Recharge and Water-Quality Controls for a Karst Aquifer in Central Texas

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Abstract

The Edwards Aquifer is a prolific karst aquifer system in Central Texas that provides drinking water to about 2 million people. Because a significant portion of the water recharging the Barton Springs segment of the Edwards Aquifer enters the subsurface through caves and enlarged fractures in the bed of Onion Creek, the presence of nonpoint source pollution in storm water flowing in Onion Creek can have a direct impact on water quality in the Barton Springs segment of the Edwards Aquifer. To address this concern, the Barton Springs/Edwards Aquifer Conservation District constructed a concrete vault over the entrance to Antioch Cave in the bed of Onion Creek. This structure was designed to prevent entry into the cave of contaminated storm water by closure of two valves on the vault during storm events. When the storm water passes, the valves open and allow the cleaner baseflow water to enter the cave. Results of water-quality sampling at Antioch indicate that the system is capable of significant reduction of nonpoint source pollution entering the aquifer through Antioch Cave. Over a period in 2010 that included five storm events, approximately 1105 kg (2436 lbs) of nitrogen from nitrate/nitrite, 134 kg (295 lbs) of total phosphorus, and 86,385 kg (190,480 lbs) of sediment were prevented from entering Antioch Cave. This amount of sediment is equivalent to about eight dump-truck loads that are prevented from entering the aquifer.

1 Introduction

The Onion Creek Recharge Project was conducted by the Barton Springs/Edwards Aquifer Conservation District to improve the quality of water recharging the Barton Springs segment of the Edwards Aquifer (herein called Barton Springs aquifer) through Antioch Cave. This cave is situated within the bed of Onion Creek about 2 km (1.3 miles) west-southwest of the center of Buda, Texas (Fig. 1), and is capable of recharging large amounts of water to the aquifer when it is not filled with sediment and other debris. The most common contaminants in Onion Creek are sediments, bacteria, nutrients, and other nonpoint source pollutants that are brought into Onion Creek during storm events. Because the Barton Springs aquifer provides drinking water to about 60,000 people plus industrial, commercial, and irrigation users, and is the source of water at Barton Springs where endangered species live (BSEACD 2007), the quality of water recharging the aquifer is very important.

In 1997, a Best Management Practices (BMP) structure was constructed over Antioch Cave by the District with funding provided by a Clean Water Act Section 319(h) grant from the US Environmental Protection Agency (EPA). The grant was administered by the Texas Natural Resources Conservation Commission (TNRCC). These grants are awarded to address environmental issues associated with nonpoint source pollution. The purpose of the BMP at Antioch was to control the flow of water into the cave and to prevent clogging of the cave with sediment and storm debris. Opening and closing a valve on the BMP controls the flow of water from Onion Creek into Antioch Cave. During and following storm events, the valve is manually closed to

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W.B. White et al. (eds.), *Karst Groundwater Contamination and Public Health*,
Advances in Karst Science, DOI 10.1007/978-3-319-51070-5_35

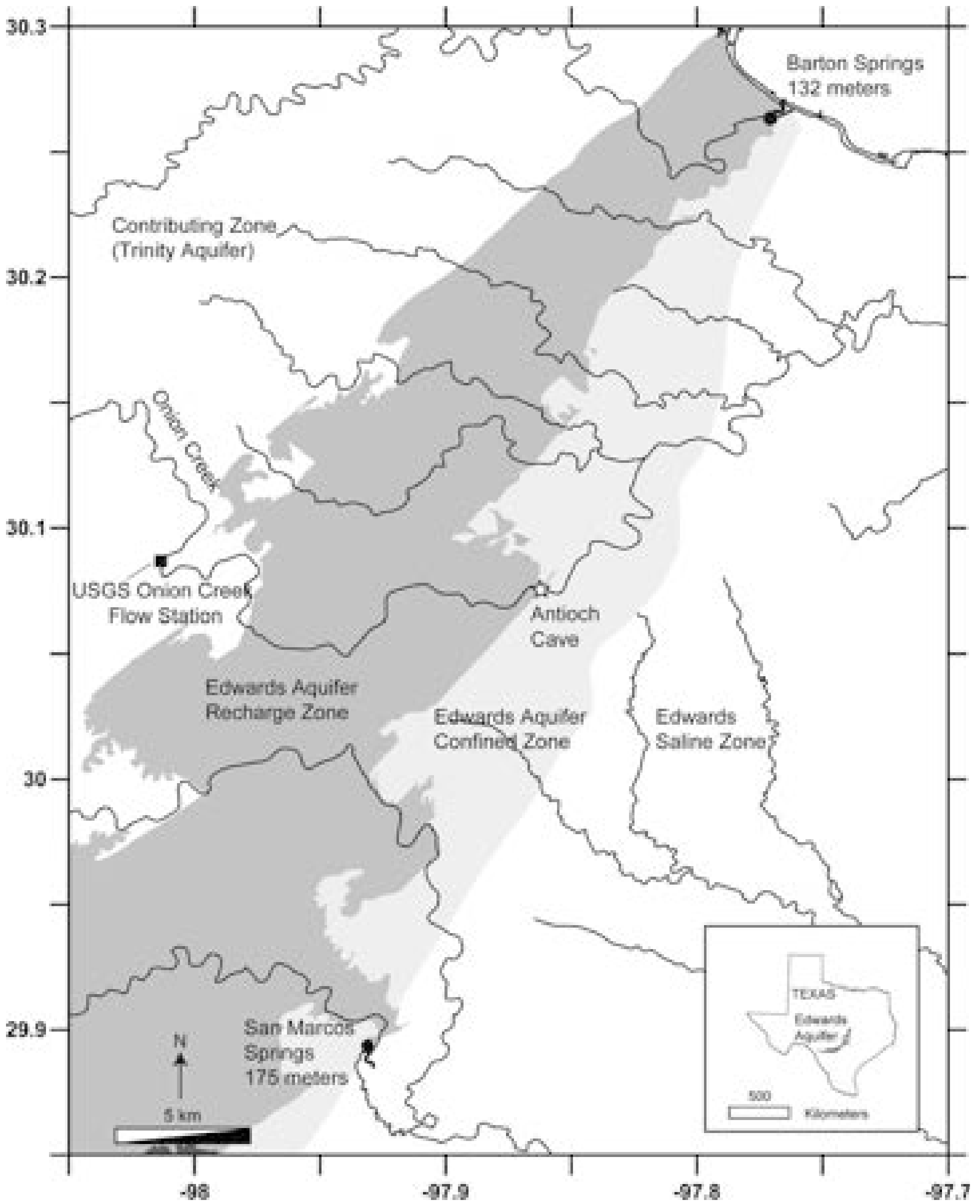

Fig. 1 Location map of the study area and a portion of the Edwards Aquifer

prevent entry of storm water and associated contaminants into the cave and subsequently into the Edwards Aquifer. When better quality water is flowing in Onion Creek, the valve is opened to allow recharge to occur. The system at Antioch Cave has been permitted by the Texas Commission on Environmental Quality (TCEQ) as a Class V injection well.

In 2006, the District was awarded another grant by EPA and TCEQ. The goal of this grant was to provide real-time monitoring of water quality and quantity at Antioch with a Continuous Water Quality Monitoring Network (CWQMN) system, to improve the intake system on the BMP, and to automate the opening and closing of the valve. As completed in 1997, the valve was operated manually by District staff and the grate over the valve was prone to clogging with storm debris. An automated system for opening and closing the valve based on water quality was deemed to be more efficient and protective of the aquifer than a manual system. The automated system was designed to close the valve when the turbidity of water in Onion Creek rises to 100 NTUs. This would prevent entry of contaminated storm water from entering Antioch Cave. As the storm pulse passes and the turbidity drops below 50 NTUs, the valve opens automatically. An intake screen with a large surface area allows for maximum recharge without being clogged with storm debris.

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2 Background

Onion Creek is a major contributor of recharge water to the Barton Springs aquifer of Central Texas. Because thousands of people depend on this aquifer for their sole source of drinking water, and because the endangered salamanders at Barton Springs need a sufficient quantity of flow of high-quality water, the quality of water recharging the aquifer from surface streams is very important. Numerous studies have shown the relationship between these surface streams and the flow of groundwater through the aquifer to water-supply wells and the springs (Slade et al. 1986; Hauwert et al. 2004).

2.1 Purpose and Scope of Project

The TCEQ lists the Barton Springs aquifer as an impaired groundwater resource (TNRCC 1999). Onion Creek is listed on the TCEQ 303(d) list of impaired streams. Increases in sediment, bacteria, and other contaminants in groundwater as a result of storm-flow events in the Barton Springs aquifer have been documented by analysis of water samples from monitor and water-supply wells and Barton Springs (Fieseler 1998; Mahler et al. 2006a, 2011). The purpose of the project was to increase recharge to the Barton Springs aquifer while minimizing the amount of contaminants entering the aquifer during storm events.

To reduce the amount of sediment and other storm-related contaminants entering one of these recharge features, an automated control system was designed and installed at the BMP that was previously constructed over Antioch Cave on Onion Creek (Fig. 2). Two valves on the BMP control flow into the cave.

Fig. 2 Photograph ca. 1996 showing recharge and the entrance to Antioch Cave before the BMP was constructed. The debris over the entrance and also sedimentation within the cave decrease the amount of recharge entering the cave (Photograph from Fieseler 1998)

2.2 Previous Work: 1993–1998 Onion Creek Recharge Project

When District staff became aware of the existence of Antioch Cave, they quickly realized the significance of the cave for recharge to the Edwards Aquifer. Figure 2 is a photograph of the entrance to Antioch Cave prior to construction of the BMP. In 1992, the District began discussions with TNRCC about using federal 319(h) funds for conducting studies on Onion Creek and constructing a BMP at Antioch to improve the quality and increase the quantity of water entering the cave. Construction began on the BMP in August 1997 and was operationally completed by December 1997. A final report on the project was issued in December 1998 (Fieseler 1998). The BMP that was constructed was a steel-reinforced concrete vault. The BMP was situated directly over the cave entrance and is approximately 2 m (7 ft) high, 2.4 m (8 ft) wide, and 3.7 m (12 ft) long. Figure 3 is an aerial photograph of the study site showing the location of the upgraded BMP in the bed of Onion Creek. Figure 4 is a schematic cross section of Onion Creek showing the BMP and a portion of Antioch Cave. The BMP has two steel manhole accesses on top and two 91 cm-(36-in.) diameter spools to hold 91-cm diameter (36-in.) pneumatically operated butterfly valves. Only one valve was installed during the original project, and the other spool was sealed with a steel plate. Air hoses connected the valve to a 1-ft by 1-ft by 2-ft concrete box on the north bank of Onion Creek. From this box, the valve could be opened using either an air compressor or a tank with compressed air. A 4-in. diameter PVC pipe was the conductor pipe for air hoses from the valve in the BMP to the concrete box. In addition, a 6-in. PVC pipe connected the BMP to the concrete box to allow air from the cave to vent to the surface when water is flowing into the cave entrance. Such venting prevents undue pressure build-up in the BMP and allows more water to recharge the aquifer.

Fig. 3 **a** Aerial photograph showing major features near Antioch Cave including Onion Creek. **b** Close-up of aerial photograph showing the BMP after the upgrade

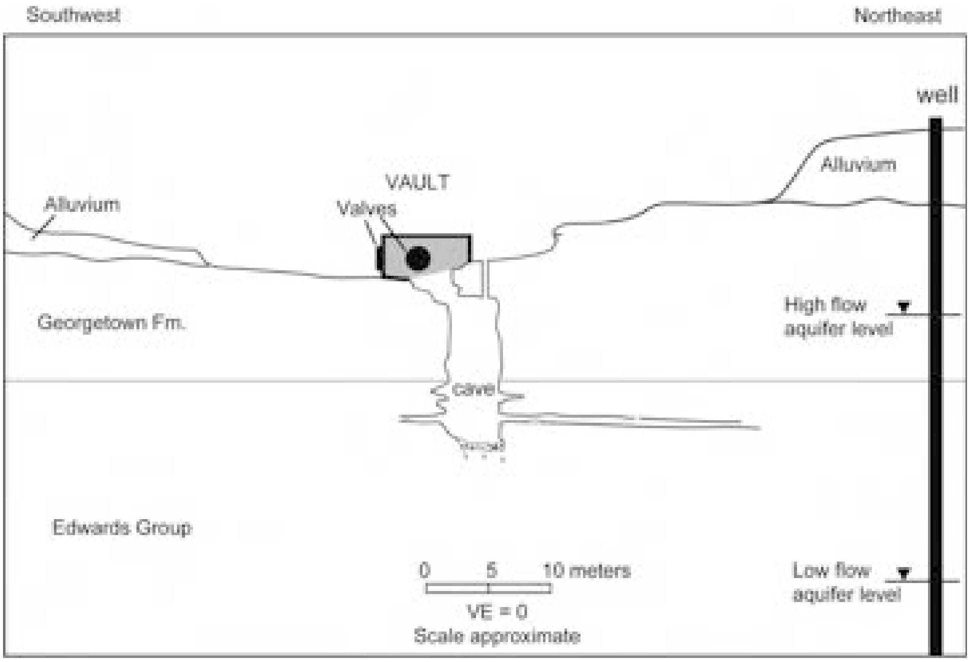

Fig. 4 Schematic cross section across Onion Creek and Antioch BMP looking upstream

The following text from the December 1998 final report (Fieseler 1998) describes the procedures and protocol for opening and closing the valve:

> The 36″ [91 cm] butterfly valve remains closed during non-flow conditions. Any spring flow, seepage or low flow recharges via the 4″ [10 cm] weep hole. When flooding occurs or whenever the creek is in a flow condition, the valve will remain closed during "first flush" conditions. This first flush condition contains heavy sediment loads, high bacteria counts, and large quantities of trash, debris, and organic material. Once conditions have improved, based on visual observations and turbidity measurements by District personnel, the air compressor will be turned on and the valve opened to allow recharge to occur. The valve will remain open as long as the water level in Onion Creek is approximately one foot deep or greater. Should subsequent flood events and/or first flush pulses occur which increases the turbidity, sediment load, or trash and debris content, or if some hazardous condition presents itself, the valve will be closed until conditions warrant re-opening the valve to continue recharge.

As this description indicates, management of the BMP is labor intensive and is dependent on District staff being available at key times when conditions are changing in Onion Creek. Recommendations were made in the 1998 report for adding a second valve to the BMP and for automating the system. An opportunity for doing this additional work arrived in 2006 when 319(h) funds became available.

3 Hydrogeologic Setting

3.1 The Edwards Aquifer

The Edwards Aquifer of Texas is a karst aquifer developed in faulted and fractured Cretaceous-age limestones and dolomites. Ford (2004) defines karst as terrain with distinctive hydrology arising from the combination of high rock solubility and well-developed solution channel porosity underground. Karst terrains and aquifers are characterized by sinking streams, sinkholes, caves, springs, and an integrated system of pipe-like conduits that rapidly transport groundwater from recharge features to springs (White 1988; Todd and Mays 2005).

The Edwards Aquifer system lies within the Miocene-age Balcones Fault Zone (BFZ) of south-central Texas and consists of an area of about 10,900 km^2 (4200 mi^2) (Fig. 1 inset). The aquifer extends about 435 km (270 miles) from the Rio Grande River along the Mexico/US border at

Del Rio, east to San Antonio, then northeast through Austin to Salado. Groundwater from the Edwards Aquifer is the primary source of water for about 2 million people plus numerous industrial, commercial, and irrigation users. Hydrologic divides separate the Edwards Aquifer into three segments. North of the Colorado River is the northern segment of the Edwards Aquifer, and south of the southern hydrologic divide near the City of Kyle is the San Antonio segment (Fig. 1). The Barton Springs segment is situated between the northern and San Antonio segments. Ryder (1996) and Lindgren et al. (2004) provide detailed and regional information on the overall Edwards Aquifer.

Development of the Edwards Aquifer was influenced significantly by fracturing and faulting associated with the Miocene-age BFZ and dissolution of limestone and dolomite units by infiltrating meteoric water (Sharp 1990; Barker et al. 1994; Hovorka et al. 1995). In addition, development of the aquifer is also thought to have been influenced by deep dissolution processes along the saline–fresh water interface, what is known as hypogenic speleogenesis (Klimchouk 2007).

Environmental Protection Agency identifies karst aquifers as one of the water supplies most vulnerable to pollution because of rapid groundwater velocities and limited ability to filter contaminants (Schindel et al. 1996). Numerous tracer tests have been performed on portions of the Edwards Aquifer demonstrating that rapid groundwater flow occurs in an integrated network of conduits discharging at wells and springs (Hauwert et al. 2004; BSEACD 2003). During higher flow conditions, a portion of this groundwater flows from the conduits into the diffuse matrix of the aquifer building up storage in the aquifer. Water from storage flows diffusely to wells or back into the conduit network during lower flow conditions (Mahler et al. 2006b). This dual flow system results in contamination having the potential to rapidly impact wells and springs, as well as slowly accumulate and move within the matrix of the aquifer.

3.2 Barton Springs Aquifer

The Barton Springs aquifer is the focus of this project. Approximately, 60,000 people depend on water from the Barton Springs aquifer as their primary or sole source of drinking water. Groundwater use is characterized as 80% public supply, 13% industrial (quarry operations), and 7% irrigation (golf courses and athletic fields). The various spring outlets at Barton Springs are the only known habitat for the endangered Barton Springs salamander (*Eurycea sosorum*). To protect existing users of the aquifer and the endangered salamanders, pumping from the Barton Springs aquifer has been capped at 14 million m^3/yr(3.77 billion gallons/yr) under non-drought conditions. During periods of drought, permitted users are required to make significant reductions in groundwater use with reductions of 50% of permitted volume during droughts equivalent to the drought of record in the 1950s.

The Barton Springs aquifer is 400 km^2 (155 mi^2) in area, with about 80% of the area consisting of unconfined aquifer conditions, although the percentage fluctuates according to hydrologic conditions. The primary discharge point is Barton Springs located in Barton Creek about 0.4 km (¼ mi) upstream of its confluence with the Colorado River (Fig. 1). The Barton Springs aquifer is bounded to the north by the Colorado River and by the outcrop and saturated thickness of the Edwards Group to the west. The eastern boundary of the aquifer is the interface between fresh and brackish water (>1000 mg/L total dissolved solids (TDS)) and is a complex three-dimensional boundary commonly known as the “saline” or “bad-water” interface. The saline zone of the Edwards Aquifer is characterized by a decrease in relative transmissivity (Flores 1990). Hovorka et al. (1998) describe this boundary as hydrodynamically controlled rather than separated by a distinct hydrologic barrier, although local fault control was noted. The southern hydrologic divide between the Barton Springs aquifer and the San Antonio segment of the Edwards Aquifer is located approximately between Onion Creek and the Blanco River near the City of Kyle. This divide may fluctuate according to hydrologic conditions, as supported by potentiometric surface elevations and recent tracer testing results (LBG-Guyton Associates 1994; Hunt et al. 2005; Land et al. 2010; Johnson et al. 2012).

Mapping of the Barton Springs aquifer has delineated geologic faults and several informal stratigraphic members of the Kainer and Person Formations of the Edwards Group (Rose 1972), each having distinctive hydrogeologic characteristics (Small et al. 1996). In the District, faults trend predominantly NE–SW and are downthrown to the southeast, with total offset of about 1100 ft across the study area. As a result of faulting and erosion, the aquifer ranges from about 450 ft at its thickest along the east side, to 0 ft along the west side of the recharge zone (Slade et al. 1986). Dissolution along fractures, faults, and bedding-plane partings and within certain lithologic units has created numerous sinkholes, sinking streams, conduits, caves, and springs.

3.3 Recharge

The majority of recharge to the aquifer is derived from streams originating on the contributing zone which is underlain by units of the Trinity Group and located primarily west of the recharge zone. Water flowing onto the recharge zone sinks into numerous caves, sinkholes, and fractures along its six major (ephemeral to intermittent) losing streams. Slade et al. (1986) estimated that as much as 85% of recharge to the aquifer is from water flowing in these streams. The remaining recharge (15%) occurs as infiltration through soils or direct flow into recharge features in the upland areas of the recharge zone (Slade et al. 1986). However, current studies indicate that upland recharge may constitute a larger fraction of recharge (Hauwert 2006). Mean surface recharge should approximately equal mean discharge, or about 1500 L/sec [53 cubic feet per second (cfs)]; however, maximum recharge rates during flooding may approach 11,300 L/sec (400 cfs) (Slade et al. 1986). Studies have shown that recharge is highly variable in space and time and focused within discrete features (Smith et al. 2001). For example, Onion Creek is the largest contributor of recharge to the Barton Springs aquifer (34% of total creek recharge) with maximum recharge rates up to 4530 L/sec (160 cfs) (Slade et al. 1986). Antioch Cave is located within Onion Creek and is the largest capacity discrete recharge feature known in the Barton Springs aquifer with an average recharge of 1300 L/sec (46 cfs) and a maximum of 2690 L/sec (95 cfs) during a 100-day study (Fieseler 1998). Figure 5a, b are cross-sectional views of the Antioch vicinity from a 3D geologic model (Hunt et al. 2010). Figure 5c illustrates the potentiometric mound from the high rates of recharge due to the cave and BMP. Increased recharge due to "urban leakage" from leaking water and wastewater lines, septic tanks, and applied lawn irrigation in the contributing and recharge zones is another potential source of water to the aquifer (Sharp 2010).

In the Barton Springs aquifer, the amount of cross-formational flow (subsurface recharge) occurring through adjacent aquifers is unknown, although it is thought to be relatively small on the basis of water-budget analysis for surface recharge and discharge (Slade et al. 1985) and multiport monitor well studies (Smith and Hunt 2009). Under drought and low water-level conditions, there could be an increased potential for cross-formational flow from the saline zone. Recent studies (Johnson et al. 2012) have documented recharge to the Barton Springs aquifer from the Blanco River, previously thought to only provide recharge to the San Antonio segment. In addition, recent studies (Land et al. 2010) have documented the potential for groundwater flow to bypass San Marcos Springs and flow toward Barton Springs.

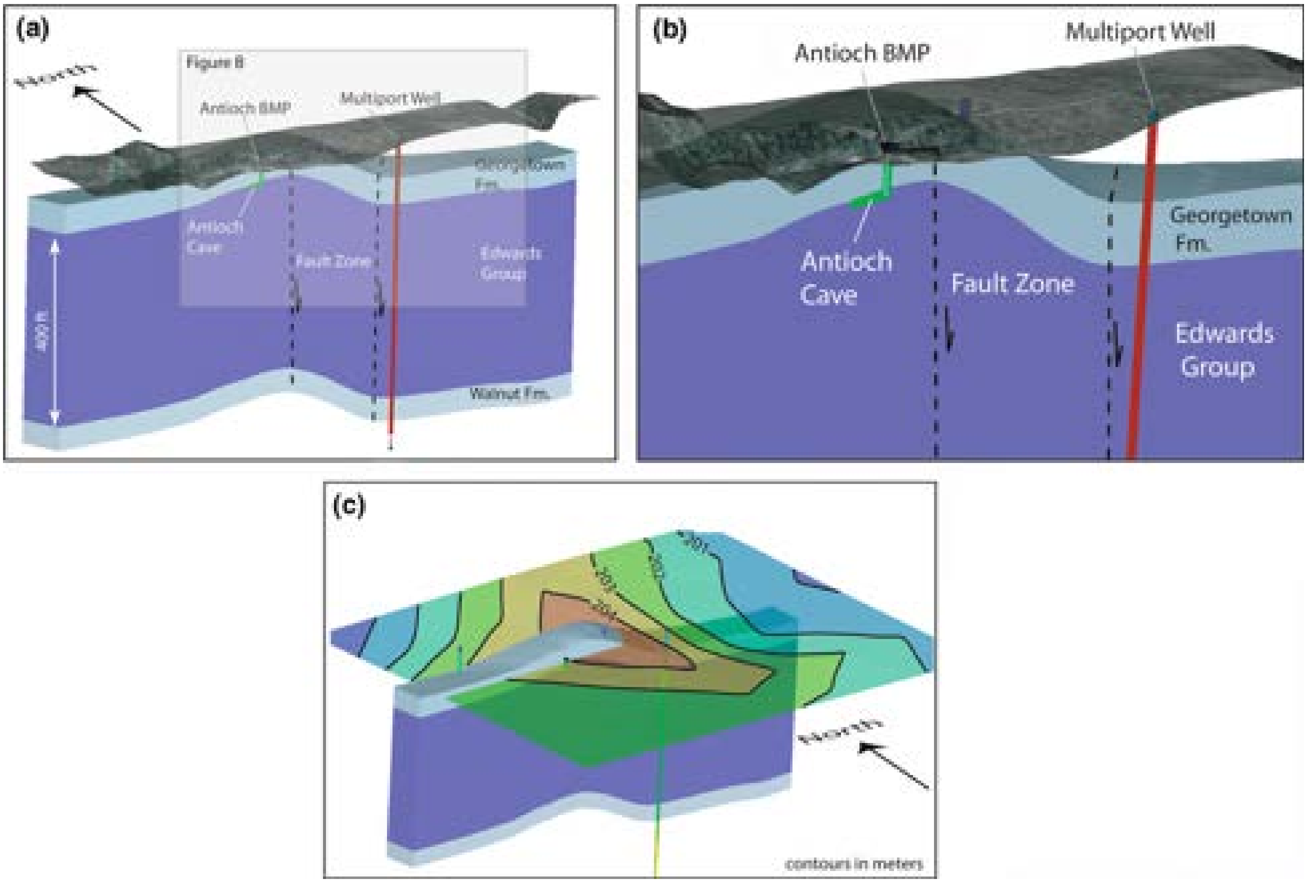

Fig. 5 **a** Oblique cross-sectional view of the Edwards Aquifer in the Antioch vicinity from the 3D geologic model. **b** Close-up view illustrating Antioch Cave and the BMP in relation to the fault zone. **c** Oblique cross-sectional view of the Edwards Aquifer with a high-flow potentiometric surface showing groundwater mounding due to high rates of recharge along Onion Creek and Antioch Cave

3.4 Groundwater Flow

The Edwards Aquifer is inherently heterogeneous and anisotropic, which strongly influences groundwater flow and storage (Slade et al. 1985; Maclay and Small 1986; Hovorka et al. 1996, 1998; Hunt et al. 2005). The Edwards Aquifer can be described as a triple porosity and permeability system consisting of matrix, fracture, and conduit porosity (Hovorka et al. 1995; Halihan et al. 2000; Lindgren et al. 2004) reflecting an interaction between rock properties, structural history, and hydrologic evolution (Lindgren et al. 2004). In the Barton Springs aquifer, groundwater generally flows west to east across the recharge zone, converging with preferential groundwater flow paths subparallel to major faulting and fracturing, and then flowing north toward Barton Springs.

Groundwater dye tracing and other studies demonstrate that a significant component of groundwater flow is discrete, occurring in a well-integrated network of conduits, caves, and smaller dissolution features (Hauwert et al. 2002a, b). Interpreted flow paths from tracer testing generally coincide with troughs in the potentiometric surface and are parallel to the N40E (dominant) and N45W (secondary) fault and fracture trends presented on geologic maps, indicating the structural influence on groundwater flow. Rates of groundwater flow along preferential flow paths, determined from dye tracing, can be as fast as 6.4–11.2 km/day (4–7 mi/day) under high-flow conditions or about 1.6 km (1 mi/day) under low-flow conditions (Hauwert et al. 2002a; Johnson et al. 2012).

In one trace, dye injected into Cripple Crawfish Cave on Onion Creek displayed diverging flow paths to Barton and San Marcos Springs (Hunt et al. 2006). This has implications for the groundwater divide separating the Barton Springs and San Antonio segments of the Edwards Aquifer. Traces from Cripple Crawfish Cave and Antioch Cave in Onion Creek have demonstrated divergent flow paths that appear to converge before discharging at Barton Springs. Dye-trace tests were performed three times from Antioch Cave in Onion Creek (Hauwert et al. 2004; Hunt et al. 2005). The first trace was performed under drought conditions (March 2000), and the dye was tentatively detected at a few nearby wells. Subsequent injections under wet, creek-flowing conditions (November 2000 and August 2002) resulted in repeated dye detections in up to 17 water-supply wells, including some public water-supply wells, and at Barton Springs. The paths of flow demonstrated by dye tracing revealed several divergent flow paths that appear to converge before discharging at Barton Springs. Arrival of dye at Barton Springs from Antioch Cave under high-flow (August 2002) conditions was about 7-day travel time with an apparent velocity of about 3.2 km/day (2 mi/day) (Hunt et al. 2005).

3.5 Water Levels and Storage

Water levels in the Edwards Aquifer are very dynamic and heterogeneous. Water levels do not show long-term declines in storage, but generally recover quickly from low levels reached during drought to previous high conditions typical of wet periods (Smith et al. 2001). Water levels and discharge at the springs respond very quickly to recharge events and then decline at variable rates, influenced by both conduit and matrix permeability and storage (Lindgren et al. 2004; Worthington 2003).

Figure 6 shows a potentiometric mound, or ridge, from recharge along Onion Creek and paths of dye injected into Antioch Cave (Hunt et al. 2007). Even under low-flow conditions, the mound is still present. The presence of a mound beneath Antioch and much of Onion Creek indicates that water recharging along Onion Creek is going into aquifer storage in addition to more direct, conduit flow to Barton Springs. The conduits that have been demonstrated through dye-trace studies to connect with Barton Springs are not of sufficient capacity to carry all of the recharging water directly to Barton Springs. The excess water must be entering storage that consists of a matrix of non-conduit dissolution features and primary porosity.

3.6 Geology of the Antioch BMP Vicinity

Antioch Cave is located on District property within the bed of Onion Creek about 2 km (1.3 miles) west-southwest of the center of Buda, Texas. The cave is located about 244 m (800 ft) upstream of a significant fault (Mountain City Fault Zone) delineating the eastern extent of the Edwards Aquifer Recharge Zone for this area. Geologic units at the surface include Cretaceous-age limestones (Georgetown and Buda) and claystones (Del Rio and Eagle Ford), which are in places overlain by more recent terrace, alluvium, and fill deposits.

The entrance and uppermost 6 m (20 ft) of the cave is formed along a solution-enlarged fracture within the highest stratigraphic unit of the Edwards Aquifer, the Georgetown Formation. The cave continues downward into the Edwards Group to a depth of about 12 m (40 ft) below the entrance (Fig. 4). The cave passage then extends laterally along a bedding plane about 15 m (50 ft) to the north then about 23 m (75 ft) to the northwest where it splits into two passages, one continuing northwest for about 45 m (150 ft) and the other trending west about 53 m (175 ft) (Fig. 7). All passages become too tight for a person to continue exploring. The Mountain City Fault Zone, trending NE-SW with about 30 m (100 ft) of vertical throw, is mapped on the property. The fault zone creates unconfined aquifer

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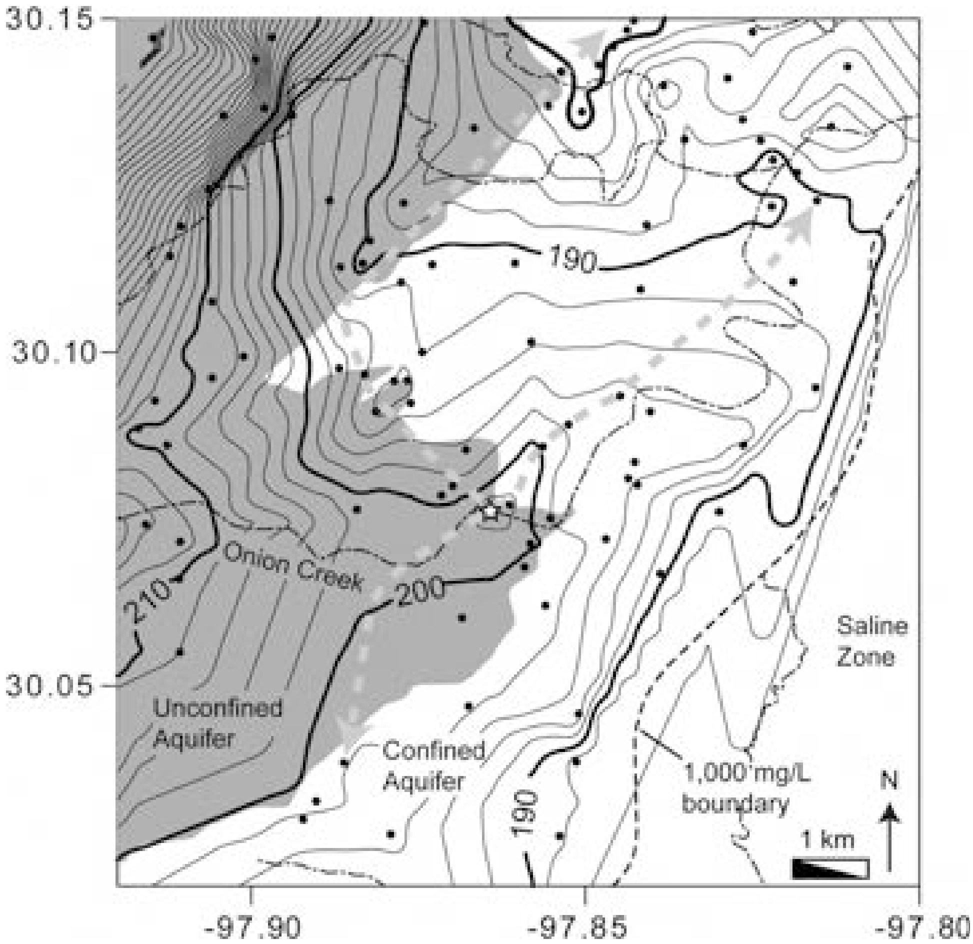

Fig. 6 **a** Regional potentiometric map along Onion Creek during high-flow conditions (February 2002). The 200-m contour illustrates the mounding effect due to discrete recharge from Antioch Cave. *Lines with arrows* indicate direction of groundwater flow from dye-trace studies

conditions on the upthrown side of the fault where the BMP is located and confined aquifer conditions on the downthrown side (Fig. 5).

3.7 Storm Water Contaminants in Onion Creek

Studies by the USGS (Web site data) indicate that high levels of bacteria and lead are associated with storm events in Onion Creek. The USGS collected water samples at their Onion Creek Driftwood station during multiple storm events between February 1994 and March 1998. Analyses were conducted for major cations and anions plus selected constituents commonly found in storm water.

A more recent study by the USGS (Mahler et al. 2011) finds that nitrate levels in Barton Springs and the five major streams that cross the recharge zone are significantly higher than samples collected between the early 1990s and November 2008. Samples were collected from these streams and Barton Springs during November 2008 and March 2010. Another conclusion of the study is that the probable source of nitrate in the recharging streams is biogenic (human and animal) sources.

Mahler and Lynch (1999) collected samples of water discharging from Barton Springs to determine the quantity, chemistry, and grain sizes of sediment discharging from the spring following two storm events in November 1995 and May 1996. They calculated that 805 kg (1775 lbs) and 1012 kg (2233 lbs) of sediment discharged from the spring during the two storm events, respectively. An analysis of the sediment and sediment peaks on the discharge hydrographs suggests that much of the sediments are derived from outside of the aquifer, meaning that the sediments are carried into the aquifer by recharging surface streams. Antioch Cave and other caves are potential pathways for sediment to enter the aquifer and eventually discharge at Barton Springs.

4 Methodology

This project involved the installation and operation of a continuous water-quality monitoring network (CWQMN), upgrade of the BMP at Antioch, and storm water sampling. Using CWQMN data and results of storm water sampling, the amount of contaminant reduction due to operation of the Antioch BMP was calculated.

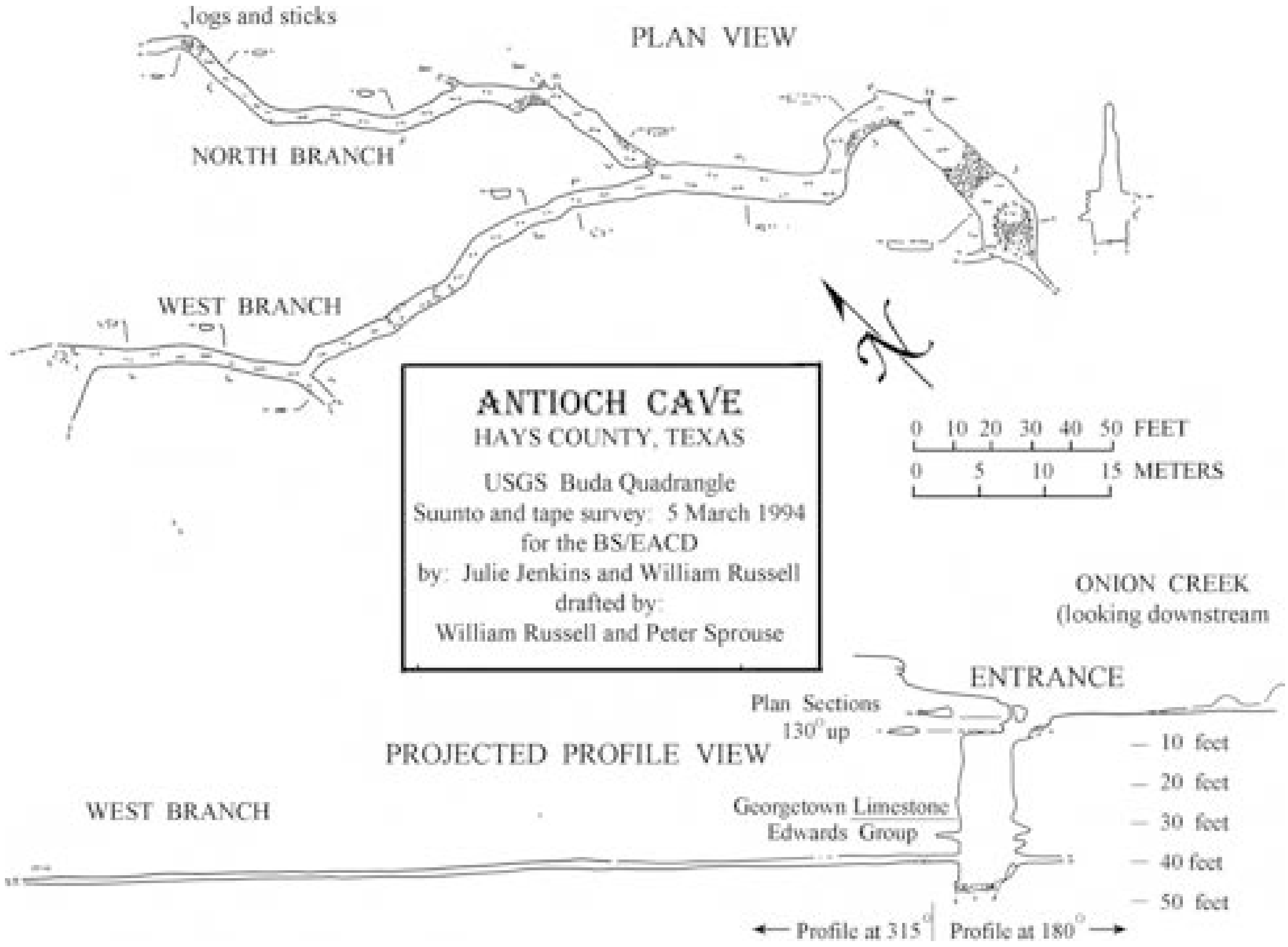

Fig. 7 Map of Antioch Cave showing plan and profile views

4.1 Continuous Water Quality Monitoring Network Sites

A CWQMN system was installed at the Antioch Cave site in Onion Creek to monitor water quality. This system provides real-time continuous data for surface water entering Antioch Cave and leaving the recharge zone within the Onion Creek watershed.

Data from the sensors are collected and stored in data loggers at the site and transmitted via wireless modem to the TCEQ MetroStar/Leading Environmental Analysis and Display System (LEADS) in Austin, Texas, where the data are processed and archived. Hourly averaged data are then posted to appropriate TCEQ Web sites for public use and review. Monthly site visits are conducted to verify or calibrate the multiparameter water-quality sensor, provide complete system maintenance, and monitor the CWQMN site for vandalism and acts of nature.

The Antioch CWQMN site includes the following equipment:

- In Situ Troll 9500 water-quality sensor (T, conductivity, DO, turbidity, pressure)
- Zeno data logger
- Enfora modem and cellular telephone
- Isco 2150 flow meter with area velocity/pressure
- Air compressor and tank
- Solar panel and 12-volt batteries.

District staff began the construction phase for the Antioch CWQMN system in April 2008. This monitoring site was brought onto the TCEQ real-time data collection system on August 16, 2008. The Troll 9500 was installed in a perforated 10-cm (4-in.) diameter PVC conduit about 4 m (15 ft) upstream of the BMP. The flow meter was installed in the 91-cm (36-in.) diameter pipe that connects the intake screen to the BMP. A stainless-steel equipment housing was installed above flood stage to house the Zeno data logger, modem, communications equipment, air compressor, and tank. Cables connecting the data logger to the probes run through the PVC conduit buried in a trench for a portion of the distance between the BMP and the equipment housing. From September 2009 to September 2010, water-quality measurements were made at Antioch for six storm events. Data continue to be collected to the present.

4.2 Upgrade of Antioch BMP

The original BMP, constructed at the Antioch site in 1997, was upgraded as part of this project to improve and automate the function of the BMP. The goal for the BMP when it was constructed was to reduce the amount of nonpoint source pollution entering the aquifer from storm water flow in Onion Creek. As part of this current project, modifications were made to improve the efficiency of the BMP by automating the opening and closing of the intake valves and by installing an intake screen over the second valve so that less storm debris and sediment could enter the cave and that the intake structure would not get clogged with debris.

An intake structure for the Antioch BMP, consisting of a 91-cm (36-in.) diameter screen and pipe, was installed in September 2008. The screen is 10 m (32 ft) long, and the pipe is 5 m (16 ft) long. The function of the intake structure is to allow water to flow into the cave while filtering out most of the debris that is carried in Onion Creek. A second 91-cm (36-in.) diameter valve was installed in the BMP on September 9, 2008 (Fig. 8). The valve controlled by the CWQMN equipment is programmed to close when turbidity of the water in Onion Creek rises to 100 NTU and to open when turbidity drops to 50 NTU. The default position of the valve is open since the turbidity meter is either sensing low turbidity water between storm events or air when there is no flow in the creek. When a storm pulse first arrives and turbidity levels increase above this threshold, the valve will automatically close. After the storm pulse passes and turbidity levels decrease, the automated valve opens to allow water to enter the BMP.

An Isco 2150 velocity meter was installed near the midpoint of the 5-m (16-ft) long pipe. This velocity meter measures flow of water into the second valve. From the velocity data, a volume of flow can be calculated by multiplying the velocity by the cross-sectional area of the pipe. By measuring the volume of water entering the system when the valve is first opened following a flow event, the mass of storm contaminants prevented from entering the aquifer when the valves are closed can be calculated (Eq. 1—Calculation of Contaminant Reduction). Figure 9 is a photograph of the completed system.

4.3 Storm Water Sampling

District staff selected storm water parameters for analysis that include total suspended solids (TSS), total dissolved solids (TDS), turbidity, nitrate and nitrite as nitrogen (N), and total phosphorus (P). Storm water sample collection followed field sampling procedures for conventional parameters documented in the TCEQ Surface Water Quality Monitoring Procedures Manual (TCEQ 2008).

Samples were collected from an open channel environment using a Teledyne Isco system (3700 series). An Isco bubbler flow meter (4230 series) initiates the sampling program for the automatic sampler. The flow meter logs water levels every 5 min and triggers the automatic sampler to start sampling when there is a rise of water level in the creek indicative of a storm pulse. The sampler and flow meter were placed about 6 m (20 ft) in elevation above the BMP so that the sampler pump will be capable of delivering

Fig. 8 Installation of second valve (automated) on Antioch BMP

Fig. 9 View of Antioch BMP following upgrade completion. View looking upstream

samples to the bottles in the sampler, but will not be subjected to flooding by all but the most severe storms. Volumetric calibration of the automatic sampler was performed to verify correct volumes were being collected. The automatic sampler fills two 1-L (about 1 quart each) bottles for every sample collected.

The collection of samples focused on peak flows from a given storm event with sampling continuing as the storm subsides. Samples were collected at intervals ranging from every 15 min to every 6 h. A selected number of samples thought to represent the storm hydrograph were sent to the laboratory for analysis. From October 2009 to September 2010, samples were collected from five storm events. Five to seventeen samples were analyzed for each storm event.

4.4 Calculation of Contaminant Reduction

Currently, the CWQMN system is set to close the intake valve when turbidity values rise to 100 NTU and to reopen when the turbidity value of storm water drops to 50 NTU. The contaminant reduction Eq. (1) is used to quantify the mass of contamination being prevented from entering the BMP.

$$Q * C_{\mathrm{N,P,S}} * T = M_{\mathrm{N,P,S}} \tag{1}$$

where

Q Rate of flow into Antioch BMP when valve is first opened after storm pulse.

$C_{\mathrm{N,P,S}}$ Concentration of N (nitrate/nitrite), P(phosphorus), or S (sediment) during storm pulse.

T Duration of time that valve on BMP was closed.

$M_{\mathrm{N,P,S}}$ Mass of contaminant prevented from entering aquifer.

5 Results of Sampling and Data Collection

As described in the methodology section, the data collection part of this project consisted of continuous water-quality monitoring with a CWQMN system at Antioch Cave and storm water sampling at Antioch. Data collection at Antioch began in May 2009. Other than some brief periods when the system was not functioning or data were not transmitted, there is a nearly continuous record of temperature, specific conductivity, turbidity, dissolved oxygen, and gage height for the Antioch site. However, between May 2009 and September 2009, there was no flow in Onion Creek at Antioch due to a severe drought.

5.1 Sampling of Storm Events

A summary of the six storm events recorded at the Antioch CWQMN site is presented in Fig. 10, which includes data from flow in Onion Creek at the U S Geological Survey (USGS) Driftwood station and maximum gage height at the Antioch CWQMN. Table 1 is a compilation of CWQMN and laboratory data shown in a chart format for each of the six storm events. Laboratory data include turbidity, nitrogen from nitrate and nitrite, total phosphorus, suspended solids, and total dissolved solids. A description of each of the six storm events is provided below.

5.1.1 Storm Event 1 (September 29–30, 2009)

At the beginning of September 2009, most of Texas was experiencing a severe drought that had been going on for close to 2 years. The District had declared an Alarm Stage Drought on June 23, 2008, for the Barton Springs aquifer. By the beginning of December 2008, the District was in Critical Stage Drought, and was on the verge of entering into Exceptional Stage Drought in September 2009. Heavy rain, up to 250 mm (10 in.) in some parts of the recharge and contributing zones, fell between September 9 and 12. However, this significant amount of rain did not cause any flow in Onion Creek at the USGS gaging station in Driftwood. Because of the extremely hot and dry conditions at the time of this rain, there was very little runoff of rainfall to the creeks.

On September 28 and 29, light rain of less than 13 mm (½ in.) fell over much of the study area. However, a small area on the north side of Onion Creek, upstream of Antioch, received about 76 mm (3 in.) over a few hours on September 29. This led to flow in some tributaries to Onion Creek starting about 3 km (2 miles) upstream of Antioch, but there was no flow at the Driftwood station. The flow soon reached the Antioch BMP with a maximum gage height of about 1.4 m (4.6 ft). Water-quality data were collected by the CWQMN system, but the automated sampler was not activated for sample collection. CWQMN data show a short but brief peak for flow at Antioch. Within less than 24 h, flow had decreased to virtually zero. The turbidity of the water first reaching Antioch was 776 NTU. Turbidity values dropped steadily until the end of the flow event. Conductivity values spiked initially, then declined sharply, then rose steadily until the end of the flow event, which lasted less than 17 h.

5.1.2 Storm Event 2 (October 27–28, 2009)

The second storm event recorded at Antioch occurred following a moderate amount of rain of about 50 mm (2 in.) on

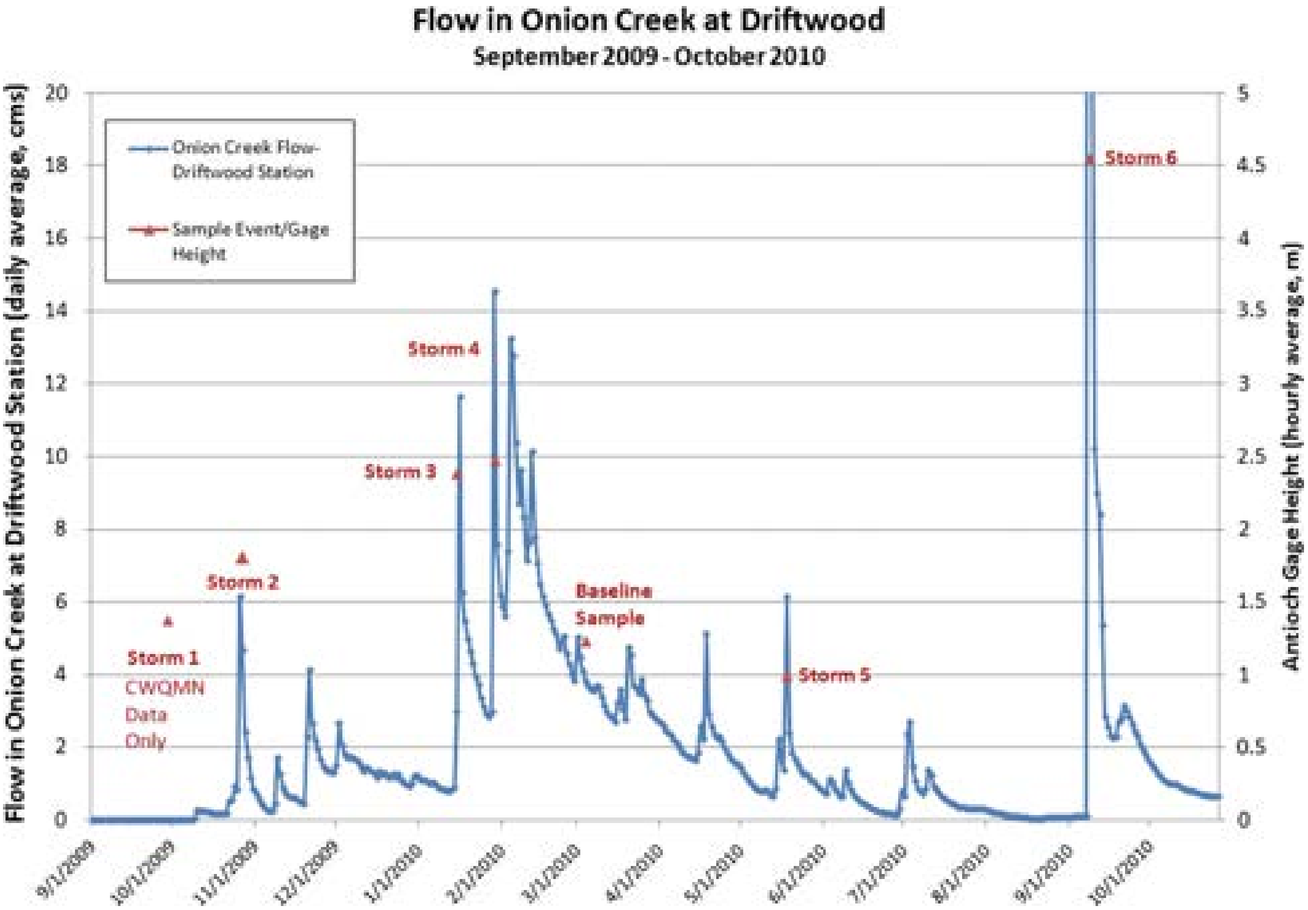

Fig. 10 Storm events sampled for this project are shown superimposed on a hydrograph of Onion Creek at the USGS Driftwood station from August 2009 to October 2010. The Driftwood station is about 21 km (13 miles) upstream of the Antioch Cave site

Table 1 Mass of contaminant reduction from operation of Antioch BMP for five storm events

Storm event	Start (NTU > 100)	End (NTU < 50)	Duration (days)	Duration (hours)	Average peak storm values[b] (mg/L)			Contaminant reduction[c] in lbs (kg)		
					N[a]	P[a]	TSS	N[a]	P[a]	TSS
1	Samples not collected for laboratory analysis									
2	10/27/09 1:41	10/27/09 2:27	0.03	0.8	6.16	0.075	57.5	**106** (48)	**1.3** (0.6)	**990** (449)
3	1/15/10 21:30	1/16/10 8:15	0.45	10.7	0.53	0.195	70.0	**128** (58)	**47** (21)	**16,905** (7666)
4	1/29/10 11:15	1/31/10 0:30	1.55	37.3	0.92	0.02	30.2	**770** (349)	**17** (7.6)	**25,271** (11,461)
5	5/18/10 2:56	5/18/10 12:31	0.40	9.6	0.33	0.005	31.2	**71** (32)	**1.1** (0.5)	**6717** (3046)
6	9/9/10 14:26	9/7/10 21:46	1.69	40.7	1.49	0.25	153.9	**1361** (617)	**228** (104)	**140,597** (63,763)
		Total duration	**4.1**	**99.0**			Totals (lbs)	**2436**	**295**	**190,480**
							Totals (kg)	1105	134	86,385

[a] N is nitrogen from nitrate and nitrite; P is total phosphorus. [b] For period during which the valve was closed. [c] Mass of contaminants not entering Antioch Cave while valves are closed

Fig. 11 Photograph of the top of the BMP about 8 h past the peak storm pulse on October 27, 2009, with a whirlpool near the corner of the vault due to water entering the original valve

October 26, 2009. This followed a very wet September, as described in Sect. 5.1.1, that had a rainfall total of about 330 mm (13 in.) over much of the recharge and contributing zones. Total rainfall in October was about 170 mm (6.5 in.) as measured at the District office in Manchaca, Texas. The maximum gage height at Antioch during this storm event was 2.0 m (6.2 ft). Turbidity reached a peak of 782 NTU at the very beginning of the storm pulse which quickly declined to less than 50 NTU within 50 min. Conductivity values spiked initially, then declined sharply, then rose steadily before leveling off for the remainder of the storm event. Figure 11 is a photograph showing water flowing in Onion Creek and the top of the BMP about 8 h past the peak storm pulse on October 27, 2009.

5.1.3 Storm Event 3 (January 15–17, 2010)

The third storm event occurred between January 15 and 17 following a 76-mm (3-in.) rain on January 15 and 16. January was also a very rainy month with a rainfall total of about 120 mm (4.7 in.), about 60 mm (2.5 in.) above average rainfall for the month. The gage height at Antioch reached a maximum of 2.4 m (7.9 ft) within 9 h of the start of the event (Fig. 12). A turbidity peak of 144 NTU occurred about 1 h after the start of the event. A second peak of 151 NTU occurred about 5 h after the first peak. Three conductivity peaks occurred during the first 12 h of the storm event followed by a slow decrease for the next 12 h, then a slow but steady rise in conductivity.

5.1.4 Storm Event 4 (January 29–31, 2010)

The fourth storm event was brought about by 41 mm (1.6 in.) of rain between January 28 and 29. Prior to the storm, flow in Onion Creek at the Driftwood station had been about 100 cfs, but there was no flow at Antioch prior to the storm. The gage height at Antioch reached a maximum of 2.5 m (8.2 ft) within about one hour of the start of the event. A turbidity peak of 144 NTU occurred immediately when the storm pulse reached the instruments at Antioch. Two conductivity peaks occurred during the first 12 h of the storm event followed by a slow decrease for the next 20 h, then a slow, but steady, rise in conductivity. Following this storm event, flow at Antioch continued until March 15 when the instruments recorded a gage height of 0 m. On that date, the USGS station on Onion Creek at Driftwood was recording flow of about 2831 L/sec (100 cfs).

5.1.5 Storm Event 5 (May 18–19, 2010)

The fifth storm event followed about 43 mm (1.7 in.) of rain between May 14 and 17. Flow began on May 18 and continued until May 19, for a total of about 42 h of flow. The peak gage height of 1.0 m (3.3 ft) occurred 5 h after the commencement of flow at Antioch. Of the five storm events sampled for this project, this event had the lowest recorded gage height. A turbidity peak of 962 NTU occurred immediately at the beginning of the storm pulse. Conductivity immediately peaked at the beginning of the storm pulse, then peaked again about an hour later, then decreased for another 5 h before rising steadily until the end of the flow event.

On June 30, 2010, Hurricane Alex landed in northern Mexico and brought more than 130 mm (5 in.) of rain to parts of the Edwards recharge zone. Flow in Onion Creek at the Driftwood station increased to about 2831 L/sec (100 cfs), but no flow occurred at Antioch as a result of this rain.

5.1.6 Storm Event 6 (September 7–10, 2010)

The sixth storm event was the largest storm event of the project. It followed about 190 mm (7.5 in.) of rain from Tropical Storm Hermine from September 7 through 8. Two days of light rain, that totaled about 15 mm (0.6 in.), preceded the storm by 4 days, so soil conditions were fairly wet. Hermine arrived in Central Texas on September 7 with about 167 mm (6.6 in.) of rain. The rain continued into September 8 with about 23 mm (0.9 in.). Flow began at Antioch at about 8:00 pm on September 7. A peak gage height of about 4.6 m (15 ft) occurred about 13 h later. A second gage height peak of about 4.0 m (13 ft) occurred about 12 h later. The maximum flow rate recorded at the USGS Driftwood station was 74,300 L/sec (2630 cfs) (hourly average). Five peaks were recorded at Antioch for turbidity during this storm event. The greatest turbidity reading was 1210 NTU that occurred 13 h after the beginning of flow at Antioch. There were three conductivity peaks within the first 26 h of the storm event followed by a steady rise. Flow at Antioch ended on September 13 for a total duration of about 6 days.

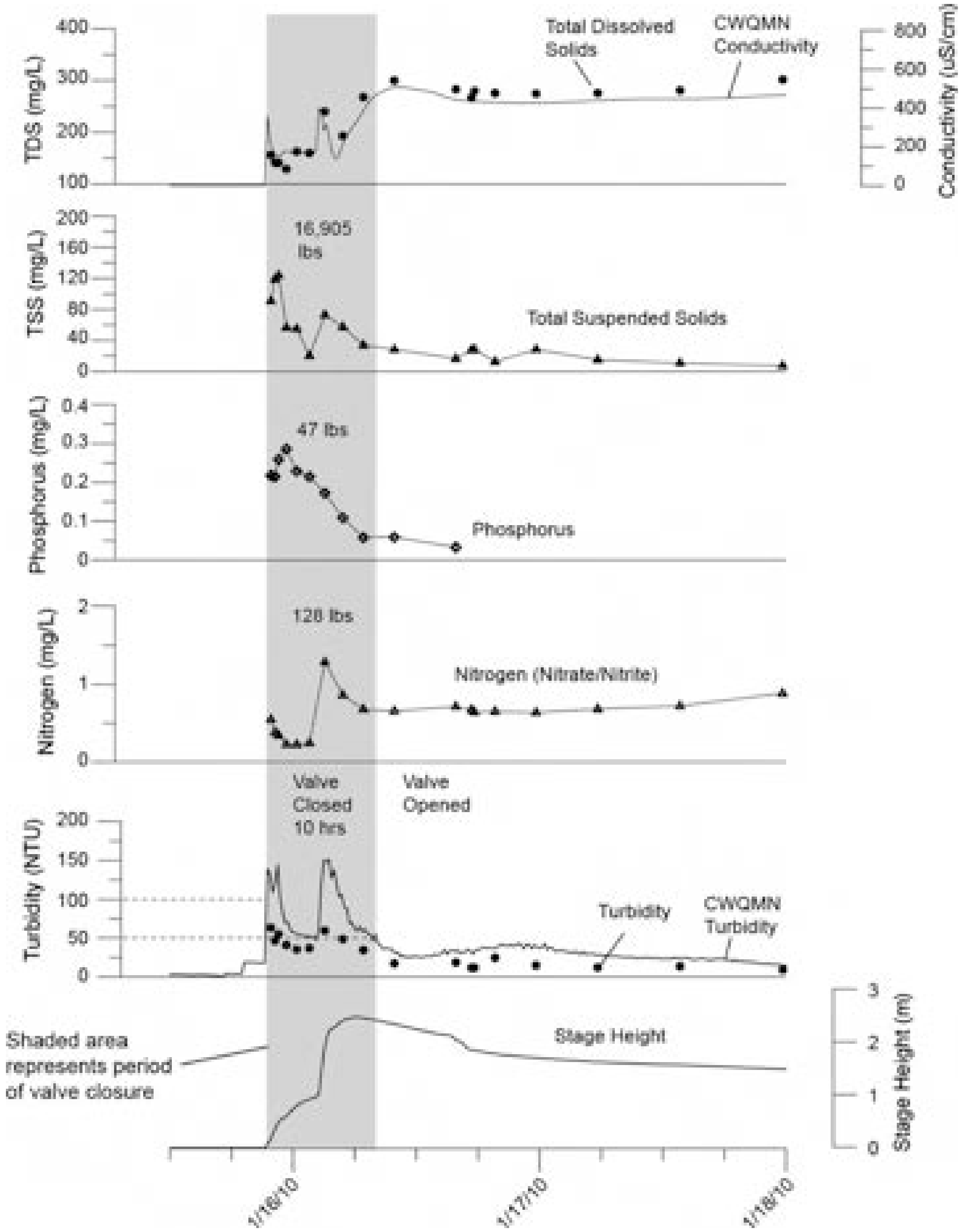

Fig. 12 CWQMN and laboratory analytical data for Storm Event 3

5.2 Comparison of Storm Events

Laboratory and CWQMN data for the five storm events show considerable variation in the relationships between the various parameters analyzed by the laboratory or recorded by the CWQMN system. A comparison of stage height to turbidity data from the CWQMN system at Antioch does not indicate any distinct pattern. The analytical results follow mostly irregular paths throughout the progression of each storm event. Many factors need to be considered in the analysis of each storm event. Antecedent conditions such as soil moisture and the amount of water in Onion Creek can significantly affect storm water runoff and subsequent flow in the creek. The intensity of rainfall and location of that rain can also affect the amount of flow and the variation in contaminant load of the storm water.

Unlike the storm events sampled for this project at Antioch, each storm event in the USGS study (Web site data) shows a clear trend with high turbidity levels associated with high flow rates. However, both studies show that each storm event is unique with respect to contaminant loads.

Figure 13 shows the results of laboratory analyses of samples from five storm events. Values for a given parameter vary considerably during the first 10 h of the storm event. Values tend to either rise or fall slightly after the first

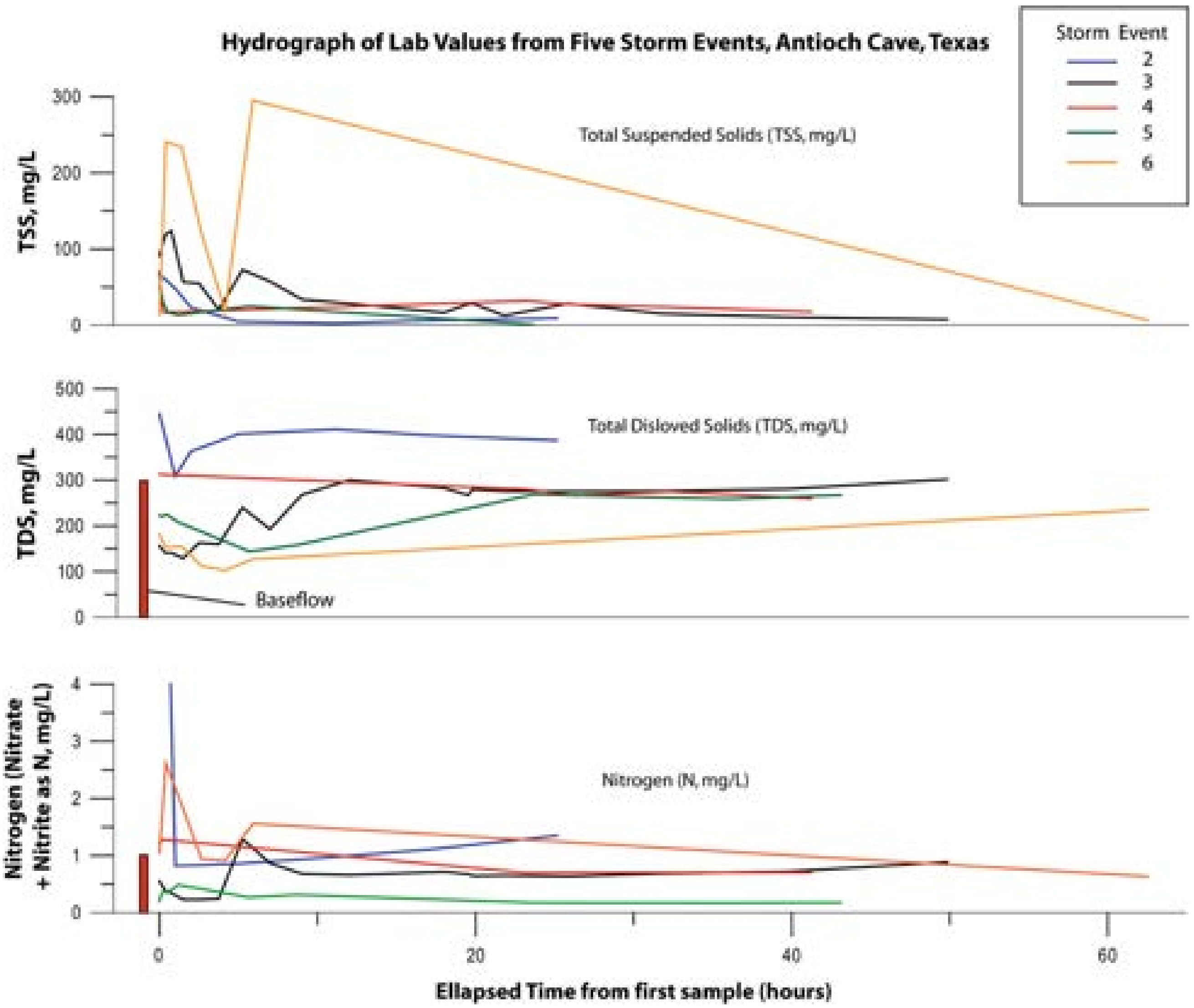

Fig. 13 Hydrograph of laboratory analytical results for five storm events at Antioch Cave. Also shown are the results from the baseflow sample as a *bar graph*. TSS was below the detection level for the baseflow sample

10 h. This pattern applies to each of the five storm events. A sample was collected from Onion Creek at Antioch on March 4, 2010, that is considered to be representative of baseflow conditions. Laboratory analytical results for TDS, nitrogen (nitrate/nitrite), and TSS were 299, 1.01 mg/L, and below detection level, respectively. The trends of each of these parameters for each storm event show that over time, the values are heading in the direction of the baseflow sample values.

5.3 Contaminant Reduction from Operation of BMP

The principal goal of the BMP constructed over Antioch Cave has been to reduce the amount of storm water contaminants entering the aquifer through Antioch Cave. This had been accomplished with the construction of the original BMP and has been improved with the recent upgrades made to the BMP.

The amount of contaminants not entering the aquifer due to operation of the BMP can be calculated by measuring the flow of water entering the BMP the moment the valve is opened, then multiplying that value by the concentration of contaminants in the water and by the duration of time that the automated valve was closed. The manually operated valve (original valve) is left in the closed position following passage of each storm pulse. The automated valve is closed when turbidity from a storm pulse goes above 100 NTU and is opened when turbidity drops below 50 NTU. Of these parameters, the most difficult to determine is the amount of flow that would be going into the aquifer during the peak storm pulse if both valves are open. This is accomplished, in part, by measuring the flow into the new valve and intake screen when the valve is first opened following passage of the peak storm pulse, which is the point at which turbidity in Onion Creek drops below 50 NTU. An Isco 1250 velocity meter is situated in the 5-m (16-ft)-long, 91-cm (36-in.)-diameter pipe placed between the intake screen and the new valve. Because the velocity meter was damaged during a storm event, there are limited velocity data from storm events. Flow data were collected for the January 15–16, 2010 storm event (Storm Event 3). At about 17:45 on January 16, the valve opened automatically and the instrument recorded a velocity of 3.9 m/s (12.5 ft/sec) that converts to a flow rate of about 2435 L/sec (86 cfs), or 2.4 cubic meters per second [cms]. As soon as possible after the new valve is opened, the original valve is manually opened to maximize flow into the cave. Although it is difficult to measure flow into the original valve, the combined flow into the cave is certainly greater than the measured flow into the new valve. For this evaluation, an estimated total flow into the system of 2831 L/sec (100 cfs) is used for the contaminant reduction calculations. This assumes that the additional flow into the original valve is a least 400 L/sec (14 cfs). This is a minimum flow value and it is likely that total flow into the system is greater than 2831 L/sec (100 cfs), but additional studies are needed to better determine this flow. The intake system for the BMP was designed to handle up to 7000 L/sec (250 cfs). However, it is not known what the upper limit of flow into the cave is.

The results of the contaminant reduction calculations are shown in Table 1. Calculations were made from data for five storm events. The first storm event recorded at Antioch with the CWQMN system did not include laboratory analytical data because the automated sampler was not yet programmed to operate during a storm event. The average duration of the storm events for which the turbidity level of the water in Onion Creek was greater than 100 and 50 NTU was 20 h. The longest time that the valve was closed was 40.7 h, and the shortest time was 0.8 h. As shown in Table 1, concentrations of contaminants and the amount of contaminant reduction varied considerably between storm events. Storm Event 6, with the longest duration of valve closure and the highest level of contaminants, except for nitrogen in Storm Event 2, had the highest amount of contaminant reduction with 617 kg (1361 lbs) of nitrogen, 104 kg (228 lbs) of phosphorus, and 63,763 kg (140,597 lbs) of sediment. These numbers show that by closing the valves on the BMP during storm events, a significant amount of contaminants from nonpoint sources can be prevented from entering the aquifer. This is certain to provide some protection to nearby water-supply wells and ultimately to lessen degradation of groundwater in much of the Barton Springs aquifer and Barton Springs. Contaminant reduction due to operation of the BMP also applies to other contaminants that were not included in the analytical program such as bacteria, lead, biological oxygen demand (BOD), and pesticides.

5.4 BMP Operation During Storm Event 3

Laboratory analytical and CWQMN data for Storm Event 3 are shown in Fig. 12, including the amount of contaminant reduction for each parameter and an indication of where on the hydrograph the automated valve closed and opened. Based on 15-min CWQMN data, the first storm water to reach the CWQMN multiparameter sensor had a turbidity value of 139 NTU. The automated valve closed immediately upon sensing a turbidity level of 100 NTU or greater. During the next 5 h, the turbidity of the storm water in Onion Creek decreased to 48 NTU. It is presumed that the valve opened due to a turbidity value of 50 NTU or less. However, turbidity then rose above 100 NTU within less than 30 min and presumably closed the valve again. The valve stayed shut for another 5 h until turbidity dropped below 50 NTU again.

As shown in Table 1 and Fig. 12, the amount of sediment, nitrogen (from nitrate and nitrite), and phosphorus prevented from entering the aquifer during Storm Event 3 was 76,668 kg (16,907 lbs), 58 kg (128 lbs), and 21 kg (47 lbs), respectively. Greater amounts of contaminants could be kept out of the aquifer by having the valve open at a lower turbidity level, but that would also decrease the amount of water recharging the aquifer. The results of Storm Event 3 indicate that below a turbidity of 50 NTU, the decrease in total suspended solids is at a slower rate than at levels above 50 NTU.

6 Conclusions

The upgraded BMP at Antioch Cave has demonstrated that such a system is capable of reducing the amount of storm water contaminants entering the Barton Spring aquifer through Antioch Cave. These contaminants can potentially impact water-supply wells and water quality at

Barton Springs where endangered salamanders live. The key findings and conclusions derived from this study are summarized below:

- The upgraded Antioch BMP is capable of significantly reducing the amount of nonpoint source contaminants entering the aquifer through Antioch Cave.
- It is estimated that during this period of operation of the upgraded BMP, 1105 kg (2436 lbs) of nitrogen from nitrate/nitrite, 134 kg (295) lbs of total phosphorus, and 86,385 kg (190,480 lbs) of total suspended solids (TSS) were prevented from entering the aquifer.
- Although bacteria concentrations were not a parameter monitored during this study, previous studies suggest that bacteria are a significant contaminant in Onion Creek during storm events and were reduced as a result of the operation of the BMP.
- The best water-quality indicators of storm flow are turbidity and TSS.
- Because the vault prevents the cave from plugging with debris, a greater quantity of water enters the aquifer. Water-level measurements from wells near the cave show that at times of maximum recharge, a groundwater mound develops below the cave. This increase in storage can help reduce the impact of drought on the aquifer.
- Installation of a flow meter near the main valve provides more accurate and reliable data for determining volume of flow into the BMP. This flow value is also used to estimate how much storm water is not entering the BMP when the valves are closed.
- A CWQMN system installed at Antioch Cave provides flow and water-quality data for water recharging the aquifer and leaving the recharge zone.
- Data provided by the CWQMN system and laboratory analyses of grab samples can be used to compare future water quality in Onion Creek as the Onion Creek watershed becomes more developed.
- During moderate to severe drought conditions, significant rainfall is needed for water to flow in Onion Creek. During non-drought conditions, much less rainfall is needed to get water flowing or to increase the rate of flow in Onion Creek.

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