Terrain factors in Capitan recharge, northeastern Guadalupe escarpment, New Mexico

Scott Rice-Snow and James Goodbar

New Mexico Geology, v. 34, n. 1 pp. 15-22, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v34n1.15

This page is intentionally left blank to maintain order of facing pages.

Terrain factors in Capitan aquifer recharge, northeastern Guadalupe escarpment, New Mexico

Scott Rice-Snow, Department of Geological Sciences, Ball State University, 2000 W. University Avenue, Muncie, Indiana 47306, ricesnow@bsu.edu; *James Goodbar*, U.S. Department of Interior, Bureau of Land Management, 630 East Greene Street, Carlsbad, New Mexico 88110-6292

Abstract

The Guadalupe escarpment southwest of Carlsbad, New Mexico, is under accelerating oil and gas development and also comprises the most direct recharge area for the Capitan aquifer. Key infiltration areas on the escarpment landscape must be identified for special ground water quality protection measures during petroleum drilling and production. The landscape has 120–180 m of local relief, with 22% of surface area in uplands, 61% in slopes, and 17% in canyon floors. Infiltration on uplands and slopes must generally pass through soil-filled fracture openings and move downdip on open bedding planes. Slope areas include many headwater stream channels in V-shaped valleys, with abundant signs of ephemeral ground water seepage. On the floor of Dark Canyon, the most important drainageway traversing the area, bedrock pavement sections have some potential for storm-flow infiltration via abrasion-formed basins along fracture lines, and by eastward-dipping strata with unusual levels of karst conduit development. Depth of boulder fill along some reaches of the canyon exceeds 10 m, providing a large-volume medium for stream-flow transfer to the subsurface during and after floods.

It is likely that water moving slowly downdip through backreef units will only feed the reef aquifer if it does not again contact the surface. Two simplified end-member models can be postulated for escarpment area recharge to the Capitan aquifer. In the first model, infiltrating water descends vertically through carbonate units and then runs downdip on the major sandstone beds. The second model treats the entire mass of the backreef as a material with strongly anisotropic permeability, much enhanced along the dip direction, with infiltrating water proceeding in a downdip direction immediately on reaching bedrock. The likely real condition resides between these end members, but the two models agree in identifying the following portions of the escarpment landscape as recharge areas that should be given special attention in terms of water quality protection: (1) the floors and downdip side slopes of Dark Canyon and other major canyons, (2) upland surface and slope areas that are updip of major fracture lines, and (3) the outer escarpment, extending 2 km west from the escarpment front. In the latter area, zones of rectangular, fracture-associated drainage warrant special attention as potential quick recharge sites.

Introduction

The Capitan aquifer is situated along the eastern margin of the Guadalupe Mountains in southeast New Mexico. This intensely karstified ground water system supplies abundant high-quality municipal water to Whites City and the city of Carlsbad, as well as to a number of ranch and farm wells at the base of the east-facing Guadalupe escarpment. Additional springs and wells providing water for livestock and wildlife in the uplands are connected to the system under study.

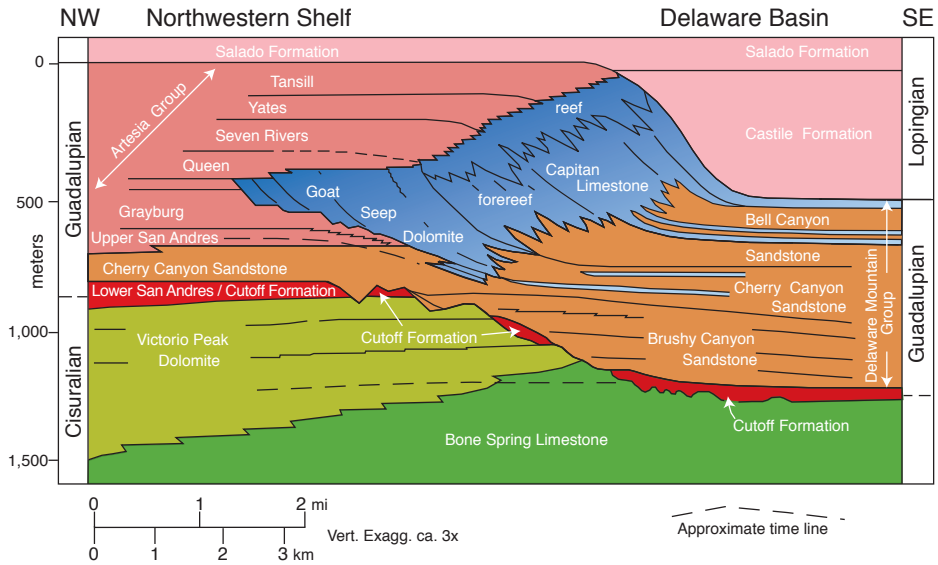

FIGURE 1—Regional stratigraphy, as compiled by P. Scholle from many sources including King (1948), Tyrrell (1969), and Pray (1988). In the study area, uplands of the Guadalupe escarpment are developed in the Tansill Formation, and adjacent lowland surfaces of the Delaware Basin consist of alluvium overlying Castile Formation bedrock.

Bedrock immediately underlying the escarpment front is Capitan Limestone, reef, and forereef members. Shelf (backreef) carbonates extend westward from the crest of the front (Fig. 1). Shelf stratigraphic divisions are based largely on the presence of sandstone and siltstone beds within the carbonate sequence: the Queen, Grayburg, and Yates Formations contain many sandstone beds, whereas the Seven Rivers and Tansill Formations contain few (Motts 1968).

The regional dip of beds in the Guadalupes is commonly less than 3° to the east and southeast. With beds dipping more steeply than the upland surface, higher/younger strata are exposed on that surface (and in canyon floors) farther to the east. Hendrickson and Jones (1952) note, however, that many minor flexures cause dips in various directions. High original dip angles of 20° or more are found on the outer reef front.

Motts (1968) identifies the Capitan aquifer as an interconnected hydrologic system including reef-zone and carbonate-shelf-zone facies, with significantly higher permeability in the former. Downdip movement of water in the shelf (backreef) units slowly feeds the reef aquifer. In addition to storm recharge from Dark Canyon and other major canyon floors, workers also identify the Guadalupe uplands as diffuse recharge areas (Motts 1968; Barroll and Shomaker 2003), especially for snowmelt (Hendrickson and Jones 1952). The most recent decade has seen accelerating oil and gas development on the Guadalupe escarpment. As this work proceeds, it is important to protect the ground water resource from contamination by petroleum and drilling fluids (Goodbar 2009). There is an urgent need to identify especially sensitive surface recharge areas and key subsurface flow routes that warrant special water quality protection measures as drilling and development proceeds. In this initial study we apply geomorphic criteria in the identification of significant Capitan aquifer recharge sites within the Guadalupe escarpment landscape.

The study area

The Guadalupe escarpment is a dominating physiographic feature of the Carlsbad area. From a distance to the east it appears as a near-unbroken, smooth-fronted wall, rising in height toward the southwest. On closer examination the escarpment is the well-dissected edge of a broad upland, with a dense network of deep canyons developed as much as 7 km in from the visible front. This high-relief escarpment zone grades over a short distance into more muted Guadalupe uplands to the west, including Azotea Mesa.

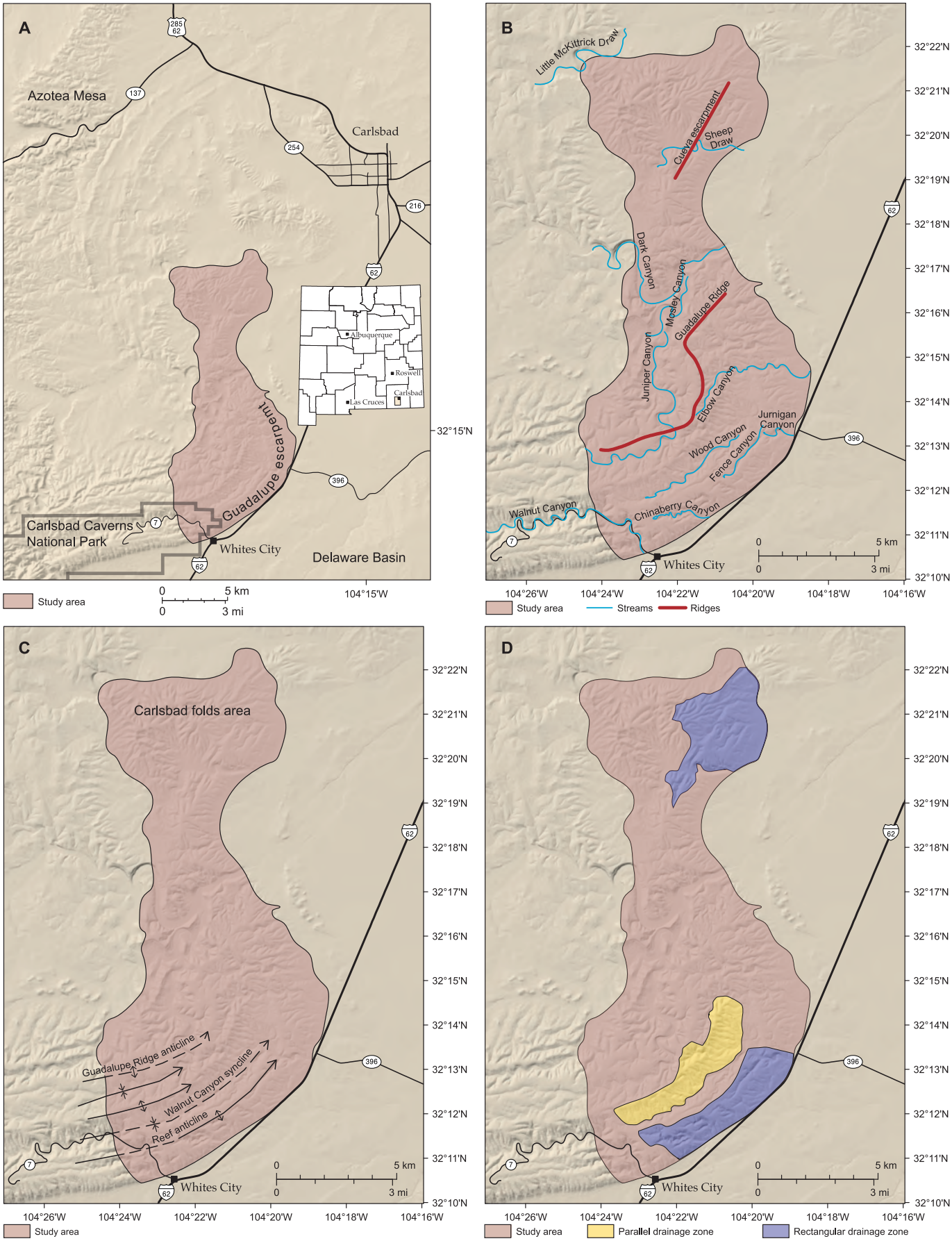

FIGURE 2—Study area maps. **A**—Regional location of the study area. **B**—Key hydrologic and upland features. **C**—Structural features. **D**—Zones of distinctive surface drainage development.

The study area (Fig. 2A) comprises the northernmost section of the Guadalupe escarpment, running north from the Whites City area to southwestern Carlsbad. It ranges from 32°9′30″ to 32°22′30″ N latitude, and is approximately 100 km^2 in area (Fig. 2B). This area encompasses the portion of the Capitan aquifer most directly feeding municipal water supply wells such as the Carlsbad municipal wells near the mouth of Sheep Draw.

The escarpment study area as a whole has 280 m of relief, but this includes the effect of a gradual 60-m rise in upland and piedmont elevations from north to south. Local relief across any portion of the escarpment zone is 120–180 m.

The southeast-facing portion of the escarpment, south of 32°15′ N latitude, is relatively wide, ranging 5–7 km northwest from the escarpment front to the limit of the high relief zone (Fig. 2B). This area exhibits strong development of major canyons and ridge lines parallel to the escarpment front. Large-scale structures influencing the topography (Fig. 2C) are the adjacent linear folds including the Reef anticline on the escarpment front, Walnut Canyon syncline, which extends through much of Wood Canyon, and Guadalupe Ridge anticline, all plunging to the northeast (Hayes 1964; Kelley 1971; Hill 1996). The major canyon feature in the interior of the escarpment zone is Juniper Canyon, which meanders in a northerly direction apparently less structurally controlled than canyons closer to the front (Fig. 2B).

The escarpment zone north of 32°15′ N latitude is embayed, trending northwest up to 32°18.5′ N and then north-northeast beyond this point until cut off at the north end by the cross valley of Little McKittrick Draw (Fig. 2B). The escarpment zone is at its minimum width at the center of embayment: little more than 2 km from escarpment base westward to the less-dissected uplands of Azotea Mesa. Tansill units capping the uplands in the northern part of the study area are draped across broad domal structural highs of the "Carlsbad folds" (Fig. 2C), interpreted as biohermal mounds, with intervening canyons formed along the tracks of ancient sand-bypass channels (Hill 1996; Longley 1999). The major canyon features are drainages of Dark Canyon, Mosley Canyon, Sheep Draw, and Little McKittrick Draw crossing west to east (Fig. 2B), carrying significant throughflow from the greater Guadalupe uplands.

Terrain and surface/ground water interactions

The Guadalupe escarpment topography is well characterized by Davis' (1899) classic division of landscape into upland, slope, and valley floor surfaces. Most of this landscape is occupied by slopes, a nearly "mature" erosional condition by the old genetic scheme (Hayes 1964). However, upland surfaces and canyon bottoms each have qualitatively distinct significance in terms of ground water recharge.

Uplands

The low-relief, rolling upland surface in the Guadalupe Mountains has been described as an ancient erosion surface predating by millions of years the excavation of the Pecos River valley. King (1948) identifies it as a peneplain, whereas McKnight (1986) refers to it as a pediment surface grading northward into a dip slope. In many places it truncates bedding on structures such as the Guadalupe Ridge folds (Hill 1996).

Edges of upland surfaces meeting canyon wall slopes in this area are visually quite distinct on topographic maps and digital elevation model (DEM) plots. Upland surface gradients range up to approximately 10% slope. In GIS mapping of upland and canyon floor areas, we worked from DEM-derived surface gradient values, setting a threshold of 15% slope and a minimum area of four contiguous hectares. By this approach, uplands occupy 22% of the escarpment study area.

Upland surfaces are underlain by shallow soil over rock, float blocks set in soil, and bedrock pavements with soil-filled fractures. Much of the soil surface is bare, especially near the escarpment front, with scattered patches of grass, brushy vegetation, yucca, agave, ocotillo, and cactus. Farther to the west some upland surfaces have near-continuous soil and grass cover.

The main evident epikarst features on these long-exposed carbonate upland surfaces are small-scale karren including pit-karren less than half an inch across, and various scales of fracture-line karren. Degree of karren development is typically quite inconsistent among locally exposed rock surfaces, even adjacent bedrock surfaces with similar drainage characteristics. Without significant excavation or possibly geophysics, it remains unclear whether these dry upland surfaces host an integrated system of soil-filled grikes aiding water collection and transport to the deep subsurface, corresponding to open grike systems noted for other arid sites (Ford and Williams 1989). Although many of the Guadalupe Mountains' abundant caves have openings on uplands or slopes, they appear to be cases of simple exposure by denudation. In most cases, surrounding land surfaces do not specially slope toward them, so they fail to act as foci for surface water drainage. Slow infiltration is the rule on upland surfaces, with occasions of torrential rainfall largely supplying runoff to canyon floors.

Slopes

Typical slope gradient values range from 20% to 50%, with near-vertical cliffs on canyon walls undercut by major streams. Slope profiles on the escarpment front are straight in their upper portions and concave at their bases. Slopes in the interior of the escarpment zone are commonly straight in profile, with minor ledges and benches marking variable mechanical strength of outcropping beds. Most slopes are underlain by rocky rubble with soil fill; bare bedrock slope areas are rare. The vegetation mix and density is similar to that on upland surfaces, with increased scrub and juniper growing in stratigraphically controlled bands and gulley lines along slopes.

Slope areas in our GIS analysis comprised those areas not classified as uplands or canyon floors, generally exceeding 15% surface gradient. By this approach, 61% of the escarpment study area is occupied by slopes.

Slope areas as delimited in this study include many first- and second-order mapped stream channels in well-defined, V-shaped valleys. Channel bottoms on slopes range from gravel and boulder fill to bedrock pavements. Areas underlain by carbonate bedrock are marked by blocky stream-bed margins and cascades, in some locations exposing solutionally opened bedding planes. The rarer sandstone and siltstone exposures are commonly marked by seepage erosion alcoves above the stream-bed level.

Although canyon slopes have less implied antiquity than upland surfaces, the range in degree of karren development is similar. Surface infiltration conditions on most slopes also appear to be similar to those on uplands, largely dependent on slow seepage of water through soil and buried epikarst. Blocky rubble underlying some slopes may approach the high surface permeability of taluses, but permeability appears to diminish rapidly with depth.

Deep infiltration is enhanced where strata dip into the slope, and is unlikely where the strata are parallel to the slope. For canyons aligned transverse to regional dip, it seems reasonable to expect deep infiltration to be favored on the slope that is on the downdip side of the canyon. However, Hendrickson and Jones (1952) suggest that many canyons on the Guadalupe escarpment occupy synclinal axes. In such cases, local dip angles may make both canyon walls ineffective for deep recharge, leaving the limited upland surfaces as the primary candidate areas for diffuse recharge above the runoff-dominated canyon floors.

Most sections of the Guadalupe escarpment study area show dendritic drainage development, as is typical for a region of nearly flat-lying sedimentary rocks. The mapped surface drainage net is fully integrated on the ground surface, not altered in any apparent way by the presence of underlying cavernous porosity in the Capitan aquifer. Some parts of the study area show distinctive rectangular and parallel drainage networks, reflecting local structural controls. These zones warrant special attention, as each has significant implications for local aquifer recharge.

FIGURE 3—Rectangular drainage on Guadalupe escarpment front, north of Whites City, which appears in the upper left. Aerial view to the southwest.

Hayes (1964) describes a conspicuous system of nearly vertical joints parallelling the reef front, developed in the Capitan Limestone and adjacent parts of the equivalent backreef Artesia Group. He notes that many small drainage courses are controlled by this set of joints, giving as examples Calamity Cove and Lefthook, Yucca, Nuevo, and Fence Canyons—all but the last well southeast of the present study area. The most notable zone of such joint-controlled rectangular drainage in the study area occupies the southern part of the escarpment front, the 1–2-km-wide outer slope of the first major escarpment ridge (Fig. 2D), facing directly over the Delaware Basin, south of 32°13.5′ N latitude.

The structure-controlled streams have very consistent form and orientation (Fig. 3), draining from their headwaters in linear, northeast paths and then turning abruptly right (southeast) to empty out through the ridge front. The lower "breakout" portions of the drainages are not so distinctly linear, although possibly following to some degree a lesser, front-perpendicular joint system noted by Hayes (1964), as suggested by McKnight (1986). The portions of the rectangular drainage system parallel to the front of the escarpment intercept the runoff from the front slope and concentrate it to flow along major fracture lines. Accordingly, these reaches of the drainage system have significant potential to divert surface and shallow subsurface flows downward to the reef aquifer.

Another zone of aligned northeast-flowing first-order streams extends as much as 3 km westward from the escarpment front in the northern extreme of the study area, between 32°20.5′ and 32°22′ N latitude (Fig. 2D). Structural elements influencing drainage direction here include the fault-controlled Cueva escarpment ridge.

Parallel drainage patterns—elongated networks of closely spaced channels—are typically known to develop on steep, planar regional slopes. On the Guadalupe escarpment these drainage patterns are associated with a strong degree of structural control, with streams running down the southeastern flanks of ridges near the escarpment front, localized to areas where fairly high angles of bedrock dip are aligned with slope direction. This type of stream development marks the slope on the northwest side of Wood Canyon, the first major front-parallel drainage behind the escarpment front in the southern part of the study area (Fig. 2D). It also extends farther to the west beyond the study area, on the northern slope of Walnut Canyon in Carlsbad Caverns National Park.

The parallel stream courses are developed mostly in the strata of the lower Tansill Formation, above the major clastic interval that marks the top of the Yates Formation. Near their heads the streams have gradients steeper than bedrock dip, cutting farther down section as they progress until they breach the top of the Yates. Channel gradients nearby downstream become less than the dip of bedding, and the valley floors rise above the Yates once again. As a result, the upper portion of each valley provides a window down through the upper Yates water-perching clastics (Fig. 4). This pattern shows up well in Hayes' (1964) detailed geologic mapping that reaches into this portion of the study area.

The heads of the valleys in the parallel drainage zone are abrupt, with concentric convergence of valley slopes. Marks of ephemeral seepage are abundant in the upper reaches of the valleys, especially at their heads and in the zone of incision through the upper Yates. Valley heads host uncommonly dense and water-affine vegetation, and in some cases show carbonate conduit development on bedding planes. The clastic layers in the upper Yates interval are commonly marked by disintegrating rock surfaces and seepage alcoves. Carbonates at the top-of-Yates contact also show micro-cave conduit development. The upper portions of these stream valleys are significant exit points for ground water perched above and within the upper Yates strata.

Canyon floors

Major canyons have identifiable floodplain surfaces ranging in width from 10 m (e.g., upper Wood Canyon) to 450 m (Dark Canyon). These surfaces, well below 10% gradient, commonly are marked by secondary as well as primary channelways, with bedrock as well as boulder/cobble/gravel streambed sections. Grass and brush patches are sparsely scattered on rock and cobble sections, with denser scrub growth on adjacent gravel and soil covered floodplain surfaces. Grassy boulder and soil stream beds occur in upper reaches of some small canyons. GIS analysis indicates that 17% of the escarpment study area is occupied by canyon floors.

Researchers of Guadalupe hydrology (Hendrickson and Jones 1952; Motts 1968; Barroll and Shomaker 2003) highlight the role of storm-flow infiltration through floors of canyons, especially Dark Canyon, in recharge of the Capitan aquifer. Dark Canyon drains a very large area of the Guadalupe Mountains upstream of the escarpment zone. Floods pass great volumes of water through the canyon over a very brief time; supply to the aquifer depends on the capacity of the canyon floor for very rapid

FIGURE 4—Aerial view of parallel drainage valleys on the north side of Wood Canyon. Note the dense vegetation bands on valley interior slopes that approximately coincide with upper Yates exposure. View to the west.

FIGURE 5—Bedrock outcrop "micro-cuestas" facing upstream in Dark Canyon channel near east end of Horseshoe bend, with strata showing unusually steep dip to the east, part of a local bedrock flexure. Water entering bedding plane openings in this area would be rapidly conveyed to the subsurface. View to the southwest.

infiltration or water retention to support slower seepage.

Bedrock portions of major canyon floors are marked by fracturing and, in some locations, up to meters scale of local bedrock relief produced by stream erosion exploiting those fractures. This bedrock relief provides some potential volume of storm-water pooling to supply slow seepage. In a stream-bed walk of Dark Canyon passing through the escarpment zone, we inspected bedrock stream-bed fractures and found them rather tight, lacking signs of secondary flow path development. Karst conduits likely to facilitate quick drainage from stream bed to the subsurface appeared limited to solutionally opened bedding planes in areas where dip of strata would allow for deep infiltration to the east (Fig. 5).

Alluviated sections of major canyon floors hold significant potential as storm-water infiltration areas. If a zone of diffuse cavernous permeability were to be exposed in a canyon floor, and the canyon were carrying relatively large bedload, one would expect that canyon floor zone to be a deposition site as some of the stream flow is diverted away and its sediment load sieved out on the channel bed. Once in place, alluvium also provides a temporary storage mass that, if saturated by flashy storm flow, can supply water at a slower pace for infiltration through available bedrock permeability to the deep subsurface (Hendrickson and Jones 1952). This infiltration model implies that whatever the huge volume of water that passes through a canyon during a monsoon storm, the volume and porosity of alluvium (in addition to depression storage) on that canyon floor will set the absolute limit of water supply to the aquifer from that rare event. Only the coarsest of alluvial fill (cobble to boulder sizes, with little interstitial finer component) will allow active throughflow to bedrock during floods to exceed this limiting volume.

Considerations of canyon floor sediment volume, porosity, and permeability do support a focus on Dark Canyon as a singularly important infiltration site. Its channel in the study area is primarily floored with loose, rounded boulders. Its alluvial fill is in many places quite deep, as evidenced by colossal bedforms as much as 10 m in relief along canyon walls, developed entirely within the material (Fig. 6). With active channel widths commonly exceeding 30 m, this provides a large storage volume of high porosity and permeability.

Other major canyons of the escarpment zone, such as Juniper Canyon, Jurnigan Canyon, and Sheep Draw (Fig 2B), have similar stream-bed sediment characteristics but much lower volumes of potential storage. The floors of most small valleys and canyons, such as Wood, Chinaberry, and Elbow Canyons, have little potential for storm-flow storage, as the few boulder and cobble deposits there are mixed with fine alluvium and soil, more colluvial in character.

Active throughflow from canyon floors, and possibly slopes and uplands, does occur in some places. This is the case in Jurnigan Canyon near the escarpment front where the canyon overlies a 12-m-deep pit in the back of Doc Brito Cave. The canyon and the cave are normally dry, but during flood events, when the canyon is running water, the dome above the pit becomes a waterfall, funneling large amounts of water directly into the open fracture systems of the cave as evidenced by field observations. Stratigraphically the lowest traversable point of the pit is only a few tens of meters above the Capitan reef.

Farther back into the Guadalupe escarpment, similarly rapid cave hydrologic response to major rainfall events has been noted at major fracture intersection sites within Carlsbad Cavern and Lechuguilla Cave (P. Burger, pers. comm. 2008). A significant 2004 water level rise in the Lake of the White Roses, the lowermost pool in Lechuguilla Cave, began within three days of a severe storm following several years of drought in the Guadalupes (Land and Burger 2008).

FIGURE 6—Boulder fill in Dark Canyon. Minimum depth of the deposit here is 10 m, as shown by the scour pit between the canyon wall and the main canyon floor level, seen to the left where the observers are seated. View to the southeast.

Paths of aquifer recharge

Water moving slowly downdip through backreef units will only feed the reef aquifer if it does not again contact the surface. Where the slowly percolating subsurface water seeps out on slopes, most or all must be lost by evapotranspiration in this arid environment. Perennial and ephemeral springs are highly valued on this landscape, but by their number and placement, they can hardly account for much of the subsurface discharge. If allowed to drain into stream beds, spring water may supply some re-infiltration but also supports denser canyon bottom plant communities. Any pollutants deposited by evaporation of seepage on slope surfaces, which are later remobilized during torrential rains, will become highly diluted and removed from the escarpment aquifer recharge zone in surface flood flows.

With subsurface water flow largely moving downdip through the backreef units (Hendrickson and Jones 1952), the regional and local dips of units become primary in determining which land surface areas ultimately provide recharge to the aquifer. In general terms, likely routes for infiltration of Guadalupe Mountain water to the Capitan aquifer are the following:

- In major storms, local and basin-derived stream flow soaks into canyon floors, and then moves downdip within backreef units, in a path uninterrupted by other canyons, to the reef aquifer.
- Water from moderate and extreme precipitation events infiltrates through upland/slope surface material. As allowed by local dip angles and location of intervening canyons, this water also moves downdip within backreef units to the reef aquifer.
- Canyon flow, slope surface drainage, and downdip ground water flow are intercepted by open (especially reef-front-parallel) fractures, and directed at steep angles into the reef aquifer.

Literature and field observation suggest the two following simplified models for subsurface flow beneath the Guadalupe escarpment. They reasonably represent end-members in a spectrum of more complex, more likely flow systems.

End-member models

Motts (1968, p. 294) conceptualizes the subsurface flow system in these terms:

> Water percolates into the subsurface through stream channels or interstream areas and drains downward to the first thick clastic bed of sandstone and siltstone, which is a semi-confining bed. Thence, water moves northeastward and eastward in a direction which is generally down-dip along the confining beds. This regional water movement is modified by folds and other structures which locally distort sandstone and siltstone beds.…This latter water drains slowly from poorly permeable shelf beds into large interconnected channels of the Limestone aquifer which acts as a huge collection gallery.

The master sandstone layers noted by Motts as confining beds for consistent perched aquifers in the Artesia Group are the upper sandstone of the Yates Formation, upper sandstone of the Queen Formation, and sandstones in the upper and lower parts of the Grayburg Formation. Our field observations of active seepage erosion at clastic bed outcrops lend support to the idea that those beds are special sites of perpetual moisture availability. Motts (1968) indicates that even well-defined joints in carbonates disappear at the sandstone contacts. However, evidence we have noted for rapid transmission of storm flow along major fracture zones to the aquifer suggests that this is not the case everywhere. Known cases of rapid transmission, cited above, include ones in which the upper Yates or upper Queen sands intervene between the surface and subsurface observation sites. Although the clastic beds do not provide fully pervasive barriers to deep infiltration, they nevertheless can have strong regional significance.

In our first end-member model, then, infiltrating water descends fairly vertically through carbonate units and then runs downdip on the major sandstone beds. In the Guadalupe escarpment landscape the top-of-Yates sandstone is the crucial factor. Water that infiltrates in areas of Yates (below top sandstone) outcrop will descend at a steep angle to the upper Queen sandstone, which does not crop out in the area, and will make it readily to the reef aquifer (Fig. 7). Water infiltrating into Tansill-capped uplands and slopes in the inner escarpment area, relatively far from the reef front, is likely to return to the surface, seeping out on valley or canyon walls at the upper Yates contact, largely due to low dips in this area. Should it be intercepted by major fractures before returning to the surface, it may exploit not only a breach in the clastic flow barrier, but also a fast route to the reef aquifer. Water

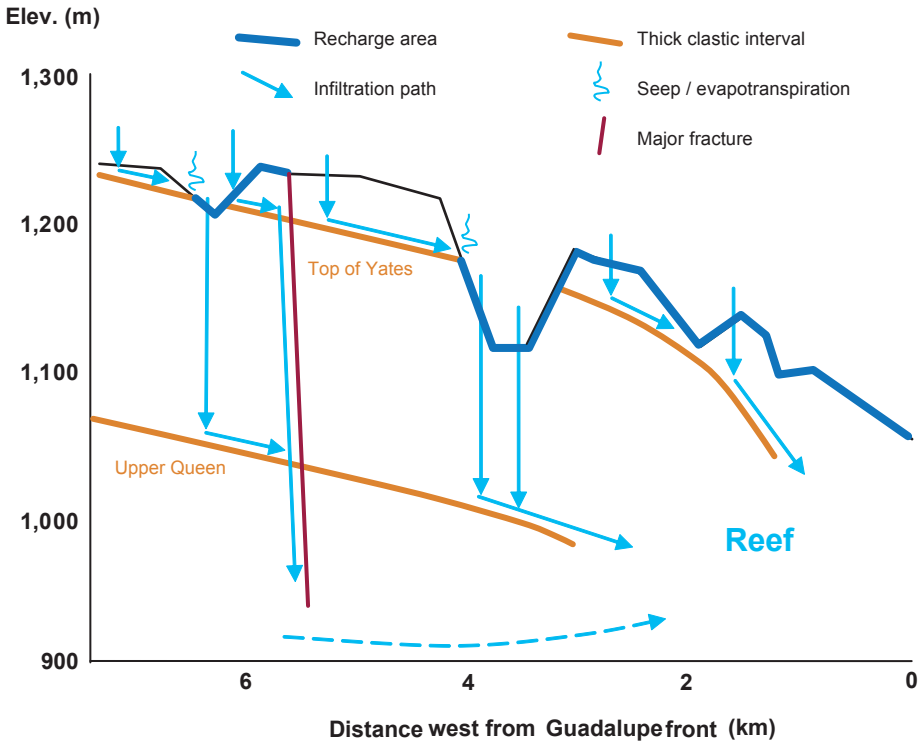

FIGURE 7—First end-member flow model for Capitan aquifer recharge. Water infiltrates vertically until reaching a major sandstone confining layer, and thereafter moves downdip, with possible diversion to greater depth along major fractures. Water seeping out at clastic layer junctions with the surface is lost to evapotranspiration. The Guadalupe front profile employed is schematic, but representative in distance, relief, and dip values.

infiltrating into Tansill rocks near the reef front is likely to stay in the subsurface due to steep dips and resulting lack of Yates outcrops, as well as high incidence of reef-front aligned fractures.

A map-based analysis of this scenario is quite easy to implement, so long as sufficiently detailed geologic mapping has been done. For example, stratigraphic and large-scale structural mapping by Hayes (1964) is available for the southern part of the study area, although detailed information on fracture lines is needed. Structural contours on the top of the Yates give an estimate of local perched water flow direction, and any Tansill outcrop areas that drain toward upper Yates contact locations, without interception by fracture zones, are eliminated as aquifer recharge areas. The parallel drainage valleys on the north side of Wood Canyon turn out to have a special role in this analysis. They are the easternmost Yates outcrops along this part of the escarpment. By their close spacing, natural tendency to provide foci for convergent flow of perched water, and field evidence of abundant seepage some distance down from their heads, these valleys can be assumed to deplete all perched water coming from the Guadalupe Ridge to the west.

This analysis marks large areas of the Guadalupe escarpment landscape near the reef front, and considerable areas of canyon floor and side slopes farther in, as aquifer recharge areas. This conceptual flow model also suggests specific subsurface zones that might be considered especially sensitive for water quality protection, in particular the junction of the upper Yates contact with major fracture zones, and directly with the reef aquifer.

The second end-member model treats the entire mass of the Tansill, Yates, and lower units as a material with strongly anisotropic permeability, much enhanced along bedding. This approach gains support from descriptions of the Artesia Group as a continuous series of carbonate-clastic cyclothems (Hill 1996). It is supported by a view of the area from the air, in which uplands and slopes are marked by dozens of vegetation bands, all implying some degree of enhanced water availability, rather than just a few bands at master sandstone outcrops. It also fits our field observations of solution opening development in the backreef carbonates, much more common along bedding planes than normal to them.

The resulting rule for this model is that infiltrating water proceeds in a downdip direction immediately on reaching bedrock (Fig. 8). Any water that re-emerges at the surface following this path is lost from the system. Much more of the land surface is eliminated as recharge area under this model, including the bulk of upland areas and some canyon walls quite close to the escarpment front. Upland and slope areas directing seepage to major fracture lines gain even more significance as exceptional recharge sites. Most recharge areas are in the floors and downdip side walls of large canyons throughout the escarpment zone and smaller valleys near the escarpment front. The graphic example shown here only incorporates regional dip trends, but this end-member model will be especially sensitive to local variations of dip direction. Some additional areas of valley side slopes may be omitted from the identified recharge areas on that basis.

A map-based version of this model is more difficult to implement. It involves selecting individual canyons and valleys one at a time, taking individual elevation points along their bottoms, and projecting rays back updip from them with gradual elevation rise matching local dip angle until those rays intersect either fracture lines or the ground surface to delineate infiltration watersheds for the seepage and evapotranspiration areas on downdip-facing canyon/valley walls. Land surface not thus eliminated remains as recharge area.

It is likely that publicly available, local strike-and-dip mapping of the study area is not adequate at present to carry out this analysis in detail. However, some trials using regional dip values do yield very long projected rays in the inner part of the Guadalupe escarpment due to lower dip angles, and shorter ones rarely crossing more than one ridge line near the escarpment front. In short, the trials support the preliminary profile-based conclusions regarding recharge areas described above.

The likely real situation is intermediary between these simplified end members. Lesser clastic beds typically are less laterally continuous, allowing some downward deflection of flow (Hendrickson and Jones 1952). Fractures can also increase the overall downward angle of subsurface flow through carbonate-dominated cyclothems, even in situations where lesser fractures do not breach major sandstone intervals.

Capitan aquifer recharge areas on the Guadalupe escarpment include all land surfaces designated as such by the second end-member model. They also likely include significant portions of the additional recharge areas specified by the first end-member model.

Conclusions

In the Guadalupe escarpment between Whites City and Little McKittrick Draw, storm-flow recharge to the Capitan aquifer is focused mainly in the floor of Dark Canyon, and to a lesser degree the stream beds of other major canyons. Deep boulder deposits on canyon floors have significant capacity for temporary storage and subsurface transmission of water from torrential rains. From low-lying canyon floors, infiltrating water has uninterrupted subsurface paths for flow through backreef units to the reef aquifer. Although the

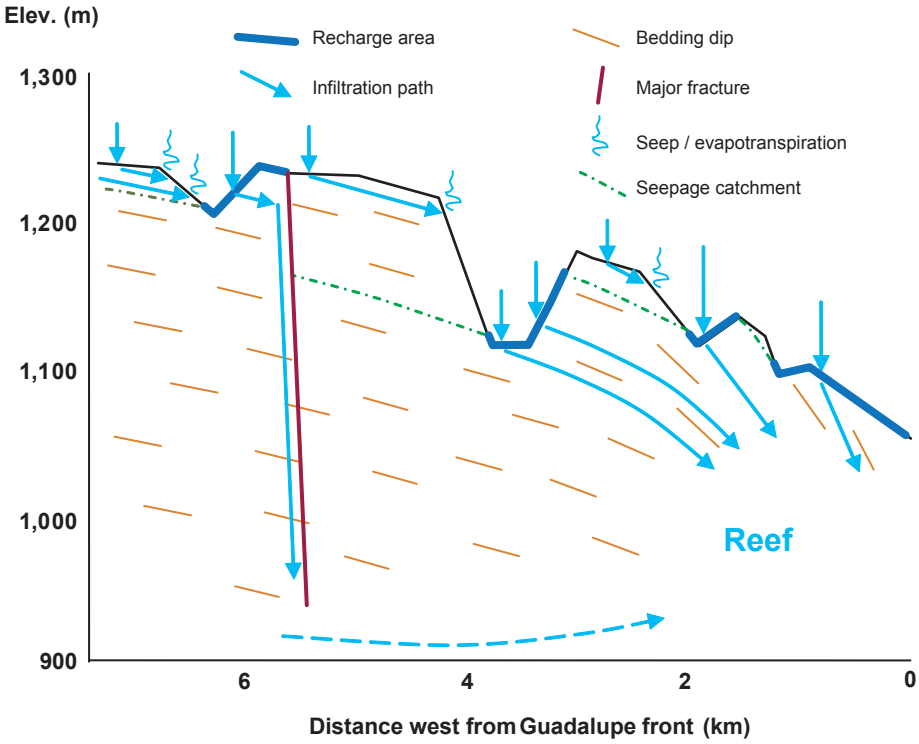

FIGURE 8—Second end-member flow model for Capitan aquifer recharge, shown with the same schematic Guadalupe front profile used in Figure 7. Water moves immediately in a downdip direction following infiltration, with possible diversion to depth by major fractures. Water seeping out at the surface is lost to evapotranspiration, creating subsurface catchments that do not contribute to aquifer recharge.

storm-flow recharge areas are on the canyon floors, consideration of sensitive areas for special ground water quality protection should extend to sites on slopes and uplands that are likely to provide unrestricted runoff in the season of torrential rains.

Slopes and uplands have potential to provide diffuse recharge to the aquifer, but the contributions of each are contingent on bedrock factors through much of the escarpment zone. Deep infiltration from slope surfaces will be limited to places where the local dip of strata is directed into the slope. To the degree that canyons and valleys occupy synclinal axes, such deep recharge areas will be relatively rare. Aquifer recharge from upland surfaces depends on infiltrating water moving fairly vertically through the backreef carbonate strata, at least until meeting a major clastic interval. Presence of major fracture lines across the escarpment zone has great importance here, as it provides opportunities for transmission through clastic intervals, and quick recharge to the reef aquifer. Should water from precipitation instead mainly flow downdip along bedding planes of the backreef strata, it will generally seep out on canyon side slopes and be lost to evapotranspiration. Many upland areas of the inner escarpment zone must be omitted as recharge areas because their infiltrated waters are lost to seepage at major clastic unit outcrops such as those in the parallel drainage valleys on the northwestern slope of Wood Canyon.

The only slope and upland areas of the eastern Guadalupe escarpment in which diffuse recharge is certain are those on the outer escarpment, within 2 km of the escarpment front. There, recharge is assured by the steep dip of upper units, by proximity of the reef unit below, and in some locations, by rectangular drainage systems developed on front-parallel fractures. Rectangular drainage stream channels have potential for quick recharge of light to heavy storm flows as they follow joint trends where significant fractures can deliver water directly into the aquifer. In consideration of these factors, the outer escarpment, in addition to canyon floors and upland catchments of major fractures, warrants special attention for water quality protection in the face of accelerating oil and gas development.

Acknowledgments

Travel and office support for this study was provided by the National Park Service, National Cave and Karst Research Institute, and Bureau of Land Management. M. Molinar of BLM provided GIS support for the study. We thank rancher Larry Bearden for access to sites on his private and state deeded land. The manuscript was improved following suggestions by reviewers P. Burger, L. Land, and W. Lambert. Field assistance and helpful discussions on this project were provided by P. Seiser, T. Strong, M. Queen, J. Rice-Snow, P. Rice, and M. Foley. L. Hose generously provided opportunities for aerial observation and photography of the study area.

References

Barroll, P., and Shomaker, J., 2003, Regional hydrology of the Roswell artesian basin and the Capitan aquifer; *in* Johnson, P. S., Land, L. A., Price, L. G., and Titus, F. (eds.), Water resources of the lower Pecos region, New Mexico: science, policy, and a look to the future: New Mexico Bureau of Geology and Mineral Resources, Decision-Makers Field Conference 2003, pp. 23–27.

Davis, W. M., 1899, The geographical cycle: Geographical Journal, v. 14, pp. 481–504.

Ford, D. C., and Williams, P. W., 1989, Karst geomorphology and hydrology: Unwin Hyman, London, 601 pp.

Goodbar, J. R., 2009, Dye tracing oil and gas drilling fluid migration through karst terrain: A pilot study to determine potential impacts to critical groundwater supplies in southeast New Mexico, USA: 15th International Congress of Speleology, Proceedings, pp. 1507–1510.

Hayes, P. T., 1964, Geology of the Guadalupe Mountains, New Mexico: U.S. Geological Survey, Professional Paper 446, 69 pp.

Hendrickson, G. E., and Jones, R. S., 1952, Geology and ground-water resources of Eddy County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Ground-water Report 3, 169 pp.

Hill, C. A., 1996, Geology of the Delaware Basin—Guadalupe, Apache, and Glass Mountains, New Mexico and west Texas: SEPM (Society for Sedimentary Geology), Permian Basin Section, Publication 96–39, 480 pp.

Kelley, V. C., 1971, Geology of the Pecos country, southeastern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 24, 78 pp.

King, P. B., 1948, Geology of the southern Guadalupe Mountains, Texas: U.S. Geological Survey, Professional Paper 215, 183 pp.

Land, L., and Burger, P., 2008, Rapid recharge events in a karstic aquifer: an example from Lake of the White Roses, Lechuguilla Cave, New Mexico; *in* Yuhr, L. B., Alexander, E. C., Jr., and Beck, B. F. (eds.), Eleventh Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Tallahassee, Florida, Proceedings: ASCE Geotechnical Special Publication 183, pp. 396–403.

Longley, A. J., 1999, Differential compaction and its effects on the outer shelf of the Permian Capitan reef complex, Guadalupe Mountains, New Mexico; *in* Saller, A. H., Harris, P. M., Kirkland, B. L., and Mazzullo, S. J. (eds.), Geologic framework of the Capitan reef, SEPM (Society for Sedimentary Geology), Special Publication 65, pp. 85–105.

McKnight, C. L., 1986, Descriptive geomorphology of the Guadalupe Mountains, south-central New Mexico and west Texas: Baylor Geological Studies, Bulletin 43, 40 pp.

Motts, W. S., 1968, The control of groundwater occurrence by lithofacies in the Guadalupian reef complex near Carlsbad, New Mexico: Geological Society of America, Bulletin, v. 79, pp. 283–298.

Pray, L. C., 1988, Geology of the western escarpment, Guadalupe Mountains, Texas; *in* Sarg, J. F., Rossen, C., Lehmann, P. J., and Pray, L. C. (eds.), Geologic guide to the western escarpment, Guadalupe Mountains: SEPM (Society for Sedimentary Geology), Permian Basin Section, Publication 88–30, pp. 1–8.

Tyrrell, W. W., Jr., 1969, Criteria useful in interpreting environments of unlike but time-equivalent carbonate units (Tansill–Capitan–Lamar), Capitan reef complex, west Texas and New Mexico; *in* Friedman, G. M. (ed.), Depositional environments in carbonate rocks: SEPM (Society for Sedimentary Geology), Special Publication 14, pp. 80–97.