should not be applied to a karstland.

Second, karst velocities are found to be dependent on surface conditions with relatively slow movement during the dry season and rapid movement during heavy rains. In fully arid climates, permanently static karst water-bodies can be found (Bogli, 1980, p 85). This dependency of velocity on surface conditions results from variable flow regimes more than an increase in the gradient. Torbarov (1976, p 121) demonstrated at least two, and probably three, flow regimes using the decomposition of water recession curves. The calculated hydraulic characteristics (i.e., transmissivity and effective porosity) of the regimes differ. Further considerations of multiple flow regimes in a karst are given by Milanovic (1976, p 184), Yevjevich (1976, p 213), Ramljak, et al (1976, p 240) and Bogli (1980, Ch 5).

Karst results from the dissolution or corrosion of rock in a complex ground-water system which is extremely irregular in both space and time. The chemical properties of karst waters are correspondingly complex. Faulkner (1976, p 149) and LeGrand, Stringfield and LaMoreaux (1976, p 44) note chemical stratification of karst water with generally more dissolved solutes at greater depths. Chemical analysis of nine samples from the Puerto Rico karst are given by Giusti (1977, p 149-167) and for six samples for the Athabasca buried karst by Ozoray (1977, p. 85-98). These last two papers illustrate the broad range of chemical compositions of karst waters. Further discussion of geochemical studies are in Thrailkill (1976, paper 34) and Petrik (1976, paper 29).

Faulkner (1976, p 137-164) reported the analysis of a karst system discharging at Silver Springs, Florida. This article may reasonably represent the extent to which hydraulic analysis can be applied to a complex and largely inaccessible karstland like the WIPP site. The analysis used flow net techniques to model the known flow rate from the spring. Sufficient well data were available to contour the potentiometric surface. Recharge was by infiltration of local rainfall. Aquifer thickness, effective porosity, and isotropic transmissivities were assumed. The flow net analysis indicated transmissivities of 10^3 to $2.36x10^6$ meters squared per day and velocities between 0.05 to 23 meters per day, with an average of 2 to 3 meters per day. The author notes that the calculated velocity approximations must be used with care because of complications due to the presence of solution channels (p 158). He also notes that while flow net analysis of the freely flowing karst spring yielded results representative of the basin, conventional pumping tests may necessarily analyze a small part of the aquifer that is not representative of the larger segment (p 159).

Practical problems of waste disposal in a karstland result from the irregular, very fast movement of contaminated groundwater through open conduits. Authors who have identified karstlands as unreliable waste disposal environments include LeGrand (1973), LeGrand, Stringfield and LaMoreaux (1976, p 32), Yevjevich (1976, p 220), Turk (1976, paper #30 and p 861), Pokrajcic (1976, paper #31), Preka (1976, paper #32), Faulkner (1976, p 859), Petrik (1976, p 860), Corovic (1976, p 860, p 862), Vineyard (1976, p 861), Herak and Stringfield (1972, p 515), Milanovic (1981, p 3), Richter (1977, p 305), Sandlein and Palmquist (1977, p 323), and Davies and LeGrand (1972, p 480), Malatino and Lloyd (1977, p 307).

Conclusions

- The WIPP site is regionally and locally a karstland.
- Representative hydraulic characteristics cannot be measured at boreholes.
- Continuum models should not be used to establish minimum flow times. This includes the use of an anisotropic continuum approximation of fracture flow.
- Flow in the Rustler Formation is expected to be highly irregular in both space and time, through open channels with a minimum of filtration, and (under the right weather conditions) extremely fast.
- The Rustler Formation is not a reliable barrier to the migration of contaminated water.

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