Summary of Groundwater Tracing in the Barton Springs Edwards Aquifer from 1996 to 2017

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Abstract

The Barton Springs segment of the Edwards Aquifer is an important resource for the region and understanding how the aquifer functions is critical to the conservation and preservation of the resource. Groundwater tracing is an important tool used to characterize the recharge areas, flow paths, groundwater velocities, dispersion, and fate of water in karst aquifers. Results of groundwater tracing demonstrate that a significant component of groundwater flow is rapid, discrete, and occurs in an integrated network of conduits, caves, and smaller dissolution features. Groundwater generally flows west to east within the recharge zone in secondary conduit systems that converge with northeast trending primary conduits defined by troughs in the potentiometric surface parallel to faulting and fracturing. Groundwater flow is very rapid from recharge features to wells and springs, with velocities ranging from 1 to 7 miles/day (1.6 – 11.3 kilometers/day) depending on hydrologic conditions. Tracing studies have further revealed the complexity of groundwater subbasins and the dynamic nature of the southern groundwater divide within the aquifer. This report presents an overview of 23 years of groundwater tracing from 1996 to 2017 in the Barton Springs segment of the Edwards Aquifer.

This material was first presented at the annual Geological Society of America meeting in November 2018 (Zappitello and Johns 2018a).

Introduction

The Barton Springs segment of the Edwards Aquifer (also called the Barton Springs Edwards Aquifer) is an important resource for the region (Figure 1). The majority of the aquifer was designated as a sole source aquifer in 1988 by the Environmental Protection Agency (EPA,

2018) and supplies drinking water to ~60,000 people (Hunt et al., 2019). The aquifer feeds many springs, including Barton Springs, the largest spring in Austin, which contributes up to 20% of the flow downstream in the Colorado River of central Texas, provides habitat for the endangered Barton Springs Salamander (*Eurycea sosorum*) and Austin Blind Salamander (*Eurycea waterlooensis*), and fills a beloved municipal swimming pool. Detailed hydrogeologic descriptions of the Barton Springs Edwards Aquifer can be found in Hunt et al (2019).

Understanding how the aquifer functions is critical to the conservation and preservation of this important groundwater resource. Dye tracing has been a well-established tool used to characterize recharge areas, flow path, groundwater velocities, dispersion, and discharge of groundwater in karst aquifers throughout the world. While regional summaries of groundwater tracing in Edwards Aquifer are provided in Johnson et al (2019), this paper provides a detailed summary table and series of maps displaying the results of tracing between 1996 to 2017. This report also provides a map of the collective flowpath results.

Dye Tracing History

In the Barton Springs Edwards Aquifer, qualitative dye tracing began as early as 1951 with a young boy's experiment using his mother's cake dye (BSEACD 2014). However, the first dye trace conducted by government scientists occurred in Barton Creek in 1981 (Slade 2008), with inconclusive results. It wasn't until 1996 that a long-term, systematic program of quantitative dye tracing was begun by the City of Austin Watershed Protection Department and the Barton Springs Edwards Aquifer Conservation District (BSEACD) (Hauwert et al 2004). The goal of the quantitative tracing program was to understand and characterize the flow of water through the Barton Springs Edwards Aquifer. As the groundwater tracing program progressed, the understanding of the aquifer has expanded by tracing more distal features in different watersheds, under differing hydrologic conditions and settings.

Figure 1. Location of the Barton Springs Edwards Aquifer (BSEA), Austin, Texas. The contributing area includes the area from the Blanco River (Hunt et al 2019).

Methods

Groundwater tracing studies use a non-reactive, non-toxic substance to trace the flow of water underground (Dole 1906, Smart 1988, Quinlan 1990, Hauwert et al 2004, Aley 2002). Fluorescent dyes are the most common type of groundwater tracer, and six dyes are the most commonly used: Eosine, Fluorescein (also called Uranine), Rhodamine WT, Sulforhodamine B, Pyranine, and Phloxine B. Each dye has slightly different properties making them better suited for varying conditions such as anticipated distance, velocity, sunlight exposure, and amount of sediment (Aley 2002, Smart and Laidlaw 1977). The tracer is usually mixed with a small amount

of water to facilitate mobility, and then poured into a recharge feature, stream, or location of geologic interest on the ground (Figure 2). A large volume of water (natural or artificial) is typically added to flush the tracer into the groundwater system. The overall process of pouring or placing tracer and flushing it underground with water is called a tracer injection.

Once the tracer is injected, monitoring commences to detect water with the tracer and identify groundwater outflow points. Monitoring sites such as springs, wells, and aquifer cave streams are chosen by proximity, geology, and anticipated groundwater flowpath for likely locations to detect the tracer in the water along the journey from the subsurface to the surface. In addition, wells and springs may be monitored to check if there are unknown or unexpected groundwater migration directions or to verify that an injection site is not within a suspected groundwater basin. Ideal detection sites will capture the majority of the tracer as it exits the aquifer, as well as define the boundaries of the groundwater basin. Samples collected at detection sites usually include water samples and passive receptors. Water samples provide an instantaneous concentration of the tracer in the water (Figure 3) and are the hallmark of quantitative dye trace studies. Passive receptors adsorb any tracer present in the water during the time that the receptor is submerged at the site and are critical qualitative tracing data. The fluorescent dyes used as tracers for the studies listed here are passively detected using activated charcoal receptors (Figure 4). Both water samples and passive receptors were analyzed at Ozark Laboratory following the procedures detailed in Aley (2015) or at the Edwards Aquifer Authority (EAA) following procedures outlined in Hunt et al (2013). Care was taken to prevent cross-contamination among samples, and quality control procedures were followed according to agency standards.

Details about the methods for each phase of tracing can be reviewed in the project reports (Hauwert et al 2004, Hunt et al 2005, Smith et al 2006, Hauwert 2012, Johnson et al 2012, Hunt et al 2013, Vasquez 2014, Zappitello and Johns 2018b, BSEACD 2019). Barton Springs discharge is provided as a relative indicator of aquifer conditions. The variation in Barton Springs discharge, as reported by the US Geological Survey, during time periods of groundwater tracing studies is displayed in Figure 5.

Figure 2. Example of pouring tracer into a recharge feature while adding flush water from a fire hose.

Figure 3. Example of a water sample collected at a spring.


Figure 4. Example of a charcoal receptor being collected from a spring.

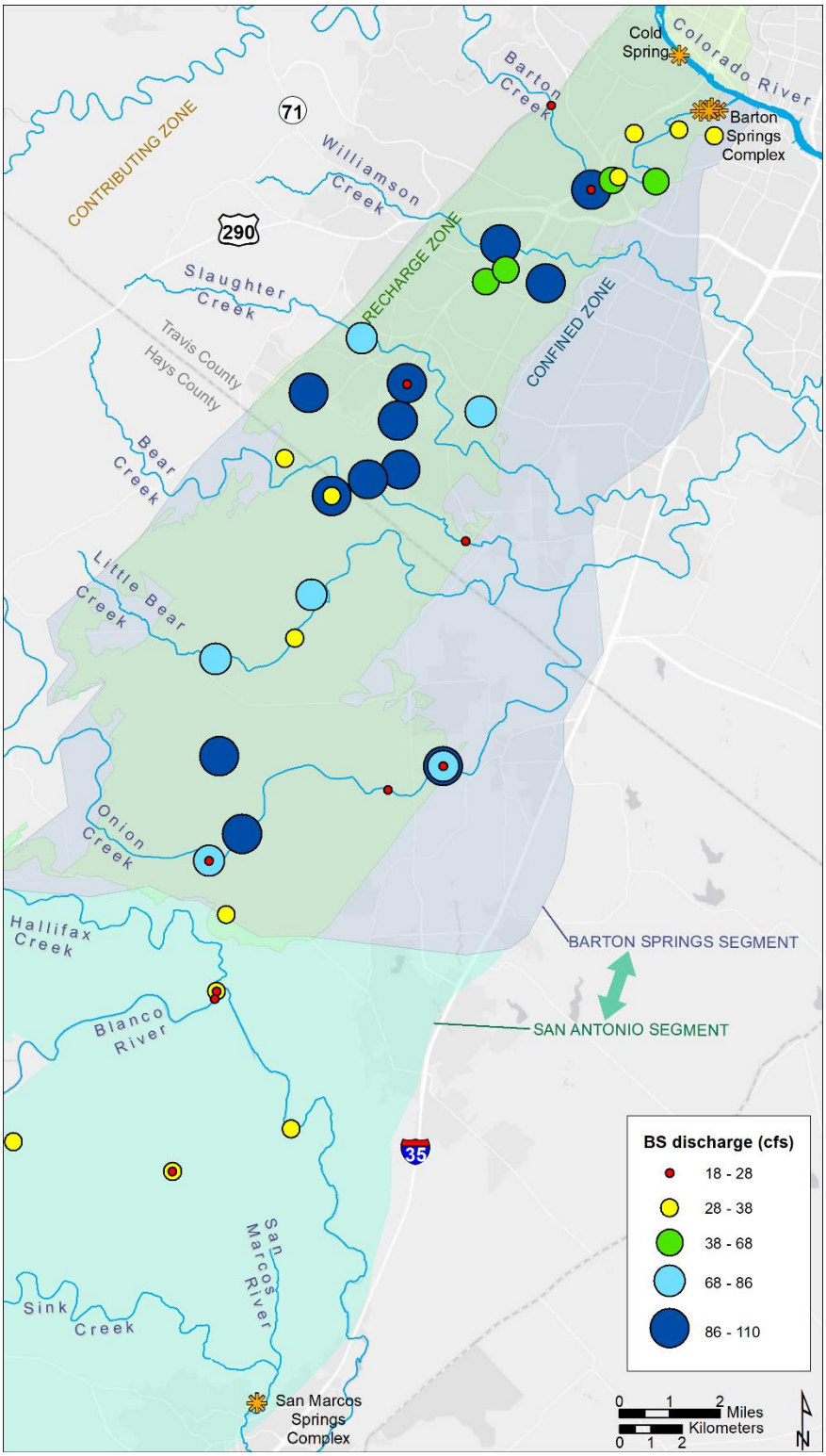

Figure 5. Barton Springs (BS) discharge in cubic feet per second (cfs) at time of injection for groundwater tracing studies, as summarized below. Symbols are shown at injection sites to represent the geographic distribution of studies during various aquifer conditions.

Results

Results of groundwater tracing studies from 1996 through 2017 are presented in Table 1. Those results are summarized in map form in Figure 6 - 18. Figure 19 summarizes all the traces and travel times. Figure 20 shows the flow paths and groundwater basins and divides.

Table 1. Summary of Barton Springs Edwards Aquifer groundwater tracing studies with a focus on studies detected at major springs. Modified and updated from Hauwert (2009).

Site Name	**Site Type**	**Watershed**	**Injection Date**	**Injection Time**	**Tracer**	**Tracer Mass** (lbs "as sold")	**Flush Water Volume** (gallons)	**First Detection at Discharge** (days)	**Min Distance to Detection** (miles)	**Tracer Discharge Spring(s)**	**Initial Velocity** (ft/day)	**Mass Recovery**	**Barton** Sp. Flow (cfs)	**Report Source**
1996														
Mopac Bridge	Creek channel sinkhole	Barton Creek	8/13/1996	9:00	Rhodamine WT	10	8,000	5	3.4	Cold	3,700	59%	18	Hauwert et al 2004
Mount Bonnell Sink	Creek channel sinkhole	Barton Creek	8/13/1996	12:00	Fluorescein	10	~8,000	6	2.7	Cold	3,700	Low	18	Hauwert et al 2004
1997														
Mopac Bridge	Creek channel sinkhole	Barton Creek	8/5/1997	15:20	Eosine	5	25,000	0.79	3.4	Cold	22,700	77%	107	Hauwert et al 2004
Dry Fork Sink	Creek channel sinkhole	Williamson Creek	6/17/1997	9:00	Fluorescein	3	3,000	<1.25	4.8	Barton	>21,100	4.2%	101	Hauwert et al 2004
Brush Country Road	Monitoring well	Williamson Creek	6/24/1997	9:20	Rhodamine WT	10	200	<8	5.3	Cold	>3,700	--	110	Hauwert et al 2004
1999a														
Brodie Sink	Creek channel sinkhole	Slaughter Creek	4/27/1999	11:00	Eosine	7	unknown	1-2	8.6	Barton	22,700 - 45,400	7.4%	83	Hauwert et al 2004
Midnight Cave	Upland cave	Slaughter Creek	4/27/1999	14:00	Rhodamine WT	5	unknown	7-8	11	Barton	7,900	16.6%	83	Hauwert et al 2004
Whirlpool Cave	Creek channel sinkhole	Williamson Creek	6/16/1999	15:35	Eosine	5	11,000	3-4	5.6	Barton	7,400 - 10,000	0.07%	68	Hauwert et al 2004
Westhill Drive	Creek channel sinkhole	Barton Creek	6/16/1999	19:00	Sulfo-rhodamine B	2	creekflow	0.4	2	Barton	26,400	7%	68	Hauwert et al 2004
1999b														
Hobbit Hole	Upland sinkhole	Bear Creek	9/28/1999	16:40	Fluorescein	5	~10,000	not recovered	--	--	--	0%	37	Hauwert et al 2004
Spillar Ranch Sink	Upland sinkhole	Bear Creek	9/28/1999	14:10	Rhodamine WT	10	10,000	wells only	--	--	--	0.0002%	37	Hauwert et al 2004
Dahlstrom Cave	Upland cave	Little Bear Creek	9/28/1999	10:45	Eosine	10	~10,000	21	14.9	Barton	3,700 - 5,800	0.7%	37	Hauwert et al 2004
2000a														
Antioch Cave	Creek channel sinkhole	Onion Creek	3/28/2000	10:35	Rhodamine WT	20	30,000	wells only	--	--	--	<0.0001 %	26	Hauwert et al 2004

Site Name	Site Type	Watershed	Injection Date	Injection Time	Tracer	Tracer Mass (lbs "as sold")	Flush Water Volume (gallons)	First Detection at Discharge (days)	Min Distance to Detection (miles)	Tracer Discharge Spring(s)	Initial Velocity (ft/day)	Mass Recovery	Barton Sp. Flow (cfs)	Report Source
Barber Falls	Creek channel sinkhole	Onion Creek	3/29/2000	9:00	Fluorescein	10	30,000	14-16	15.7	Barton	5,300	0.04%	26	Hauwert et al 2004
Marbridge Sink	Creek channel sinkhole	Bear Creek	3/28/2000	12:30	Eosine	20	10,000	36-43	11	Barton	1,600	<0.001%	26	Hauwert et al 2004
2000b														
Loop 360	Creek channel	Barton Creek	6/23/2000	10:00	Pyranine	5	creekflow	<2	3.3	Cold	>9,000	1.1%	61	Hauwert et al 2004
Tarbutton Cave	Creek channel sinkhole	Blanco River	8/3-5/2000	13:30	Fluorescein	15	10,000	not recovered	--	--	--	0%	29	Hauwert et al 2004
Crooked Oak Cave	Creek channel sinkhole	Onion Creek	8/12/2000	9:55	Eosine	25	12,000	23	18	Barton	4,200	13%	28	Hauwert et al 2004
Recharge Sink	Creek channel sinkhole	Slaughter Creek	10/6/2000	14:30	Sulfo-rhodamine B	12	10,000	not recovered	--	--	--	0%	24	Hauwert et al 2004
Antioch Cave	Creek channel sinkhole	Onion Creek	11/21/2000	11:30	Rhodamine WT	24	creekflow	wells only	--	--	--	<0.001%	81	Hauwert et al 2004
2002														
Antioch Cave	Creek channel sinkhole	Onion Creek	8/2/2002	11:30	Fluorescein	25	creekflow	7.1	14	Barton	10,600	0.8%	98	Hunt et al 2005
Crippled Crawfish Cave	Creek channel sinkhole	Onion Creek	8/6/2002	12:00	Eosine	35	creekflow	3.5	17.5	Barton	26,400	1.3%	99	Hunt et al 2005
2005														
Hoskins Hole Cave	Upland sinkhole	Onion Creek	5/4/2005	12:00	Sulfo-rhodamine B	35	2,700	not recovered	--	--	--	0%	104	Smith et al 2006
Crippled Crawfish Cave	Creek channel sinkhole	Onion Creek	5/4/2005	15:00	Eosine	35	creekflow	2.4 / 20	17.5	Barton/San Marcos	39,000	5.2%	104	Smith et al 2006
HQ Flat Sink	Upland sinkhole	Slaughter Creek	5/5/2005	9:00	Rhodamine WT	30	3,500	4.1	9.5	Barton	12,100	41.7%	103	Smith et al 2006
Spillar Sink	Upland sinkhole	Bear Creek	5/5/2005	13:15	Fluorescein	20	3,000	3.3	11.5	Barton	18,500	10.1%	103	Smith et al 2006
2006														
Saline Well	Well	Barton Creek	3/31/2006	9:05	Sulfo-rhodamine B	10	450	not recovered	--	--	--	--	39	BSEACD 2019
2007														
Hang Tree Sink	Upland sinkhole	Slaughter Creek	4/10/2007	9:10	Eosine	30	7,030	3-4	14	Barton	24,600	<4%	96	Hauwert 2012
Sand Burr Sink	Upland sinkhole	Bear Creek	4/11/2007	11:00	Rhodamine WT	45	16,000	2.9	11	Barton	20,000	4%	96	Hauwert 2012
Tabor Dam	Creek channel	Bear Creek	5/1/2007	13:30	Fluorescein	5	creekflow	2	12	Barton	31,700	45%	96	Hauwert 2012
Wildflower Cave	Upland cave	Slaughter Creek	4/9/2007	10:00	Sulfo-rhodamine B	30	7,163	2.5	10	Barton	21,100	22%	96	Hauwert 2012
2008-2009														
Bull Pasture Sink	Upland sinkhole	Onion Creek	5/20/2008	12:20	Fluorescein	0.24	10,000	not recovered	--	--	--	0%	38	Johnson et al 2012

Site Name	Site Type	Watershed	Injection Date	Injection Time	Tracer	Tracer Mass (lbs "as sold")	Flush Water Volume (gallons)	First Detection at Discharge (days)	Min Distance to Detection (miles)	Tracer Discharge Spring(s)	Initial Velocity (ft/day)	Mass Recovery	Barton Sp. Flow (cfs)	Report Source
Bull Pasture Sink	Upland sinkhole	Onion Creek	6/10/2008	--	Fluorescein	30	10,000	106-113	19	Barton	950	<0.001%	31	Johnson et al 2012
Halifax Creek Sink	Creek channel sinkhole	Blanco River	5/20/2008	13:10	Eosine	0.22	unknown	not recovered	--	--	--	0%	38	Johnson et al 2012
Halifax Creek Sink	Creek channel sinkhole	Blanco River	5/21/2008	--	Eosine	0.23	unknown	wells only	--	--	--	0%	31	Johnson et al 2012
Halifax Creek Sink	Creek channel sinkhole	Blanco River	6/10/2008	13:10	Eosine	13	unknown	55	8.3	San Marcos	790	<0.001%	31	Johnson et al 2012
Halifax Creek Sink	Creek channel sinkhole	Blanco River	9/12/2008	10:00	Eosine	13	unknown	82-122 /19	20 / 8.3	Barton / San Marcos	850/2300	<0.001%	25	Johnson et al 2012
Fritz Cave	Upland cave	Blanco River	5/21/2008	13:00	Phloxine B	0.23	"large"	not recovered	--	--	--	0%	38	Johnson et al 2012
Fritz Cave	Upland cave	Blanco River	6/11/2008	--	Phloxine B	3.13	"large"	wells only	--	--	--	0%	31	Johnson et al 2012
Fritz Cave	Upland cave	Blanco River	9/10/2008	13:30	Phloxine B	15	"large"	34	5	San Marcos	787	--	25	Johnson et al 2012
Johnson Swallet	Creek channel sinkhole	Blanco River	2/26/2009	11:00	Eosine	52.5	riverflow	36-78 /62	20 / 8	Barton / San Marcos	1400/ 690	<0.001%	19	Johnson et al 2012
2010														
Wildflower Cave	Upland cave	Slaughter Creek	5/24/2010	10:30	Sulfo-rhodamine B	33.5	10,300	17.7	10	Barton	3,000	5%	98	Hauwert 2012
2012														
Arbor Trails Sinkhole	Upland sinkhole	Williamson Creek	2/3/2012	13:00	Phloxine B	16.3	5000	<4	4.9	Barton	6,900	--	60	Hunt et al 2013
2014														
Antioch Cave	Creek channel sinkhole	Onion Creek	5/30/2014	--	Pyranine	10	creekflow	wells only	1.0	--	--	--	70	Vasquez 2014
2017														
Crooked Oak Cave	Creek channel sinkhole	Onion Creek	9/27/2017	10:30	Eosine	30	10000	4.2	18	Barton	22,700	44.69%	86	Zappitello and Johns 2018b
Fenceline Sink	Creek channel sinkhole	Little Bear Creek	9/27/2017	12:25	Rhodamine WT	30	10000	5	14.7	Barton	13,100	7.68%	86	Zappitello and Johns 2018b
Stoneledge Quarry	Quarry at aquifer level	Little Bear Creek	10/2/2017	9:50	Fluorescein	50	4500000 (pond)	6	12.5	Barton	13,300	0.17%	86	Zappitello and Johns 2018b

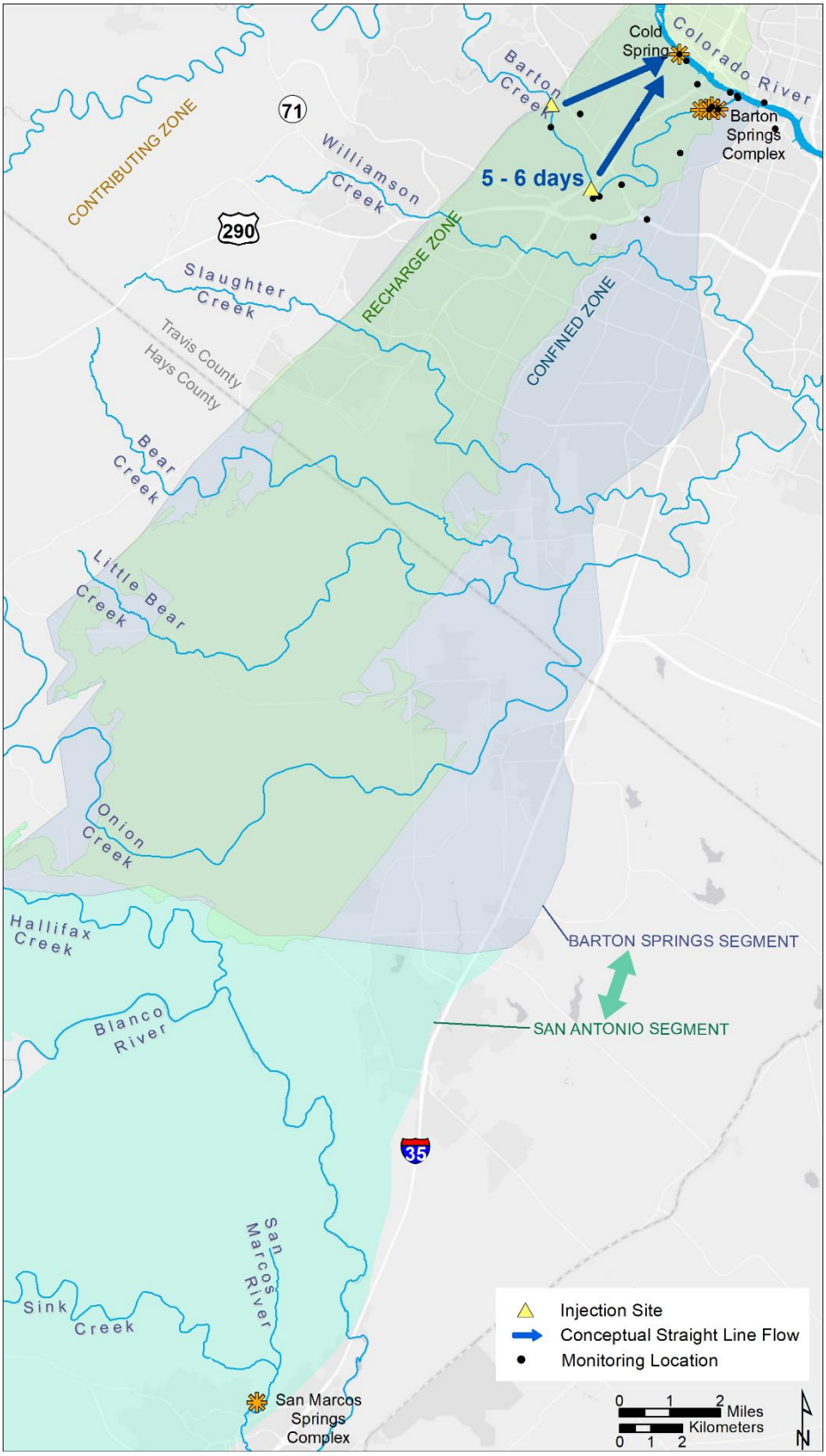

Figure 6. 1996 groundwater trace. Barton Springs discharge was 18 cfs.

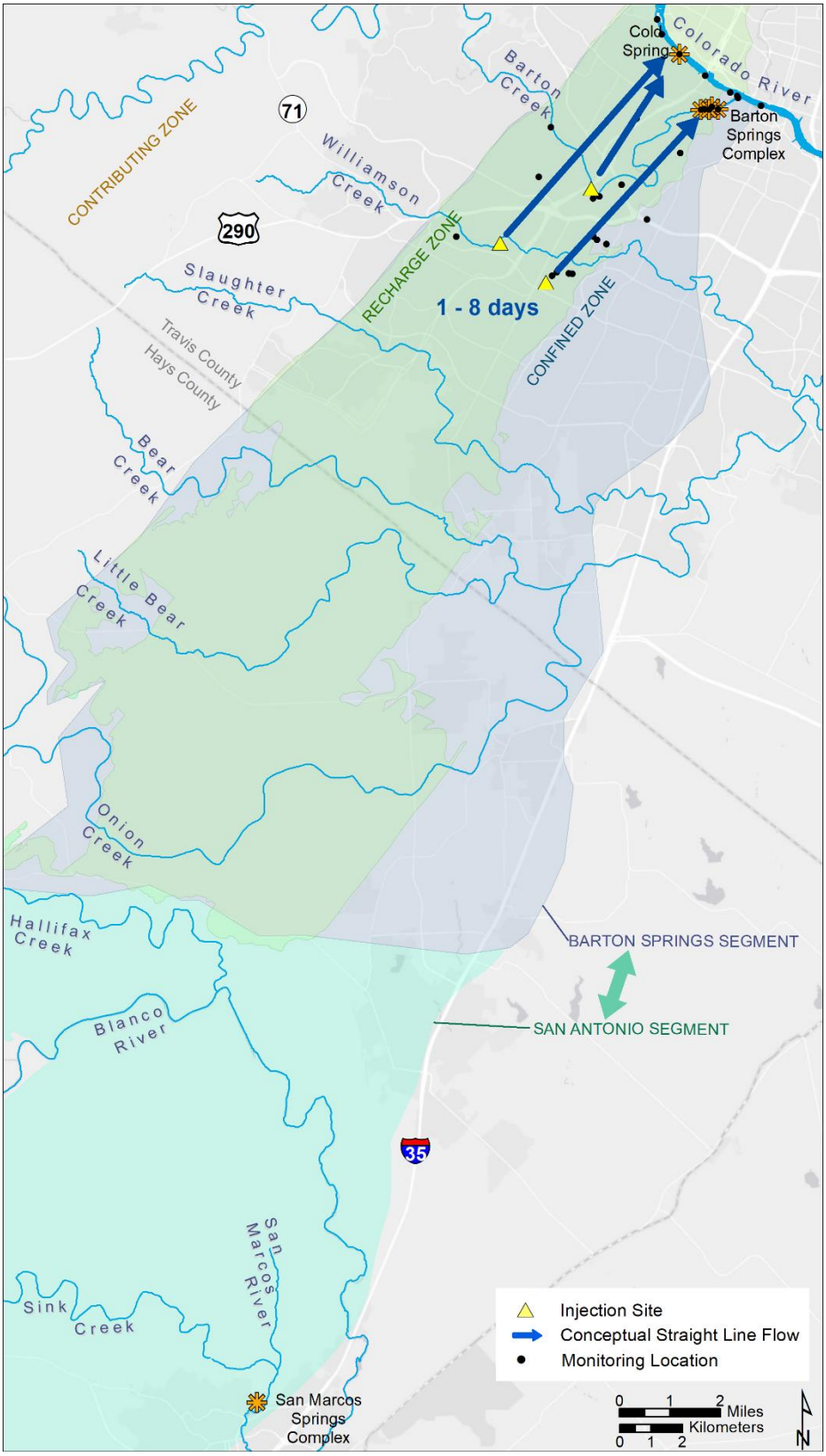

Figure 7. 1997 groundwater trace. Barton Springs discharge was 107 cfs.

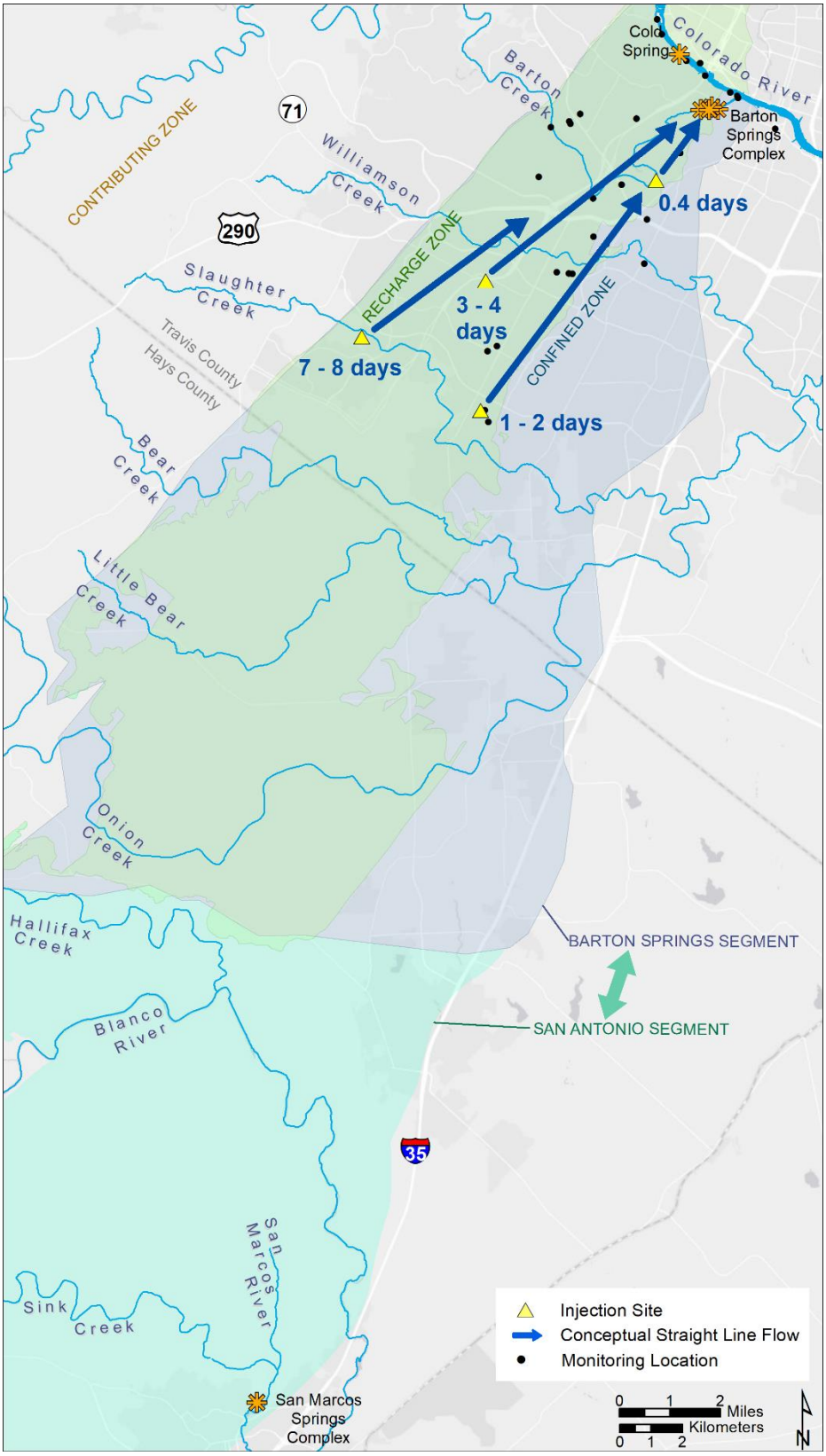

Figure 8. 1999 groundwater trace. Barton Springs discharge was 68-83 cfs.

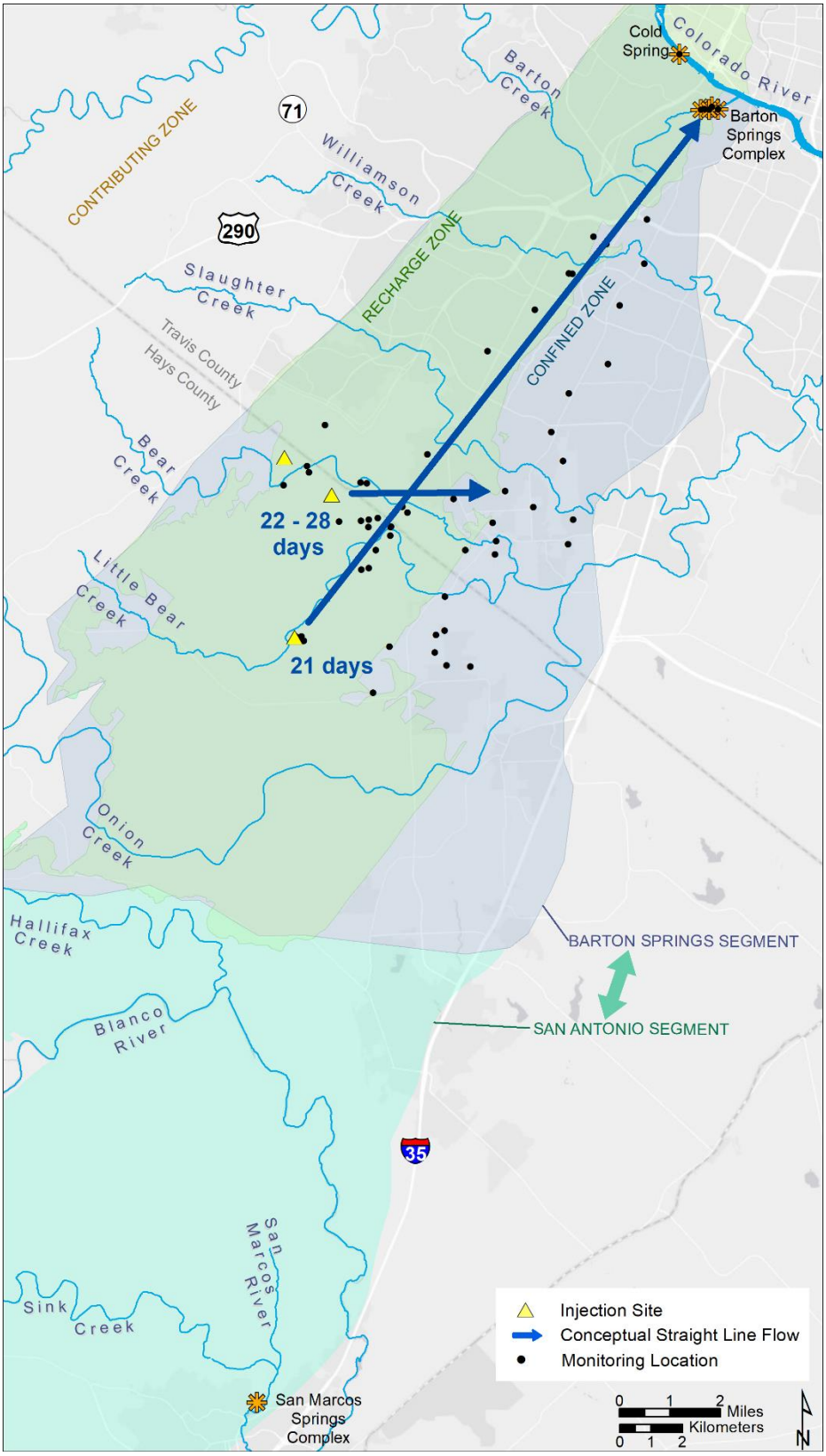

Figure 9. 1999 groundwater trace. Barton Springs discharge was 37 cfs.

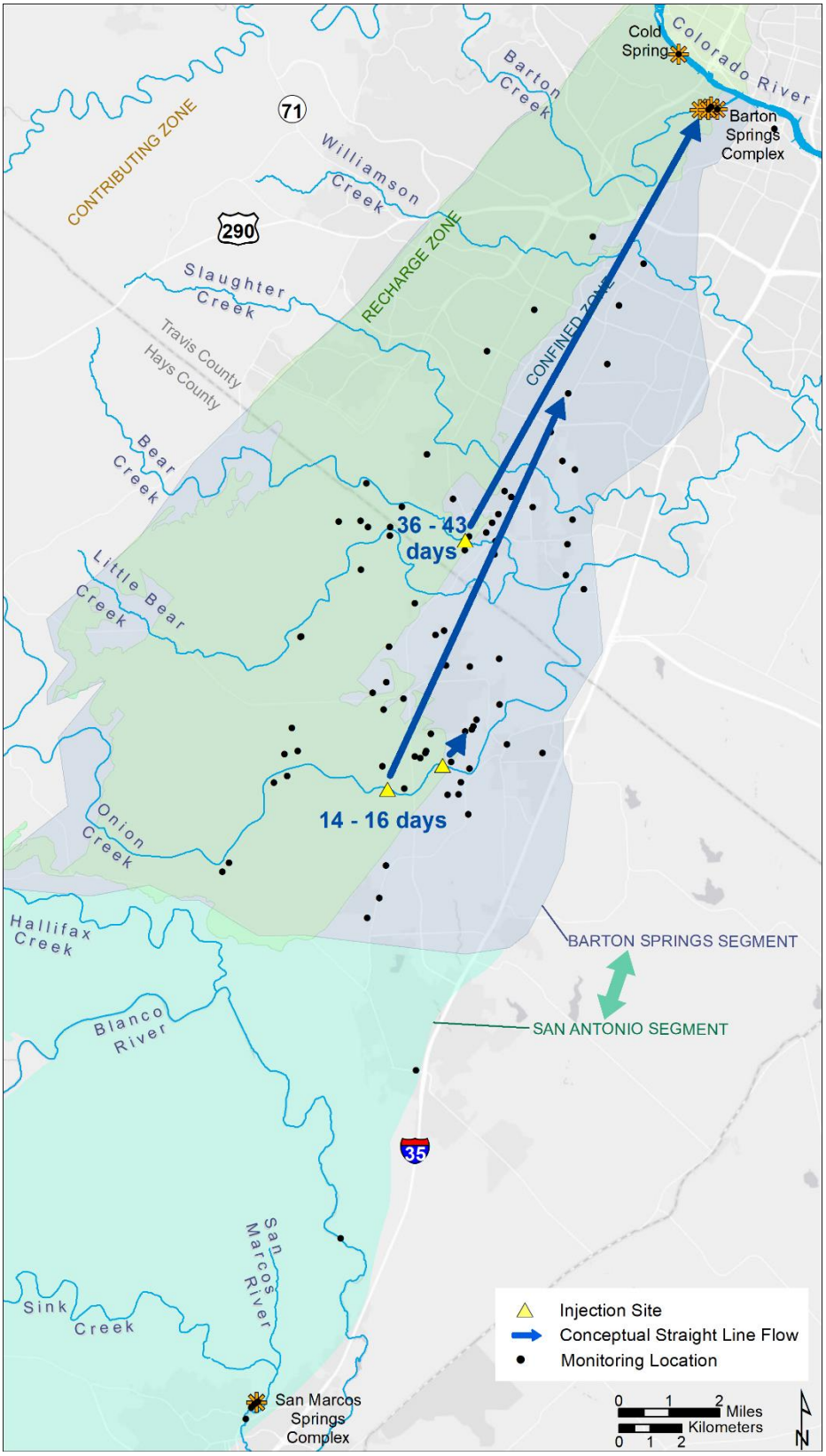

Figure 10. 2000a groundwater trace. Barton Springs discharge was 26 cfs.

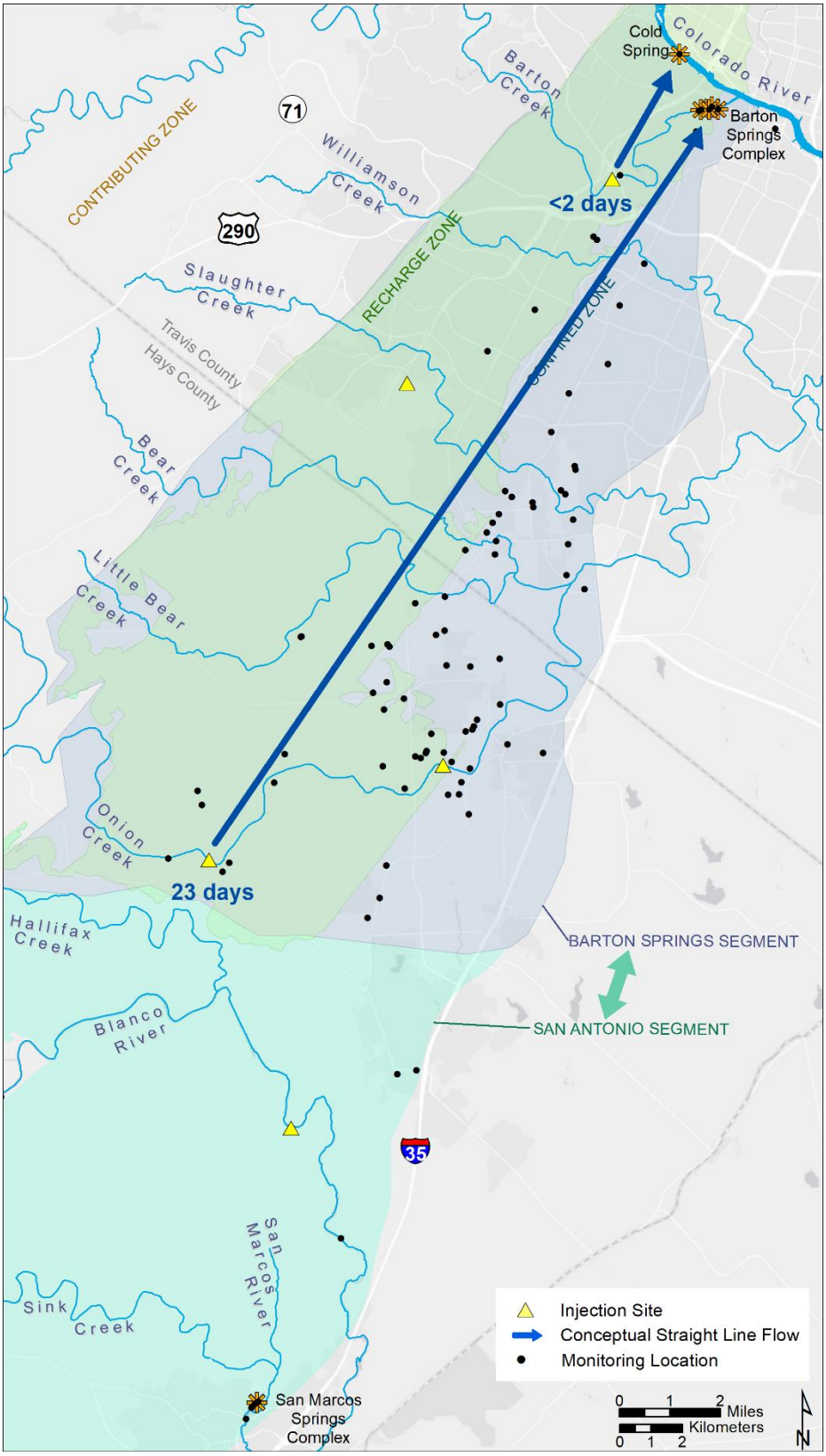

Figure 11. 2000b groundwater trace. Barton Springs was at 28-61 cfs.

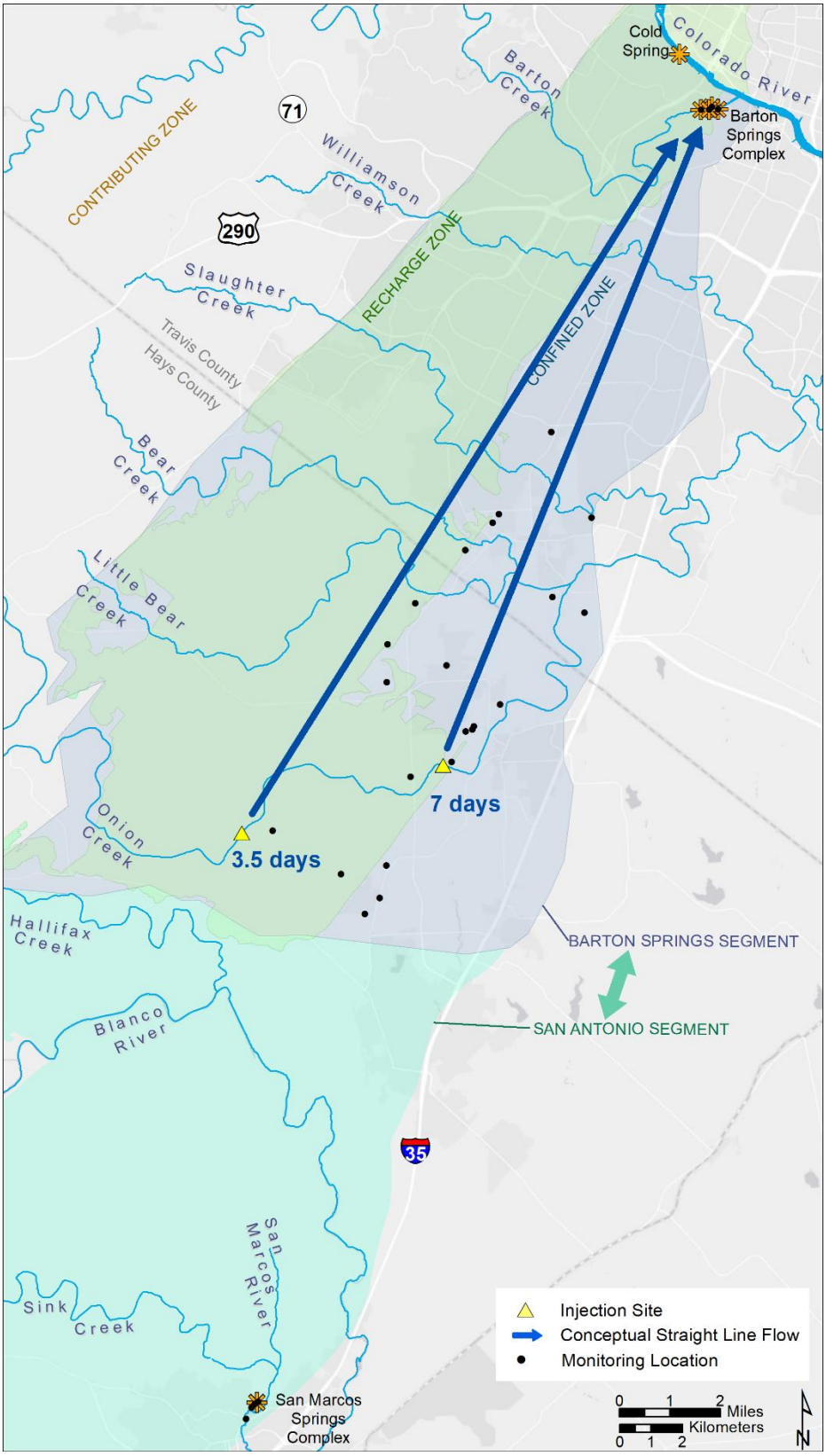

Figure 12. 2002 groundwater trace. Barton Springs was at 98 cfs.

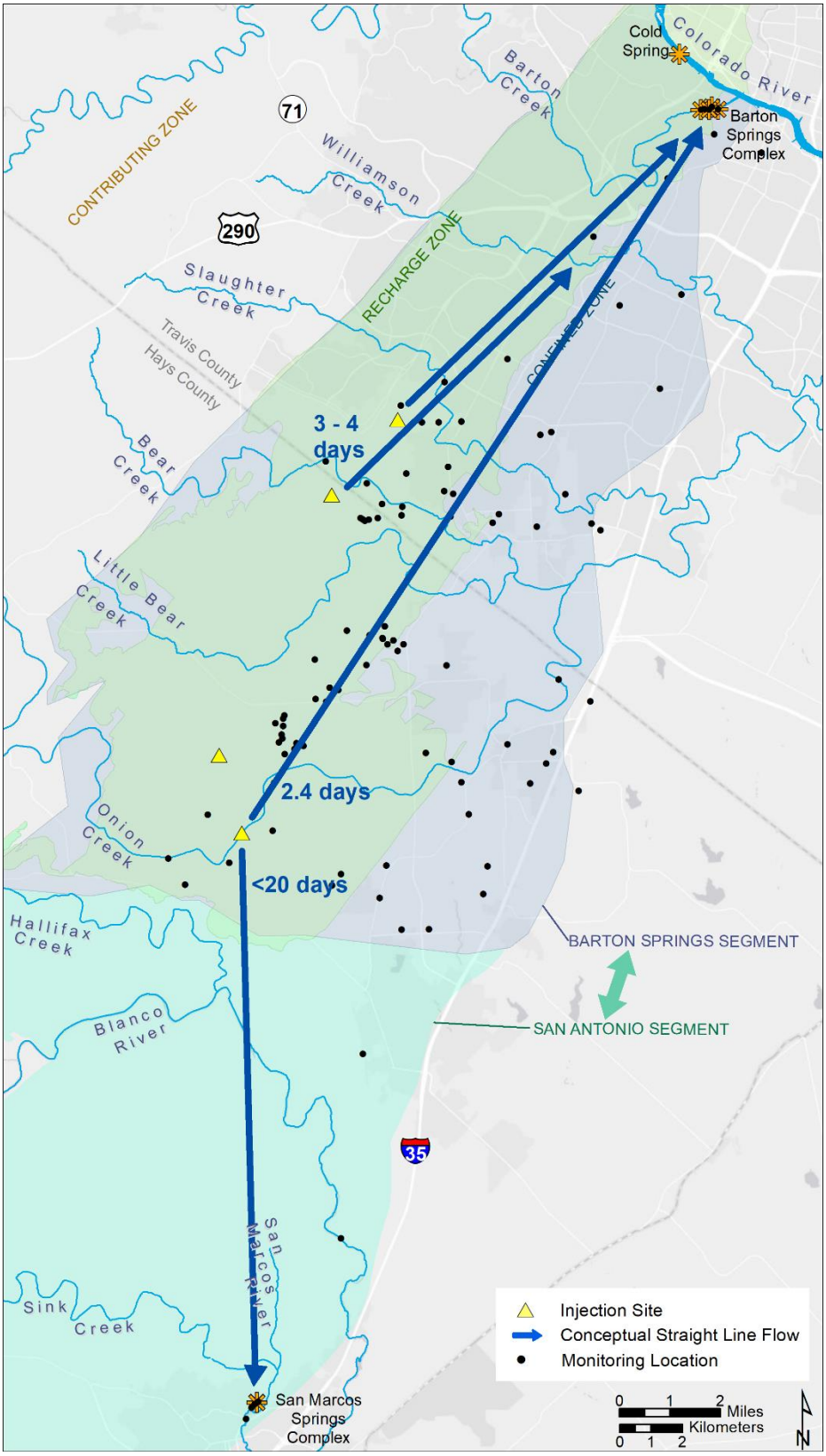

Figure 13. 2005 groundwater trace. Barton Springs discharge was at 104 cfs.

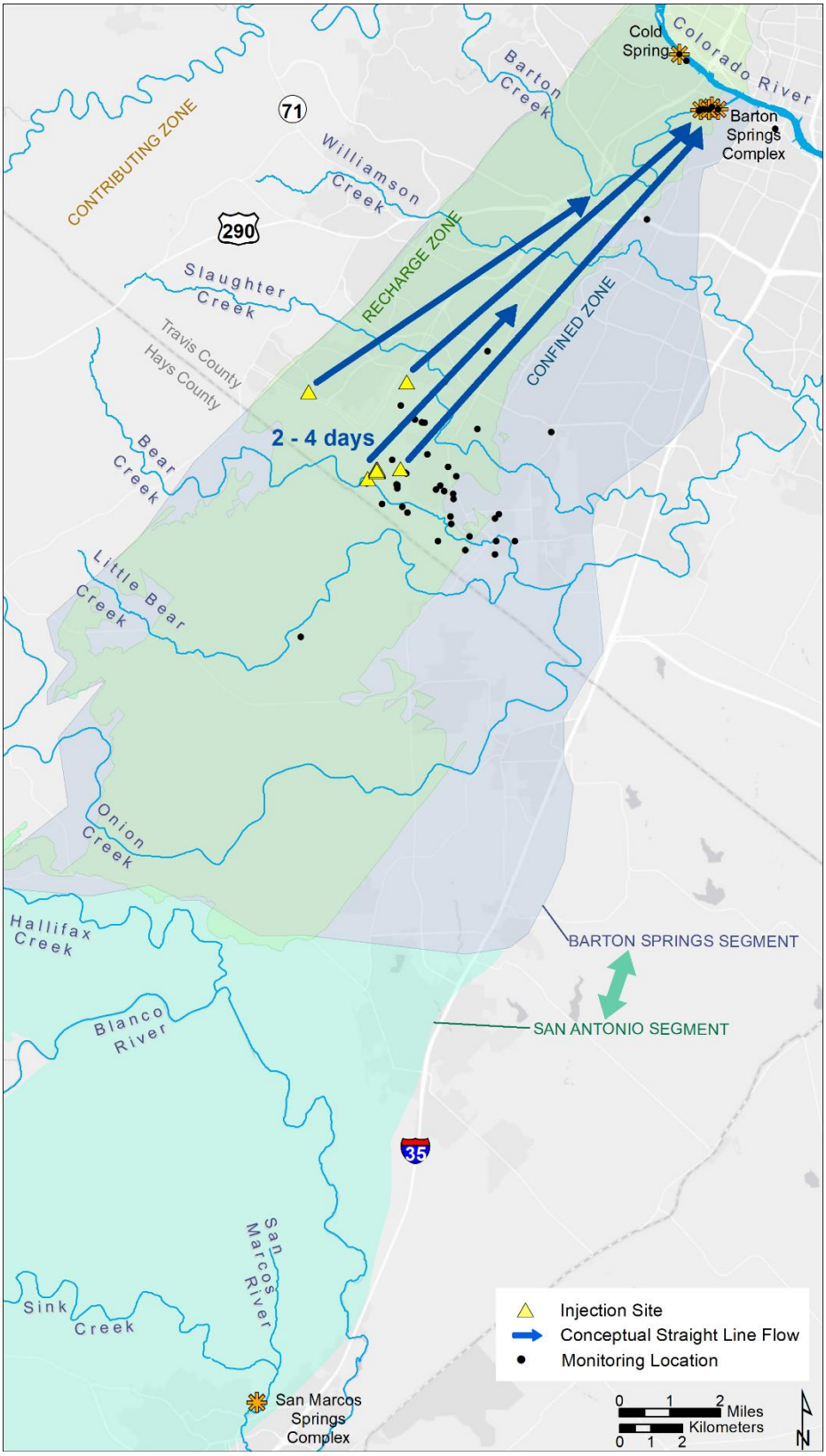

Figure 14. 2007 groundwater trace. Barton Springs discharge was at 96 cfs.

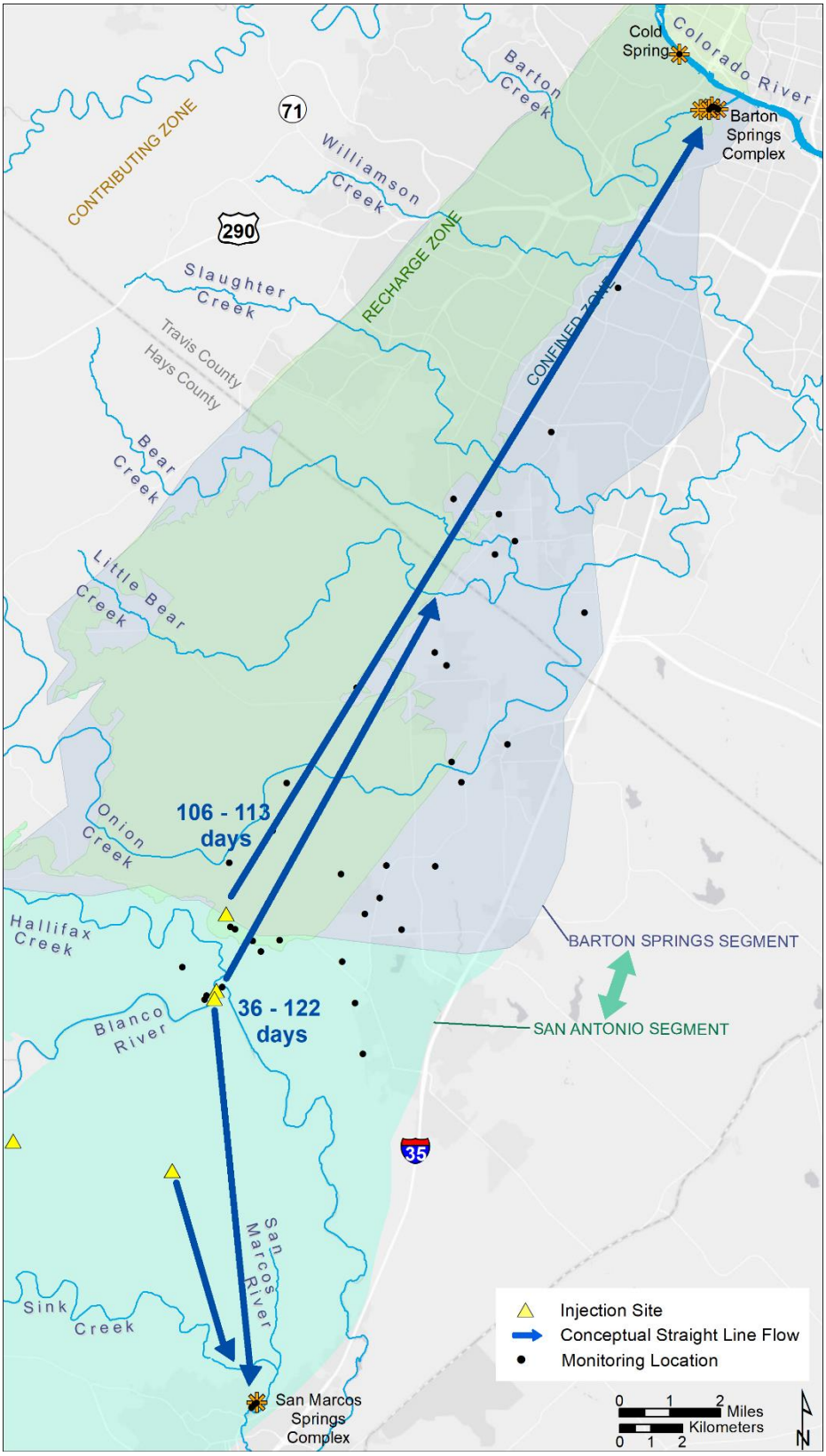

Figure 15. 2008-2009 groundwater trace. Barton Springs discharge was at 19-38 cfs.

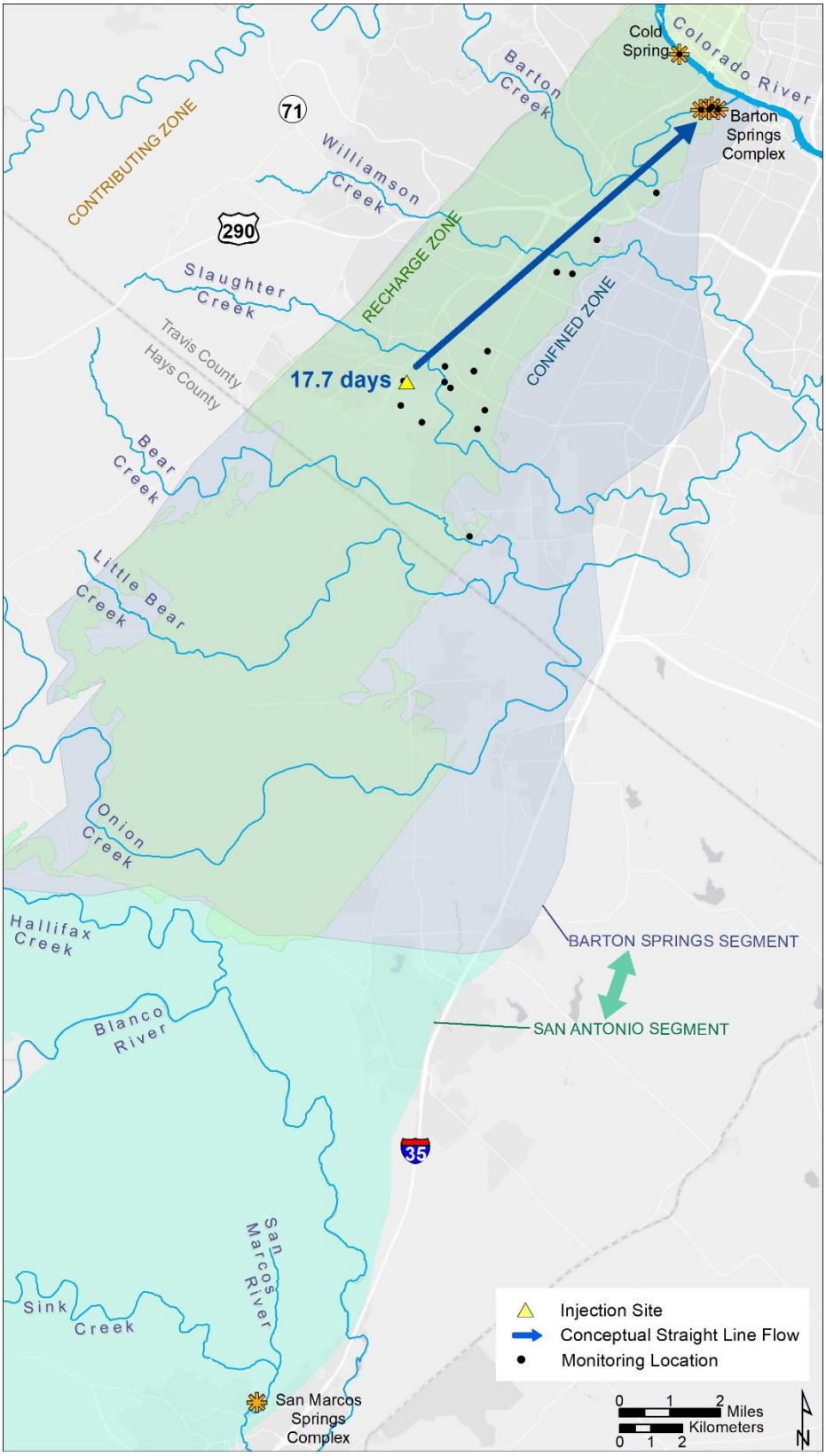

Figure 16. 2010 groundwater trace. Barton Springs discharge was at 98 cfs.

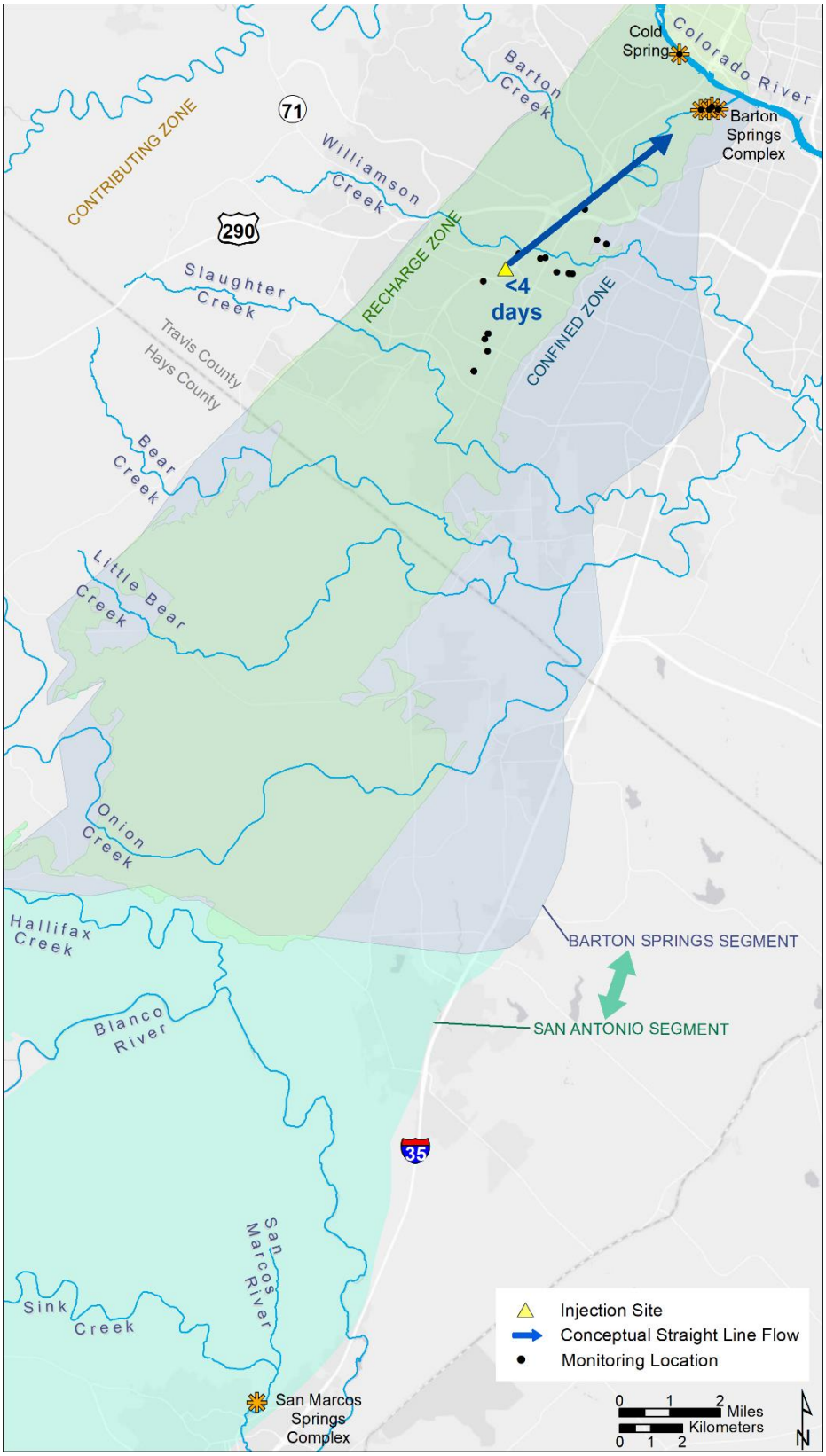

Figure 17. 2012 groundwater traces. Barton Springs discharge was at 24-60 cfs.

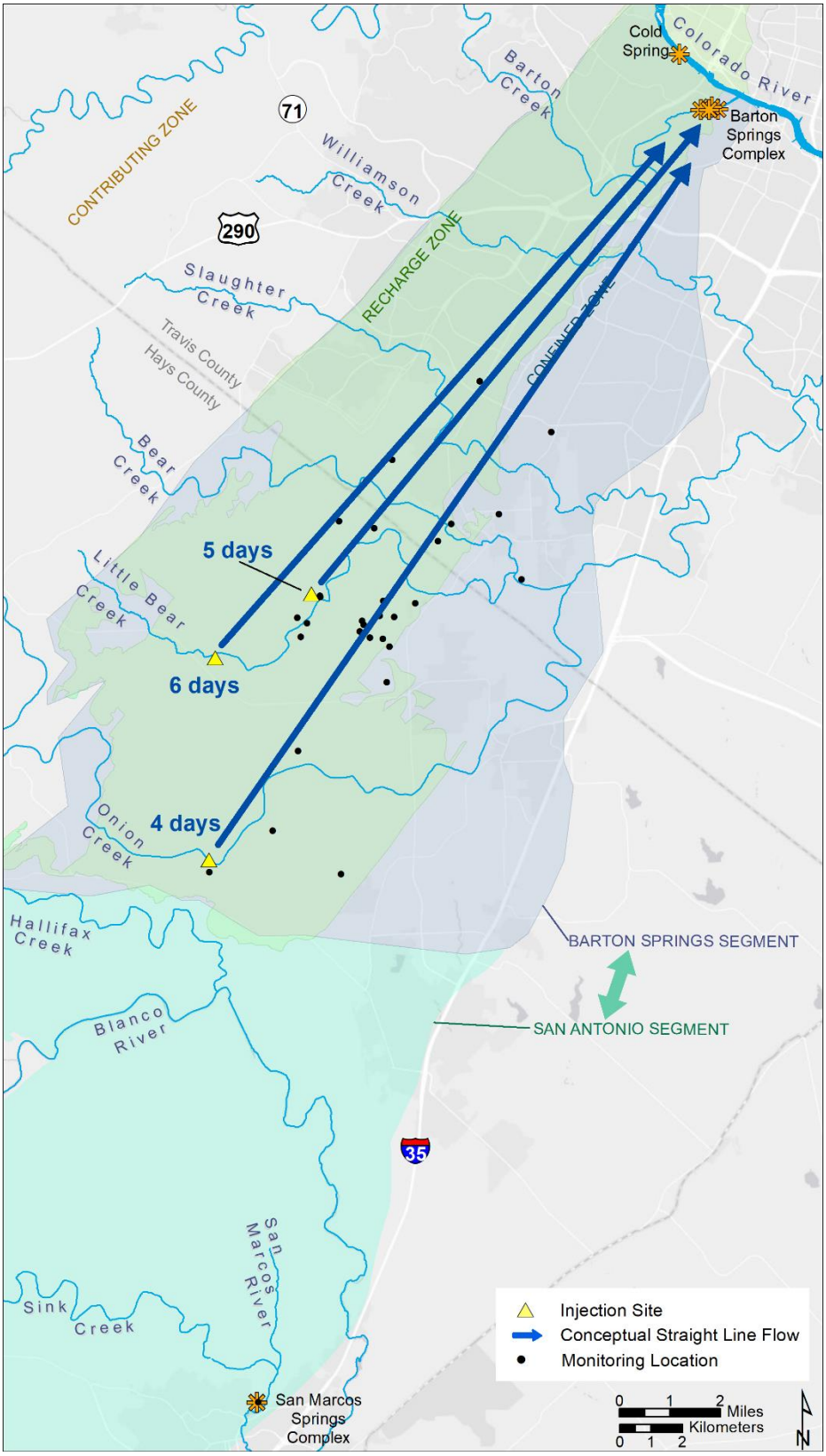

Figure 18. 2017 groundwater trace. Barton Springs discharge was at 86 cfs.

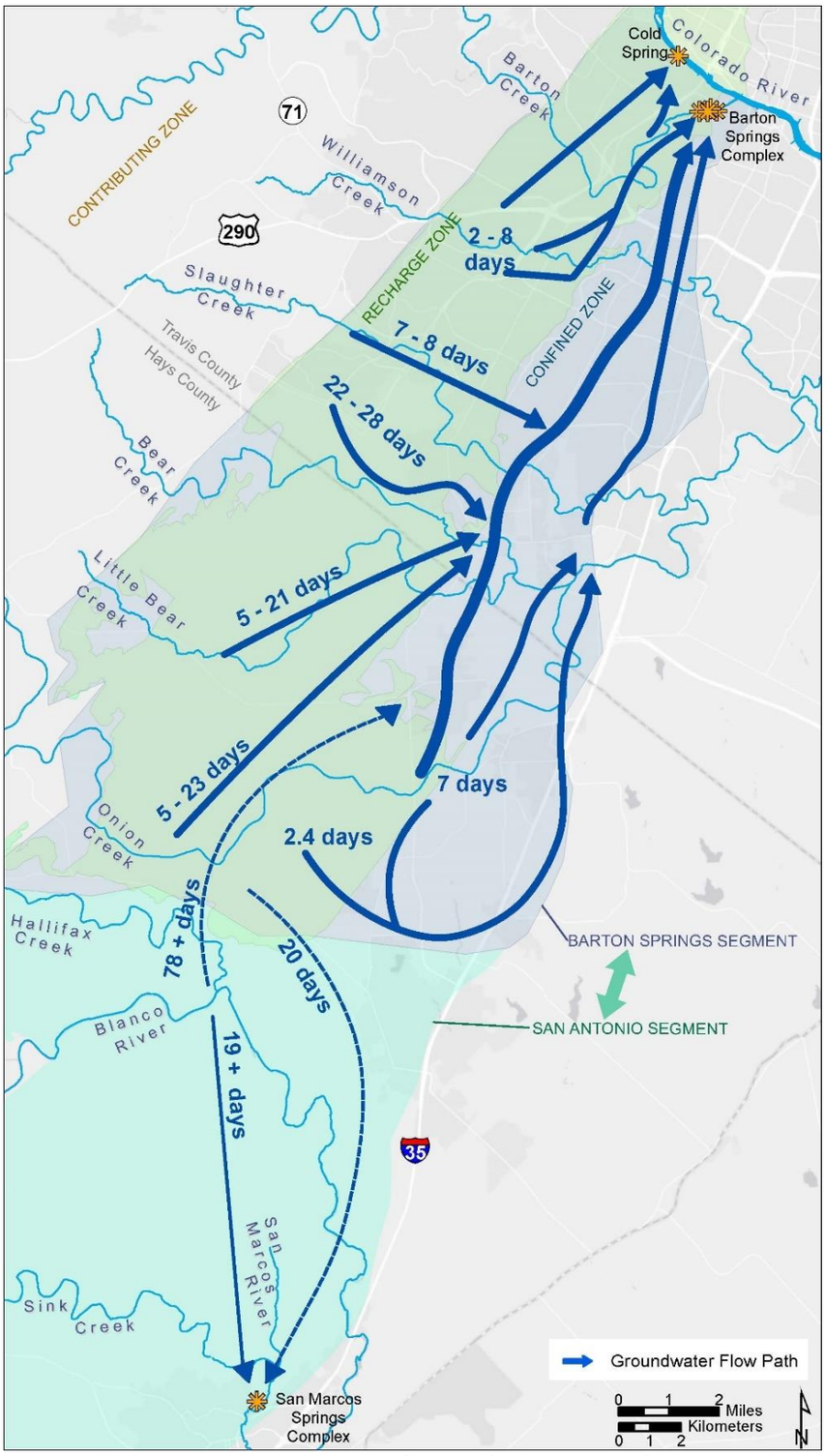

Figure 19. Summary map of groundwater flow times in the Barton Springs Segment of the Edwards Aquifer. Flowpaths adapted from (Hauwert et al 2004, Hunt et al 2005, Smith et al 2006, Hauwert 2009, Smith et al 2012, Hauwert 2012, Hunt et al 2013, Smith et al 2017, Zappitello and Johns 2018b). The boundary between the Barton Springs segment and the San Antonio segment of the Edwards Aquifer varies under different aquifer conditions. The dashed flow paths represent groundwater tracing results that have crossed the groundwater divide.

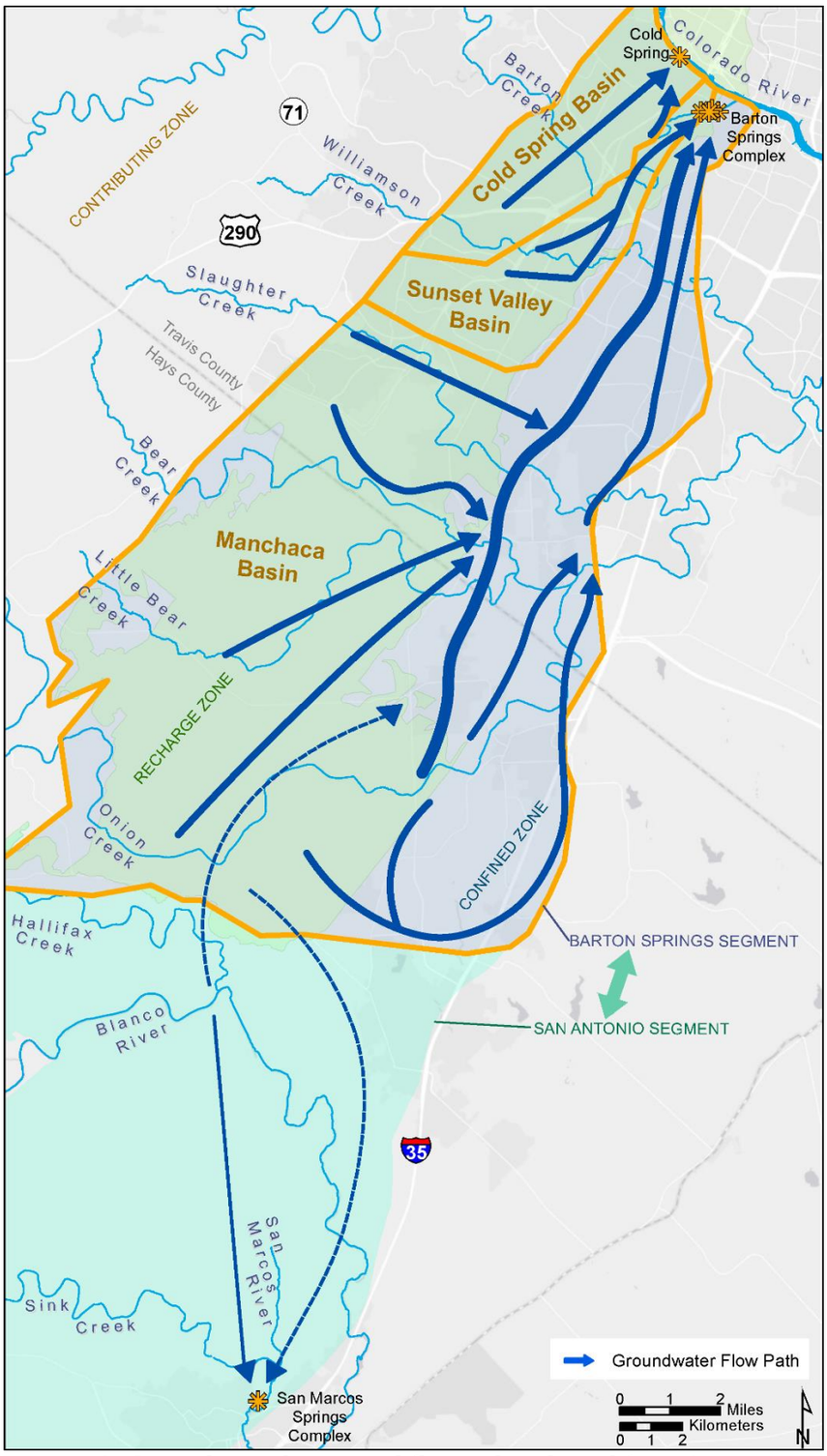

Figure 20. Groundwater basins and flowpaths adapted from (Hauwert et al 2004, Hunt et al 2005, Smith et al 2006, Hauwert 2009, Smith et al 2012, Hauwert 2012, Hunt et al 2013, Zappitello and Johns 2018b). The boundary between the Barton Springs segment and the San Antonio segment of the Edwards Aquifer varies under different aquifer conditions. The dashed flow paths represent groundwater tracing results that have crossed the groundwater divide.

Discussion and Conclusions

During the initial years of groundwater tracing in the Barton Springs Edwards Aquifer, scientists studied the creeks, watersheds, and recharge features closest to Barton Springs. In many cases, the results were surprising, and water flowed faster than expected from the recharging injection sites to the springs. As more was learned about the aquifer system and the speed of water flow underground, study sites were selected further from the springs. Eventually the groundwater studies demonstrated that water flowed to the springs consistently from across six distinct recharging watersheds (Barton, Williamson, Slaughter, Bear, Little Bear, and Onion Creeks), and under low-flow aquifer conditions from a seventh watershed 20 miles away (Blanco River) (Hauwert et al 2004, Hunt et al 2005, Smith et al 2006, Hauwert 2012, Johnson et al 2012, Smith et al 2012, Hunt et al 2013, Zappitello and Johns 2018b). Although Williamson, Slaughter, Bear, and Little Bear Creeks eventually contribute to Onion Creek, this occurs downstream of the recharge zone, so their contributing watersheds over and upstream of the recharge zone are separate. Understanding the sources of water allows the City of Austin to better protect Barton Springs and respond more effectively in case of a pollution event such as a spill. Understanding the aquifer functioning also helps the Barton Springs Edwards Aquifer Conservation District manage the resource as a water supply and a habitat for endangered species (Hunt et al., 2019).

Aquifer dynamics such as the speed of water flow and the direction of flow near groundwater basin boundaries vary with aquifer levels, represented here by Barton Springs discharge rates (Figure 5). Continuing to track and evaluate the state of knowledge about aquifer flowpaths under different aquifer conditions is important to the future management of this resource, since karst aquifers respond quickly (hours to days) to changing conditions like storms and point-source pollution and respond slowly (months to years) to the impacts of changes like drought, climate change, and increasing development. Scientific studies that are comprehensive and reproducible maximize our ability to protect and manage natural resources. These summary figures are also useful as education tools to communicate scientific knowledge to our peers and the public.

The City of Austin and the Barton Springs Edwards Aquifer Conservation District have been partners in dye tracing studies of groundwater in the Barton Springs Edwards Aquifer since 1996 (>20 years). The studies have fine-tuned our understanding of aquifer behavior. The conditions within the aquifer are naturally dynamic and vary based on influences from precipitation, drought, well pumping, and land management. Robust conceptual models of the aquifer rely on groundwater traces that are repeatable and thoroughly characterize the flow-paths at various aquifer conditions. Groundwater tracing is fundamental to understanding flow systems within karst limestone aquifers. These summary maps will help planners, regulators, managers, and scientists preserve and protect the resource and plan for future groundwater tracer studies to further refine our understanding.

Recommendations and Future Work

Additional groundwater traces under differing flow conditions and aquifer potentiometric surface conditions may allow refinement of groundwater basin boundaries. Groundwater tracing at selected sites during storm conditions will continue to refine our understanding of the rates of

aquifer flow during varying conditions. In addition, groundwater tracing from proposed sinkhole mitigation sites may help demonstrate the water quality benefits of proposed projects. While mass recovery calculations are available in the primary project reports, it may be informative to recalculate the recovery percentages to ensure the use of consistent methodology for comparative purposes.

Dye tracing has increasingly been applied to portions of the karst Trinity Aquifer located upgradient and stratigraphically below the Edwards Aquifer in central Texas (Smith et al., 2018). Results of those traces indicate similar rapid velocities. Tracer testing of the hydraulic connection between units in the Trinity Aquifer and the Edwards Aquifer has been established in the San Antonio segment (Johnson et al 2019). Tracer testing of the Trinity Aquifer and Barton Springs Edwards Aquifer connection would be a good candidate for future studies.

While the most common tracer tests use fluorescent organic dyes, there are a number of additional materials and technologies that could be used to trace the flow of groundwater (such as salts, isotopes, and DNA). In addition, contaminants have acted as inadvertent tracers, and when spills occur, could be analyzed as such (Hunt and Smith 2014, Sydow et al 2019, Zappitello et al 2019).

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