GROUNDWATER MONITORING IN KARST TERRAIN: A PILOT STUDY OF OIL-AND-GAS DEVELOPMENT IN SOUTHEAST NEW MEXICO

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Abstract

Rapid oil-and-gas exploration, drilling, and production in karst terrains in southeast New Mexico are posing increased potential for contamination of groundwater sources. There has not been a systematic analysis of karst groundwater in this region. Gathering baseline data on groundwater quality and determining its flow paths and resurgences is crucial in understanding, detecting, and mitigating undesirable incidents in the oil-and-gas drilling and production industry. A pilot study was initiated by the Bureau of Land Management in the summer of 2005 to begin gathering field data to help fill some of the voids in our understanding of karst groundwater flow in the study area referred to as the Southern Guadalupe Escarpment.

Key words: oil and gas, karst groundwater, dye tracing, contaminants, New Mexico

The Setting

The primary area of concern is the Capitan Reef aquifer near Carlsbad, New Mexico, south of Sheep Draw down to Big Canyon and the gypsum karst lands of the Delaware Basin extending eastward to the middle of Range 26 East (Figure 1). Within the boundaries of this study area are critical groundwater-recharge zones and numerous springs and resurgences. The aquifers in this area supply drinking water to the City of Carlsbad, Carlsbad Caverns National Park, White's City, Carlsbad Area Retarded Citizens (CARC) Farm (Washington Ranch operation), several ranching families, and water wells for domestic livestock in the area. These aquifers also are the source of water for numerous springs in the area that provide the basis for critical riparian areas and wildlife habitat, including Rattlesnake Springs, Preservation Spring, Cottonwood Spring, Owl Spring, Ben Slaughter Spring, Chosa Spring, and the largest, Blue Springs with an outflow of 0.3-0.4 m^3/sec(10-15 $ft.^3$/sec). Also included are the numerous springs that give rise to the Black River. These freshwater sources are critical in sustaining life along the northern edge of the Chihuahuan Desert ecosystem.

Groundwater research conducted by Hendrickson and Jones (1952) for Eddy County, New Mexico, indicates that recharge of the groundwater associated with the Capitan and Carlsbad limestones is largely through the joints and fractures in the bottom of gravel filled arroyos. Water that enters the gravel and boulders in the arroyo bottoms moves downward into the underlying bedrock. The amount of water that enters the underlying rock and into the aquifer depends on the permeability of those rocks. All the water probably enters the limestone where the gravels are underlain by cavernous limestones. Movement of groundwater after it reaches the bedrock is controlled chiefly by fractures and bedding planes, more or less enlarged by solution in limestone and dolomite.

They further state that the flow of the Black River, Rattlesnake Springs and Blue Springs is sustained chiefly by discharge near the base of the Capitan reef escarpment. The principal source of these springs is almost certainly discharged from the Guadalupe Mountains area, as the recharge in the area between the reef escarpment and the springs is not enough to provide their flow. In addition to the water discharged by the springs, groundwater probably moves from the Capitan limestone and other underlying limestones into the alluvium and underlying Castile formations, and it may supply water to several of the other springs located in the gypsum karst lands of the Delaware Basin. Perched aquifers may be present in the Quaternary piedmont alluvial deposits and the Quaternary alluvial deposits which are underlain by the Castile formation.

Potential Oil-and-Gas Impacts

The reasonable foreseeable development of the study area has yet to be determined. There have been several geophysical studies conducted in the area that indicate the potential for oil-and-gas exploration is high. The 1997 Carlsbad Resource Management Plan Amendment for Oil and Gas shows the area as having a high potential for oil and gas occurrence. To date there have been 263 oil or gas wells drilled in the area on 171 existing oil-and-gas leases. Based on the maximum allowable number of wells per section (16 oil wells and 4 gas wells) the maximum number of wells that could be located in the study area is 4,600 wells if maximum production were achieved.

Drilling in the study area could affect both the perched aquifers and the underlying Capitan aquifer. Potential groundwater impacts from drilling can be divided into those caused:

- During drilling and cementing. Drilling and

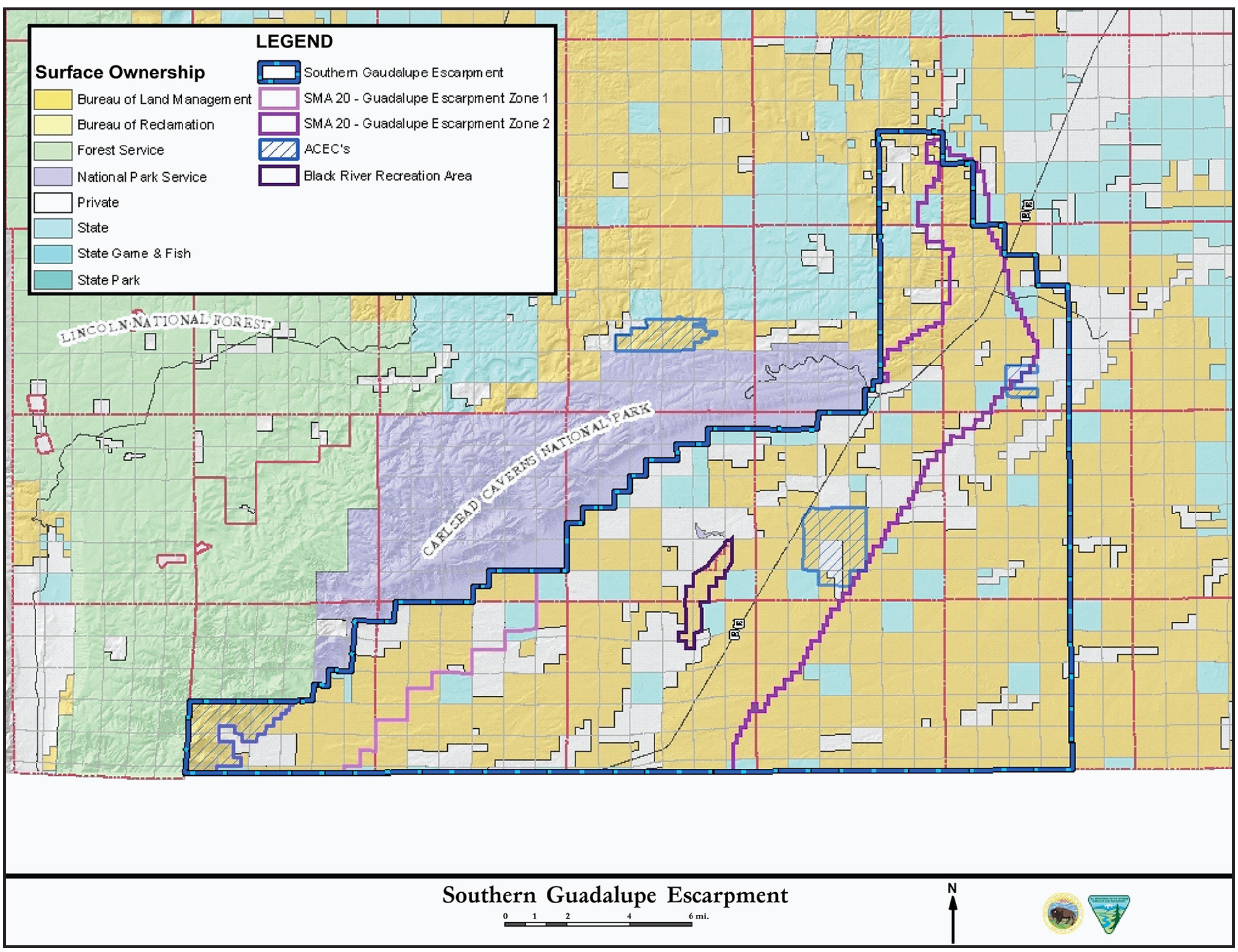

Figure 1 *Recent studies by Snow and Goodbar (2007) indicate the critical recharge areas of the Capitan Reef aquifer are within 1-2 km (1 mi.) of the reef front and along the contact zones of theYates and Seven Rivers formations in addition to the recharge into fractures in the alleviated canyon bottoms.*

cementing fluids will spill or leak into formation at any lost circulation zones.
- During testing and production. If the inner and intermediate casing strings fail following installation due to inadequate cementing or long term (≥50 years) corrosion, drilling fluids, brine, or gas could be released directly to the subsurface anywhere along the casing string.
- Following plugging and abandonment of the well. Because the atmosphere in the unsaturated part of the aquifers contain elevated concentrations of carbon dioxide and trace amounts of sulfur compounds as well as oxygen, the steel well casing could slowly become corroded and eventually fail in zones not protected by cement (U.S. Department of the Interior 1993)

A more complete description of oil-and-gas impacts on caves and karst can be found in U.S. Department of Interior (1993).

The Pilot Study

Identification and monitoring of karst areas includes gaining a better understanding of the underlying groundwater flow paths and their associated erosional features. A monitoring program needed to be established to identify potential sources of contaminants entering the aquifers, and monitor the conditions and integrity of subsurface groundwater. To begin this study the Bureau of Land Management in cooperation with the oil-and-gas industry, local land owners, the City of Carlsbad, and the center for Cave and Karst Studies at Western Kentucky University initiated a dye-tracing pilot study to help identify areas of potential concern. The purpose of the dye tracing study was to determine if contaminates could enter the groundwater through drilling and cementing operations, or during later phases of production or abandonment in the event of casing failure. Any positive results from the dye tracing study would then indicate that the BLM, in conjunction with the oil-and-gas industry, needs to ensure that all possible down-hole mitigation measures are being taken to protect these vital water resources.

As a pilot study a small area was selected to begin with. That area extends north from Whites City to Sheep Draw and east of Whites City to Black River (Figure 2). In August of 2005 activated-charcoal dye traps (bugs) were place in six locations, three in perennial springs, two in domestic water wells, and one in the outflow of a monitoring well for the City of Carlsbad. These bugs were retrieved after one month to insure that samples were taken before any dye was introduced into the system. New bugs were then installed prior to dye being added to drilling fluids during oil-and-gas drilling operations. New oil or gas wells drilled in the gypsum karst plains were then required to add 0.48 L (16 oz.) of fluorescein dye (Acid Yellow 73) to their surface interval drilling fluid. For wells drilled in the Capitan Massive or Carlsbad limestone, 0.48 L (16 oz.) of orange (eosin Y) dye were added. For wells that were drilled through the overlying gypsum karst and then through the Capitan Massif, both dyes were required to be added to the drilling fluid. Because of the large number of wells being drilled and the complexity of the project it was decided to use only two types of dye, one for the gypsum karst and one for the Capitan Limestone group. The amount of dye to add to the drilling fluid was calculated based on the amount of water needed to fill a standard reserve pit for drilling oil-and-gas wells in that area. This began during the fall of 2005. The bugs were changed out bi-monthly and sent to Western Kentucky University for analysis. In addition to the dyes in the drilling fluids, analysis was also run for rhodamine WT. This dye is sometimes used by the industry as a marker dye when conducting pre-flushing of the well bore before cementing operations. During the "pre-flush" the dyed water may also enter karst aquifers.

Initial Results

To date 21 wells have added dye to their initial drilling fluids. Thirteen of these wells are in the gypsum karst plains of the Delaware Basin. Five wells have been drilled in the transition area containing both gypsum karst and the Capitan Reef Aquifer, and three wells have been drilled on the crest of the Guadalupe Ridge anticline. Lost circulation has been reported in three of the wells drilled that were using dye. That is not to say that lost circulation zones were not encountered in the surface intervals of other wells, only that it was not reported to the Bureau of Land Management.

Twenty-seven dye traps have been sent in to Western Kentucky University for analysis. All the dye traps sent in before dyes were introduced to

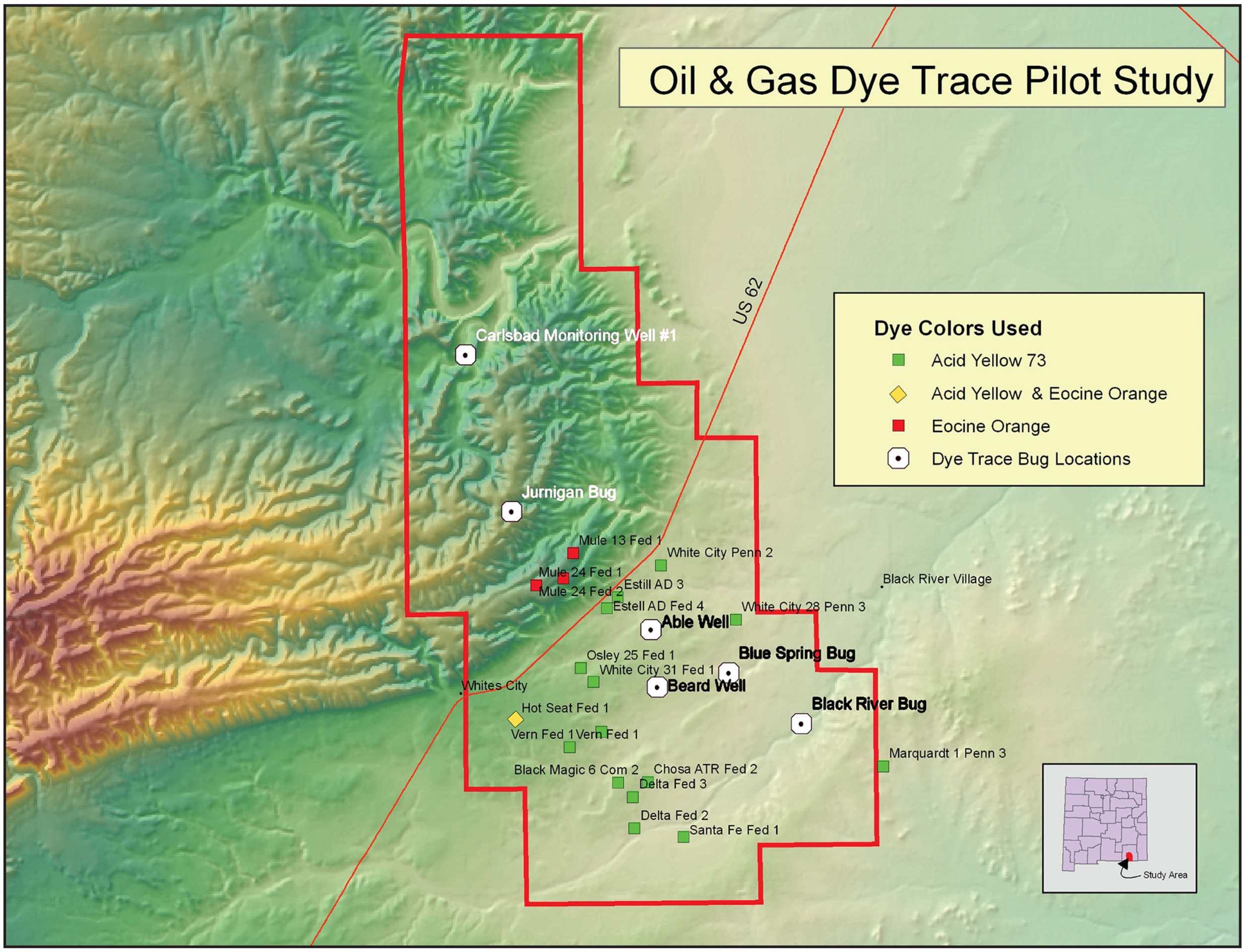

Figure 2 Oil and Gas Dye Trace Pilot Study Area.

the drilling fluids came back with no fluorescein detected and a weak background of eosine and rhodamine WT dyes detected. After 0.48 L (16 oz.) of dye were introduced to the drilling fluids the Able water well had a detectable concentration of eosine of 0.952 ppb, nearly two orders of magnitude greater than the previous background concentration of 0.042. The dye trap for this reading was put in on September 7, 2005, and taken out November 20, 2005. During that time the Estell AD #3 gas well was drilled with both eosine and fluorescein dyes being added to the drilling fluid.

The City of Carlsbad Water Monitoring Well in Juniper Canyon showed a similar increase in detectable eosine moving from a low background level up to 0.563 ppb. The dye trap showing the increase was put in on September 7, 2005, and taken out on August 20, 2006. During that time four wells were drilled using eosine dye. Subsequent dye-trap analysis produced concentrations of 0.508 ppb and 0.930 ppb of eosine dye and no detectable levels of fluorescein dye.

Another location that showed significant increases in detectable fluorescein dye was Blue Springs, from none detected to low background levels (0.068), then up to 0.601 ppb. Additionally, the detectable concentrations of rhodamine WT increased from a background level of 0.049 ppb to a concentration of 1.017 ppb. This occurred during the fifth sample period. The dye trap was put in October 20, 2006, and collected May 2, 2007. It is not known what wells in the area were drilled on private or state lands and which wells may have used rhodamine WT during their drilling operations.

The Jurnigan Spring location showed none to very low background concentrations of eosine and fluorescein dyes during the first three samplings. The fourth sample showed a possible positive detection of fluorescein dye of 0.528 ppb. The fluorescein dye could be from one of the wells drilled in the transition zone of the reef escarpment to basin margin.

At this time the Beard home and Black River are the only two dye trap locations that have not shown any detectable dye concentrations.

Below are the laboratory results (Tables 1-4) in the order in which they were received.

Discussion

It appears that there are no “solid” positive (+), very positive (++), or extremely positive (+++) concentrations of dye detected in any of the dye-trap locations. This may be attributed to the increased dilution of the dyes as they move into the

Tables 1-4 Laboratory results of dye tracing.

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Bureau of Land Management

Analysis requested by:

Jim Goodbar

	TINOPAL CBS-X	FLUORESCEIN	EOSINE	FD&C Red #3	RHODAMINE WT	SULPHORHODAMINE B
	Fabric Brightening	**Color Index:**	**Color Index:**	**Color Index:**	**Color Index:**	**Color Index:**
	Agent 351	Acid Yellow 73	Acid Red 87	Food Red 14	Acid Red 388	Acid Red 52
	Dye Receptor:	**Dye Receptor:**	**Dye Receptor:**	**Dye Receptor:**	**Dye Receptor:**	**Dye Receptor:**
	Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal
	Analysis by:	**Analysis by:**	**Analysis by:**	**Analysis by:**	**Analysis by:**	**Analysis by:**
	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer

						CHARCOAL SAMPLES																	
						TINOPAL CBS-X			FLUORESCEIN			Eosine			FD&C RED #3			RHODAMINE WT			SULPHORHODAMINE B		
Code Number	Event	Date Collected	Feature Name	Peakfit	Comment	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.005		ND						ND					
3			QA-EOSINE OJ						ND				0.006					ND					
4			QA-RHODAMINE WT						ND			ND							0.005				
EL-001-0	02		Carlsbad Monitoring Well #1						ND			+?	0.563	535.4				ND					
EL-002-0	02		Jurnigan Spring #1						B	0.052	507.6	B	0.044	NPI				B	0.016	NPI			
EL-003-0	02		Able East Stock Tank #1						ND			+	1.160	536.2				ND					
EL-004-0	02		Blue Spring #4						B	0.068	NPI	ND						B	0.049	NPI			
EL-006-0	02		Black River (Beard) BRB-3						ND			ND						B	0.054	NPI			
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.005		ND						ND					
3			QA-EOSINE OJ						ND				0.006					ND					
4			QA-RHODAMINE WT						ND			ND							0.005				

Analyzed by: **Chad Martin** **on** **11/8/2006**

Comments: Eosine OJ,RWT,FL analysis GS= Grab Sample

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	Fabric Brightening	**Color Index:**	**Color Index:**	**Color Index:**	**Color Index:**	**Color Index:**
	Agent 351	Acid Yellow 73	Acid Red 87	Food Red 14	Acid Red 388	Acid Red 52
	Dye Receptor:	**Dye Receptor:**	**Dye Receptor:**	**Dye Receptor:**	**Dye Receptor:**	**Dye Receptor:**
	Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal
	Analysis by:	**Analysis by:**	**Analysis by:**	**Analysis by:**	**Analysis by:**	**Analysis by:**
	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer

						CHARCOAL AND WATER SAMPLES											
						TINOPAL CBS-X		FLUORESCEIN		Eosine		FD&C RED #3		RHODAMINE WT		SULPHORHODAMINE B	
Code Number	Event	Date Collected	Feature Name	Peakfit	Comment	Results	Conc in ppb	Results	Conc in ppb	Results	Conc in ppb	Results	Conc in ppb	Results	Conc in ppb	Results	Conc in ppb
1			QA-ELUENT					ND									
2			QA-FLUORESCEIN						0.005								
EL-001-0	01	9/9/05	Blue Spring #1					ND		ND					0.008		
EL-002-0	01	11/20/05	Blue Spring #2					ND		ND				ND			
EL-003-0	01	5/1/06	Blue Spring #3					ND			0.050			ND			
EL-004-0	01	9/9/05	Able Home #1					ND			0.042				0.036		
EL-005-0	01	11/20/05	Able Home #2					ND			0.952			ND			
EL-006-0	01	5/1/06	Able Home #3					ND			0.289			ND			
EL-007-0	01	9/9/06	Beard Home #1					ND			0.163			ND			
EL-008-0	01	11/20/05	Beard Home #2					ND			0.311				0.012		
EL-009-0	01	5/1/06	Beard Home #3					ND		ND				ND			
EL-010-0	01	11/20/06	Black River #1					ND			0.018				0.031		
EL-011-0	01	5/1/06	Black River #2					ND			0.138				0.021		
EL-012-0	01		BLANK						0.020	ND					0.058		
3			QA-ELUENT					ND									
4			QA-FLUORESCEIN						0.005								

Analyzed by: **Mike Firkins** **on**

Comments: Eosine OJ,RWT,FL analysis **GS = Grab Sample**

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Fabric Brightening	Color Index:	Color Index:	Color Index:	Color Index:	Color Index:
Agent 351	Acid Yellow 73	Acid Red 87	Food Red 14	Acid Red 388	Acid Red 52
Dye Receptor:	Dye Receptor:	Dye Receptor:	Dye Receptor:	Dye Receptor:	Dye Receptor:
Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal
Analysis by:	Analysis by:	Analysis by:	Analysis by:	Analysis by:	Analysis by:
Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer

						CHARCOAL SAMPLES																	
						TINOPAL CBS-X			FLUORESCEIN			Eosine			FD&C RED #3			RHODAMINE WT			SULPHORHODAMINE B		
Code Number	Event	Date Collected	Feature Name	Peakfit	Comment	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.005		ND						ND					
3			QA-EOSINE OJ						ND				0.006					ND					
4			QA-RHODAMINE WT						ND			ND							0.005				
EL-001-0	03	11/30/07	Carlsbad Monitoring Well #2						ND				0.508	535.8				ND					
EL-002-0	03	5/2/07	Carlsbad Monitoring Well #3						ND				0.930	533.8				ND					
EL-003-0	03	5/2/07	Jurnigan Spring #2						ND			ND						ND					
EL-004-0	03	5/2/07	Jurnigan Spring #3						ND			ND						ND					
EL-005-0	03	5/2/07	Blue Spring #5							0.601	513.0	ND							1.017	563.0			
EL-006-0	03	5/2/07	Beard Home #5						ND				0.047	532.6				ND					
EL-007-0	03	5/2/07	Black River #4						ND			ND						ND					
EL-008-0	03		BLANK						ND			ND						ND					
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.005		ND						ND					
3			QA-EOSINE OJ						ND				0.006					ND					
4			QA-RHODAMINE WT						ND			ND							0.005				

Analyzed by: Chad Martin on 5/15/2007

Comments: Eosine OJ,RWT,FL analysis GS= Grab Sample

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Analysis requested by:

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TINOPAL CBS-X	FLUORESCEIN	EOSINE	FD&C Red #3	RHODAMINE WT	SULPHORHODAMINE B
Fabric Brightening	Color Index:	Color Index:	Color Index:	Color Index:	Color Index:
Agent 351	Acid Yellow 73	Acid Red 87	Food Red 14	Acid Red 388	Acid Red 52
Dye Receptor:	Dye Receptor:	Dye Receptor:	Dye Receptor:	Dye Receptor:	Dye Receptor:
Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal	Activated Charcoal
Analysis by:	Analysis by:	Analysis by:	Analysis by:	Analysis by:	Analysis by:
Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer	Spectrofluorophotometer

						CHARCOAL SAMPLES																	
						TINOPAL CBS-X			FLUORESCEIN			Eosine			FD&C RED #3			RHODAMINE WT			SULPHORHODAMINE B		
Code Number	Event	Date Collected	Feature Name	Peakfit	Comment	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)	Results	Conc in ppb	Peak Center (nm)
W1			QA-WATER						ND			ND						ND					
W2			QA-FLUORESCEIN							0.008		ND						ND					
W3			QA-EOSINE OJ						ND				0.016					ND					
W4			QA-RHODAMINE WT						ND			ND							0.010				
WL-001-0	04	8/31/07	Jurnigan Spring #4							0.025	509.0	ND						ND					
WL-002-0	04	8/31/07	Jurnigan Spring Catchment #2						ND			ND						ND					
WL-004-0	04	7/9/07	Comanche Well #1						B	0.001	505.6	ND						B	0.010	577.4			
WL-005-0	04	7/19/07	Comanche Well #2						ND			ND						ND					
WL-006-0	04	8/31/07	Comanche Well #3						ND			ND						ND					
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.007		ND						ND					
3			QA-EOSINE OJ						ND				0.007					ND					
4			QA-RHODAMINE WT						ND			ND						ND					
EL-001-0	04	8/31/07	Jurnigan Spring #4						+?	0.528	515.4	ND						ND					
EL-002-0	04	8/31/07	Jurnigan Spring Catchment #2						+?	0.135	511.0	ND						ND					
EL-003-0	04	8/31/07	Carlsbad Montoring Well						B	0.013	519.0	ND						ND					
EL-004-0	04	7/9/07	Comanche Well #1						+?	1.045	515.8	ND						ND					
EL-005-0	04	7/19/07	Comanche Well #2						+?	0.124	517.0	ND						ND					
EL-006-0	04	8/31/07	Comanche Well #3						B	0.008	513.8	ND						ND					
1			QA-ELUENT						ND			ND						ND					
2			QA-FLUORESCEIN							0.007		ND						ND					
3			QA-EOSINE OJ						ND				0.006					ND					
4			QA-RHODAMINE WT						ND			ND						ND					

Analyzed by: Laura Kreitzer on 9/12/2007

Comments: Eosine OJ,RWT,FL analysis GS= Grab Sample

We analyzed the water too, but the vial for Carlsbad Monitoring Well leaked and there wasn't enough to analyze.

aquifers. A second possibility is that once the drilling operation looses circulation into the first open zone, all or most of the drilling fluid and dye are lost into that zone and any other lost circulation zones below that point that may connect to aquifers may not receive any dye.

To compensate for these two possible issues the dye amounts will be doubled to 0.95 L (32 oz.), and a second addition of dye will be added after the completion of the surface drilling interval. The dye will be added to the pre-flush fluids prior to casing and cementing the well bore. In this way dyes can be pushed into the lower portions of the drilling section and enter the bottom levels of the lost circulation zones.

An unanswered question is, "What is the residence time of the dye in the aquifers?" This question may be answered as the project progresses.

Conclusions

Dye-tracing of oil-and-gas drilling fluids in the Castile gypsum and Capitan Reef aquifers appears to be a viable way of determining if drilling fluids can enter the aquifers. I infer that if production casing and cementing failures occur, hydrocarbons may also be able to enter the aquifers. With this in mind, it then becomes incumbent on the land managing agencies and the oil-and-gas industry to ensure that the best possible drilling, casing, and cementing programs are put into practice. The initial results are moderately conclusive that the drilling fluids enter the aquifers. The changes in procedures of adding additional dye during the initial spudding of the well and before the casing and cementing of the surface string may aid in producing more detectable concentrations of dye in the collection locations.

The pilot study should be continued and built upon. A more definitive study should be designed and considered to monitor and document the potential impacts in the shadow of impending oil-and-gas development in the karst areas to the south of the pilot study area.

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