VOLUME II - APPENDICES
Regional Habitat Conservation Plan For Groundwater Use and Management of the Barton Springs Segment of the Edwards Aquifer

Applicant:
Barton Springs/Edwards Aquifer Conservation District

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For:
U.S. Fish & Wildlife Service

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Appendices (Volume II)

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APPENDIX A

Species of Greatest Conservation Need in the Planning Area, by Ecoregion

SPECIES OF GREATEST CONSERVATION NEED IN PLANNING AREA

Source: Texas Parks and Wildlife Department, Texas Conservation Action Plan: http://www.tpwd.state.tx.us/landwater/land/tcap/sgcn.phtml, Accessed January 5, 2014

SPECIES OF GREATEST CONSERVATION NEED: EDWARDS PLATEAU ECOREGION

Scientific Name	**Common Name**	**Status**		**Abundance Ranking**		**General Habitat Type(s) in Texas These are VERY broad habitat types as a starting place**	**Other Notes**	**Endemic in Texas**
		Federal	**State**	**Global**	**State Code**	**State of the practice resources are listed in each taxa line for more detailed information**		
MAMMALS						W.B. Davis and D.J. Schmidly. 1997 and 1994. Mammals of Texas (online and in print). Texas Tech University (1997) and Texas Parks and Wildlife Department (1994). http://www.nsrl.ttu.edu/tmot1/Default.htm (accessed 2011)		
Antrozous pallidus	Pallid bat			G5	S5	Caves/Karst, Desert scrub, Grassland, Shrubland		N
Conepatus leuconotus	Hog-nosed skunk			G5	S4	Shrubland, Savanna/Open Woodland, Barren/Sparse Vegetation,		N
Corynorhinus townsendii	Townsend's big-eared bat			G4T4	S3? S4?	Caves/Karst, Desert scrub, Grassland, Shrubland		N
Cynomys ludovicianus	Black-tailed prairie dog			G5T3	S3	Grassland		N
Eptesicus fuscus	Big brown bat			G5	S5	Forest, Barren/Sparse Vegetation, Caves/Karst, Artificial Refugia		N
Geomys texensis bakeri	Frio pocket gopher			G2QT2	S2	Riparian		N
Geomys texensis texensis	Llano pocket gopher			G3T2	S2	Riparian		Y
Lutra canadensis	River otter			G5	S4	Riparian	Appendix II, CITES	N
Mormoops megalophylla	Ghost-faced bat			G4	S2	Desert Scrub, Riparian, Caves/Karst		N
Mustela frenata	Long-tailed weasel			G5	S5	Forest, Woodland, Desert Scrub, Shrubland, Savanna/Open Woodland	Statewide	N
Mustela nigripes	Black-footed ferret	LE		G1	SH	Grassland	Not listed endangered for TX; however if experimental populations are introduced in any ecoregion(s), black-footed ferret will have experimental population status in Texas	N
Myotis velifer	Cave myotis			G5	S4	Caves/Karst,		N

Nasua narica	White-nosed coati		T	G5	S2?	Forest, Desert Scrub, Riparian		N
Parastrellus hesperus	Canyon Bat (western pipistrelle)			G5	S5	Riparian, Barren Sparse Vegetation		N
Perimyotis subflavus	Tricolored Bat (eastern pipistrelle)			G5	S5	Caves/Karst, Artificial Refugia, Woodland		N
Puma concolor	Mountain lion			G5	S2	Forest, Woodland, Desert Scrub, Shrubland, Savanna/Open Woodland, Riparian	Statewide	N
Spilogale gracilis	Western spotted skunk			G5	S5	Agricultural, Grassland, Forest, Woodland, Desert Scrub		N
Spilogale putorius	Eastern spotted skunk			G4T	S4	Savanna/Open Woodland, Grassland		N
Sylvilagus aquaticus	Swamp rabbit			G5	S5	Riparian, Freshwater Wetland		N
Tadarida brasiliensis	Brazilian free-tailed bat			G5	S5	Cave/Karst, Artificial Refugia	Statewide	N
Taxidea taxus	American badger			G5	S5	Grassland, Desert scrub, Woodland, Savanna/Open Woodland, Forest		N
Ursus americanus	Black bear	SAT	T	G5	S3	Forest, Woodland, Savanna/Open Woodland, Desert Scrub, Shrubland	see also Louisiana black bear; may overlap with Louisiana black bear in TBPR, ECPL	N
Vulpes velox	Swift fox			G3	S3?	Grassland	common nomenclature change (2009)	N
BIRDS						The Birds of North America Online (A. Poole, Ed.). 2005 (with current updates by species). Retrieved from The Birds of North America Online database: http://bna.birds.cornell.edu/BNA/ (accessed 2011). Supported by information from the Cornell Lab of Ornithology and the American Ornithologists' Union (http://www.aou.org/).		BIRDS ONLY: instead of endemism these numbers are for taxonomic sorting
Colinus virginianus	Northern Bobwhite			G5	S4B	Grassland, Shrubland, Savanna/Open Woodland	deleted for CHIH	4
Cyrtonyx montezumae	Montezuma Quail			G4G5	S3B	Grassland, Shrubland	Year-round	5
Meleagris gallopavo	Wild Turkey			G5	S5B	Shrubland, Savanna/Open Woodland, Forest, Riparian, Agricultural	Year-round, added *merriami* for CHIH	8
Circus cyaneus	Northern Harrier			G5	S2B,S3N	Grassland, Shrubland	Year-round	23
Buteogallus anthracinus	Common Black-Hawk		T	G4G5	S2B	Woodland, Riparian	Breeding	24
Parabuteo unicinctus	Harris's Hawk			G5	S3B	Desert Scrub, Grassland, Shrubland	Year-round	25
Buteo lineatus	Red-shouldered Hawk			G5	S4B	Woodland, Forest, Riparian, Freshwater Wetland	Year-round	26
Buteo albonotatus	Zone-tailed Hawk		T	G4	S3B	Barren/Sparse Vegetation, Riparian	Breeding	30

Aquila chrysaetos	Golden Eagle			G5	S3B	Desert Scrub, Grassland, Shrubland	Year-round	32
Caprimulgus carolinensis	Chuck-will's-widow			G5	S3S4B	Woodland, Forest, Riparian	Breeding	66
Tyrannus forficatus	Scissor-tailed Flycatcher			G5	S3B	Desert Scrub, Grassland, Shrubland, Agricultural, Developed	Breeding	71
Lanius ludovicianus	Loggerhead Shrike			G4	S4B	Desert Scrub, Grassland, Shrubland, Savanna/Open Woodland, Agricultural, Developed	Year-round	73
Vireo bellii	Bell's Vireo			G5	S3B	Desert scrub, Shrubland, Riparian	Breeding	74
Vireo atricapilla	Black-capped Vireo	LE	E	G3	S2B	Shrubland	Breeding	75
Poecile carolinensis	Carolina Chickadee			G5	S5B	Woodland, Forest, Riparian, Developed: Urban/Suburban/Rural	Year-round	76
Anthus spragueii	Sprague's Pipit	C		G4	S3N	Barren/Sparse Vegetation, Grassland, Shrubland, Agricultural	Winter	80
Parula pitiayumi	Tropical Parula		T	G5	S3B	Savanna/Open Woodland, Woodland, Forest, Riparian	Breeding, Lower Pecos and Devils River in CHIH, handful of breeding pairs in EDPT recently documented	82
*Dendroica chrysoparia**	Golden-cheeked Warbler	LE	E	G2	S2B	Woodland	Breeding; *taxonomic change likely to *Setophaga chrysoparia*	83
Dendroica dominica	Yellow-throated Warbler			G5	S4B	Woodland, Forest, Riparian	Breeding	84
Seiurus motacilla	Louisiana Waterthrush			G5	S3B	Woodland, Forest, Riparian	Breeding	89
Aimophila cassinii	Cassin's Sparrow			G5	S4B	Grassland, Shrubland	Breeding	92
Aimophila ruficeps	Rufous-crowned Sparrow			G5	S4B	Grassland	Year-round	95
Spizella pusilla	Field Sparrow			G5	S5B	Grassland, Shrubland, Savanna/Open Woodland	Year-round	96
Ammodramus savannarum	Grasshopper Sparrow			G5	S3B	Grassland, Agricultural	Year-round	97
Chondestes grammacus	Lark Sparrow			G5	S4B	Grassland, Shrubland, Savanna/Open Woodland	Year-round	98
Ammodramus leconteii	Le Conte's Sparrow					Grassland	Winter	101
Zonotrichia querula	Harris's Sparrow			G5	S4	Shrubland, Agricultural	Winter	103
Piranga rubra	Summer Tanager			G5	S5B	Savanna/Open Woodland, Woodland, Forest, Riparian, Developed: Urban/Suburban/Rural	Breeding	106
Passerina ciris	Painted Bunting			G5	S4B	Shrubland, Agricultural	Breeding	107
Spiza americana	Dickcissel			G5	S4B	Grassland, Agricultural	Breeding	108
Sturnella magna	Eastern Meadowlark			G5	S5B	Grassland, Shrubland, Savanna/Open Woodland	Year-round; subspecies *lilliana* added for CHIH	109

Icterus spurius	Orchard Oriole			G5	S4B	Shrubland, Savanna/Open Woodland, Woodland, Riparian	Breeding	111
REPTILES AND AMPHIBIANS						J.E. Werler and J.R. Dixon. 2000. Texas Snakes: Identification, Distribution, and Natural History. University of Texas Press, Austin. 519 pgs. J.R. Dixon. 1987. Amphibians and Reptiles of Texas. Texas A&M University Press, College Station. 434 pp.		
Anaxyrus (Bufo) woodhousii	Woodhouse's toad			G5	SU	woodland, forest, freshwater wetland		N
Apalone mutica	smooth softshell turtle					riparian, riverine, lacustrine, freshwater wetland	added	N
Apalone spinifera	spiny softshell turtle					riparian, riverine, lacustrine, freshwater wetland	added, not AZNM	N
Cheylydra serpentina	Common snapping turtle					riparina, riverine	added	N
Crotalus atrox	Western diamondback rattlesnake				S4	barren/sparse vegetation, desert scrub, grassland, shrubland, savanna, woodland, caves/karst		N
Drymarchon melanurus erebennus	Texas Indigo Snake		T	G4	S3	shrubland, savanna		N
Eurycea latitans	Cascade Caverns salamander		T	G3	S1	caves and karst, freshwater wetland (springs)		Y
Eurycea nana	San Marcos salamander	LT	T	G1	S1	freshwater wetland (springs)		Y
Eurycea naufragia	Georgetown Salamander	C		G1	S1	caves and karst, freshwater wetland (springs)		Y
Eurycea neotenes	Texas salamander			G1	S2	caves and karst, freshwater wetland (springs)		Y
Eurycea pterophila	Blanco River springs salamander			G2	S2	caves and karst, freshwater wetland (springs)		Y
Eurycea rathbuni	Texas blind salamander	LE	E	G1	S1	aquifer, caves, and karst, freshwater wetland (springs)		Y
Eurycea robusta	Blanco blind salamander		T	G1Q	S1	aquifer		Y
Eurycea sosorum	Barton Springs salamander	LE	E	G1	S1	caves and karst, freshwater wetland (springs)		Y

Eurycea tonkawae	Jollyville Plateau Salamander	C		G1	S2S3	caves and karst, freshwater wetland (springs)		Y
Eurycea tridentifera	Comal blind salamander		T	G1	S1	Aquifer, Caves and Karst		Y
Eurycea waterlooensis	Austin blind salamander	C		G1	S1	Aquifer but often found in Freshwater Weland (springs) and Caves, Karst could apply as well		Y
Gopherus berlandieri	Texas tortoise		T	G4	S2*	savanna, shrubland	added for CHIH	N
Graptemys caglei	Cagle's map turtle		T	G3	S1	riparian, riverine		Y
Graptemys versa	Texas map turtle			G4	SU	riparian, riverine		Y
Heterodon nasicus	Western hognosed snake					desert scrub, grassland, shrubland	added	N
Holbrookia lacerata lacerata	Plateau earless lizard				S2	desert scrub, grassland, shrubland, savanna	also known as northern spot tailed earless lizard	Y
Nerodia paucimaculata	Concho water snake	LT-PDL		G2	S2	riparian,l riverine, cultural aquatic	proposed for federal delisting	Y
Ophisaurus attenuatus	western slender glass lizard					grassland, savanna	added	N
Phrynosoma cornutum	Texas horned lizard		T	G4G5	S4	desert scrub, grassland, savanna		N
Pseudacris streckeri	Strecker's Chorus Frog			G5	S3	grassland, savanna, woodland, riparian, cultural aquatic, freshwater wetland		N
Sistrurus catenatus	massasauga					grassland, barren/sparse vegetation, shrubland, coastal,	added	N
Terrapene carolina	Eastern box turtle			G5	S3	grasslands, savanna, woodland		N
Terrapene ornata	Ornate box turtle			G5	S3	grassland, barren/sparse vegetation, deset scrub, savanna, woodland		N
Thamnophis sirtalis annectans	Texas Garter Snake (Eastern/ Texas/ New Mexico)			G5	S2	riparian, around lacustrine and cultural aquatic sites		Y
Trachemys scripta	Red-eared slider					riparian, riverine, lacustrine, freshwater wetland, cultural aquatic	added	N
FRESHWATER FISHES						C. Thomas, T.H. Bonner and B.G. Whiteside. 2007. Freshwater Fishes of Texas: A Field Guide. Sponsored by The River Systems Institute at Texas State University, published by Texas A&M University Press. *Editor's Note: All freshwater fishes life history information in this table was sourced directly from the online version; citations are embedded in the online version at http://www.bio.txstate.edu/~tbonner/txfishes/*	Range in Texas, as known	

Anguilla rostrata	American eel			G4	S5	streams and reservoirs in drainages connected to marine environments	Originally found in large rivers from the Red River to the Rio Grande; Red River (from the mouth upstream to and including the Kiamichi River), Sabine Lake (including minor coastal drainages west to Galveston Bay), Galveston Bay (including minor coastal drainages west to mouth of Brazos River), Brazos River, Colorado River, San Antonio Bay (including minor coastal drainages west of mouth of Colorado River to mouth of Nueces River), Nueces River. Extirpated in several drainages (dams)	N
Cyprinella lepida	Plateau shiner			G1G2	S1S2	clear, cool, spring-fed headwater creeks, gravel and limestone substrates	Frio and Sabinal rivers May be endemic to the upper reaches of the Guadalupe River Basin, San Antonio Bay drainage unit (including minor coastal drainages west of mouth of Colorado River to mouth of Nueces River) (?), Nueces River drainage unit Conservation Actions should be coordinated across occurrence ecoregions	Y
Cyprinella proserpina	Proserpine shiner		T	G3	S2	clear, spring-fed tributaries, spring-runs; pools to swift channels and riffles, spring-influenced rocky runs and pool habitats; adapted to flood-prone environments	Devils and lower Pecos rivers; Las Moras, Pinto, San Felipe and Independence creeks	Y
Cyprinella sp.	Nueces river shiner			G1G2Q	S1S2	clear, cool, spring-fed headwater creeks	Upper reaches of the Nueces River; request actions coord across ecoregions as needed	Y
Cyprinodon eximius ssp	Devils River pupfish					sloughs, backwaters, and margins of larger streams, channels of creeks (in Mexico), and mouths of creeks tributary to larger rivers; rarely in headsprings; shallow, isolated pool habitat in the Devils River; sandy to gravelly streams, in clear, shallow waters	Devils River (TX) and Alamito Creek (TX) populations are morphologically and biochemically distinct from the Rio Conchos (Mexico) *Cyprinodon exemius* populations; conservation actions should be coordinated across relevant ecoregions	Y
Dionda argentosa	Manantial roundnose minnow			G2	S2	Headwaters and runs of spring-influenced waters	Recent genetics work and popuulation studies are revealing distinct, unstable and declining populations of this species in the Devils River, San Felipe Creek, and Independence Creek; species is known from Devils River, San Felipe and Sycamore creeks (Val Verde County), lower Pecos River at Pandale and San Felipe Spring, in Moore Park	Y
Dionda diaboli	Devils River minnow	LT	T	G1	S1	Flowing spring-fed waters near but not in spring outflow, typically near springrun confluences with creek/river over gravel-cobble substrate, usually associated with aquatic macrophytes	Devils River and San Felipe, Sycamore creeks (Val Verde County), Las Moras (extirpated) and Pinto creeks in Kinney County; coordinate conservation actions across ecoregions as needed (Devils River and/or Val Verde Co)	N
Dionda nigrotaeniata	Guadalupe roundnose minnow			G4	S4	spring-influenced headwaters	Colorado and Guadalupe river basins, San Antonio Bay (including minor coastal drainages west of mouth of Colorado River to mouth of Nueces River)	Y

Dionda serena	Nueces roundnose minnow			G2	S2	spring-influenced headwaters	Distinct and declining populations occur in the Nueces and Frio rivers, coordinate conservation actions across ecoregions as needed	Y
Etheostoma grahami	Rio Grande darter		T	G2G3	S2	Gravel and rubble riffles in spring-fed tributaries, creeks, and streams	Rio Grande and the lower Pecos River downstream to the Devils River and Dolan, San Felipe and Sycamore creeks, coordinate conservation actions across ecoregions as needed	N
Gambusia heterochir	Clear Creek gambusia	LE	E	G1	S1	springs	impounded headwater springs of Clear Creek, a tributary to the San Saba River	Y
Ictalurus lupus	Headwater catfish			G3	S2	clear streams and rivers with moderate gradients, deep spring runs	Pecos and Rio Grande basins of Texas; once found in the upper Nueces, San Antonio, Guadalupe, and Colorado basins, but appears to be extirpated from these systems	N
Micropterus treculii	Guadalupe bass			G3	S3	small lentic environments; commonly taken in flowing water	Endemic to the streams of the northern and eastern Edwards Plateau including portions of the Brazos, Colorado, Guadalupe, and San Antonio basins; species also found outside of the Edwards Plateau streams in decreased abundance, primarily in the lower Colorado River; two introduced populations have been established in the Nueces River system	Y
Percina apristis	Guadalupe darter					riffles; most common under or around boulders in the main current; moderately turbid water; absent in collections from the clearest waters tributary to the Guadalupe, namely spring heads and the main river west of Kerrville	Guadalupe River and its tributaries, the San Marcos and Blanco Rivers; apparently absent from the headwaters of the Blanco and the entirety of the San Antonio River	Y
INVERTEBRATES						www.bugguide.net – good tool for identification and taxonomic information. www.texasento.net – compilation of information on insects in Texas www.odonatacentral.org – resource for identification and distribution of damselflies and dragonflies www.butterfliesandmoths.org – resource for identification and distribution of Lepidoptera www.texasmussels.wordpress.com – resource for information on freshwater mussels in Texas Howells, R. G., R. W. Neck and H. D. Murray. 1996. Freshwater Mussels of Texas. Texas Parks and Wildlife Press, Austin. Burlakova, L. E., A. Y.Karatayev, V. A. Karatayev, M. E. May, D. L. Bennett and M. J. Cook. 2011. Biogeography and conservation of freshwater mussels (Bivalvia:Unionidae) in Texas: patterns of diversity and threats. Diversity andDistributions: 1-15.		*Editor's Note: Most karst invertebrates are likely endemic*
Allotexiweckelia hirsuta	A cave obligate amphipod			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Amphipods	
Almuerzothyas n. sp.	An aquatic mite			G1*	S1*	Caves/Karst	Karst - Arachnid - Mites	
Amblycorypha uhleri	A katydid			G2G3*	S2?*	Savanna/Open Woodland	Terrestrial - Insects - Grasshoppers	
Apocheiridium reddelli	A cave obligate pseudoscorpion			G1G2	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	

Arethaea ambulator	A katydid			G2G3*	S2?*	Savanna/Open Woodland	Terrestrial - Insects - Grasshoppers	
Arrenurus n. sp	An aquatic mite			G1*	S1*	Caves/Karst	Karst - Arachnid - Mites	
Artesia subterranea	A cave obligate amphipod			G1G2	S1?*	Caves/Karst	Karst - Crustaceans - Amphipods	
Austrotinodes texensis	Texas Austrotinodes caddisfly			G2	S2	Riparian, Riverine	Aquatic - Insect - Caddisflies	
Baetodes alleni	A mayfly			G1G2	S1?*	Riparian, Riverine	Aquatic - Insect - Mayflies	
Balconorbis uvaldensis	Balcones ghostsnail			G1G2	S1*	Caves/Karst	Karst - Mollusks - Freshwater Snails	
Batrisodes cryptotexanus	A cave obligate beetle			G2*	S2*	Caves/Karst	Karst - Insect - Beetles	
Batrisodes dentifrons	A cave obligate beetle			G1G2*	S1*	Caves/Karst	Karst - Insect - Beetles	
Batrisodes fanti	A cave obligate beetle			G1G2*	S1*	Caves/Karst	Karst - Insect - Beetles	
Batrisodes feminiclypeus	A cave obligate beetle			G1G2*	S1*	Caves/Karst	Karst - Insect - Beetles	
Batrisodes gravesi	A cave obligate beetle			G2*	S2*	Caves/Karst	Karst - Insect - Beetles	
Batrisodes grubbsi	A cave obligate beetle			G1G2	S1*	Caves/Karst	Karst - Insect - Beetles	
Batrisodes incisipes	A cave obligate beetle			G1G2*	S1*	Caves/Karst	Karst - Insect - Beetles	
Batrisodes pekinsi	A cave obligate beetle			G1G2*	S1*	Caves/Karst	Karst - Insect - Beetles	
Batrisodes reyesi	A cave obligate beetle			G2G3	S2*	Caves/Karst	Karst - Insect - Beetles	
Batrisodes shadeae	A cave obligate beetle			G1G2*	S1*	Caves/Karst	Karst - Insect - Beetles	
Batrisodes texanus	A cave obligate beetle	LE		G1G2	S1	Caves/Karst	Karst - Insect - Beetles	
Batrisodes venyivi	A cave obligate beetle	LE		G1G2	S1	Caves/Karst	Karst - Insect - Beetles	
Batrisodes wartoni	A cave obligate beetle			G1G2*	S1	Caves/Karst	Karst - Insect - Beetles	
Bombus pensylvanicus	American bumblebee			GU	SU*	Grassland, Savanna/Open Woodland	Terrestrial - Insect - Bee/Wasp/Ant	

Bombus sonorus	Sonoran bumblebee			GU	SU*	Grassland, Savanna/Open Woodland	Terrestrial - Insect - Bee/Wasp/Ant	
Bombus variabilis	Variable cuckoo bumblebee			GU	SU*	Grassland, Savanna/Open Woodland	Terrestrial - Insect - Bee/Wasp/Ant	
Brackenridgia reddelli	A cave obligate isopod			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Isopods	
Caenis arwini	A mayfly			G1G3	S2?*	Riparian, Riverine	Aquatic - Insect - Mayflies; added for CHIH, Freshwater Aquatic, coordinate with EDPT and STPL (Devils River and/or Val Verde Co)	
Calathaemon holthuisi	A cave obligate shrimp			G1G2	S1?*	Caves/Karst	Karst - Crustaceans - Decapods	
Chitrella elliotti	A cave obligate pseudoscorpion			G1G2	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Cicurina bandera	A cave obligate spider			G2G3	S2*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina bandida	Bandit Cave spider			G1G2	S1	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina baronia	Robber Baron Cave meshweaver	LE		G1G2	S1	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina barri	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina browni	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina caliga	A cave obligate spider			G1G2*	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina caverna	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina coryelli	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina elliotti	A cave obligate spider			G2G3	S2*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina ezelli	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina gruta	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina holsingeri	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	

Cicurina hoodensis	A cave obligate spider			G1G2*	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina machete	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina madla	Madla Cave meshweaver	LE		G1G2	S1	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina mckenziei	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina medina	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina menardia	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina mixmaster	A cave obligate spider			G1G2*	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina obscura	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina orellia	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina pablo	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina pastura	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina patei	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina porteri	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina puentecilla	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina rainesi	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina reclusa	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina reddelli	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina russelli	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina sansaba	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina selecta	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	

Cicurina serena	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina sheari	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina sprousei	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina stowersi	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina suttoni	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina travisae	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina troglobia	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina ubicki	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina uvalde	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina venefica	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina venii	Braken Bat Cave Meshweaver	LE		G1G2	S1	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina vespera	Government Canyon Bat Cave Meshweaver	LE		G1G2	S1	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina vibora	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina wartoni	Warton cave Meshweaver	C		G1	S1	Caves/Karst	Karst - Arachnid - Spiders	
Cicurina watersi	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Cisthene conjuncta	A lichen moth			G1Q	S1Q*	Forest, Savanna/Open Woodland	Terrestrial - Insect - Butterflies/Moths	
Colletes bumeliae	A cellophane bee			G1*	S1*	Grassland, Savanna/Open Woodland	Terrestrial - Insect - Bee/Wasp/Ant	
Comaldessus stygius	Comal Springs diving beetle			G1	S1	Aquifer, Riparian	Karst - Insect - Beetles	

Daedalochila hippocrepis	Horseshoe liptooth			G1	S1	Woodland	Terrestrial - Mollusks - Land Snails	
Dichopetala catinata	A katydid			G1?*	S1?*	Grassland, Shrubland	Terrestrial - Insects - Grasshoppers	
Dichopetala seeversi	A katydid			G1*	S1*	Grassland, Shrubland	Terrestrial - Insects - Grasshoppers	
Dinocheirus cavicolus	A cave obligate pseudoscorpion			G2G3	S2*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Eidmennella nastuta	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Eidmennella reclusa	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Elaphoidella n. sp.	A cave obligate copepod			G1*	S1*	Caves/Karst	Karst - Crustaceans - Copepods	
Haideoporus texanus	Edwards Aquifer diving beetle			G1G2	S1	Aquifer, Freshwater Wetland	Karst - Insect - Beetles	
Heterelmis comalensis	Comal Springs riffle beetle	LE		G1	S1	Aquifer, Freshwater Wetland	Aquatic - Insect - Beetle	
Heterelmis sp.	Fern Bank Springs riffle beetle			G1*	S1*	Aquifer, Freshwater Wetland	Aquatic - Insects - Beetles; unnamed sp. near *H. glabra*	
Heterelmis sp.	Fessenden Springs riffle beetle			G1*	S1*	Aquifer, Freshwater Wetland	Aquatic - Insects - Beetles; unnamed sp. near *H. glabra*	
Heterelmis sp.	Devils River Springs riffle beetle			G1*	S1*	Aquifer, Freshwater Wetland	Aquatic - Insects - Beetles; unnamed sp. near *H. glabra* ; added for CHIH, freshwater aquatic, coordinate with EDPT and STPL (Devils River and/or Val Verde Co)	
Holcopasites jerryrozeni	A cuckoo bee			G1*	S1*	Grassland, Shrubland	Terrestrial - Insect - Bee/Wasp/Ant	
Holospira goldfussi	New Braunfels Holospira			G2G3	S2?*	Woodland	Terrestrial - Mollusks - Land Snails	
Holsingerius samacos	A cave obligate amphipod			G1G2	S1?*	Caves/Karst	Karst - Crustaceans - Amphipods	
Hyalella texana	Clear Creek amphipod			G1	S1	Aquifer, Freshwater Wetland	Aquatic - Crustaceans - Amphipods	
Hydroptila melia	A caddisfly			G2G3	S2?*	Riparian, Riverine	Aquatic - Insects - Caddisflies	
Ingolfiella n. sp.	A cave obligate amphipod			G1G2*	S1*	Caves/Karst	Karst - Crustaceans - Amphipods	
Lampsilis bracteata	Texas fatmucket		T	G1	S1*	Riverine	Aquatic - Freshwater - Mollusks; new state rank and threatened state status	

Leucohya texana	A cave obligate pseudoscorpion			G1G2	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Lirceolus bisetus	A cave obligate isopod			G1G2	S1*	Caves/Karst	Karst - Crustaceans - Isopods	
Lirceolus hardeni	A cave obligate isopod			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Isopods	
Lirceolus pilus	A cave obligate isopod			G2G3	S2?	Caves/Karst	Karst - Crustaceans - Isopods	
Lirceolus smithii	Texas troglobitic water slater			G1G2	S1	Caves/Karst	Karst - Crustaceans - Isopods	
Lymantes nadineae	A cave obligate beetle			G1*	S1*	Caves/Karst	Karst - Insect - Beetles	
Macrotera parkeri	A mining bee			G1G2*	S1S2*	Grassland, Shrubland	Terrestrial - Insect - Bee/Wasp/Ant	
Macrotera robertsi	A mining bee			G1*	S1*	Grassland, Shrubland	Terrestrial - Insect - Bee/Wasp/Ant	
Marstonia comalensis	Comal siltsnail			G1	S1	Aquifer, Freshwater Wetland	Aquatic - Freshwater - Snails	
Mexistenasellus coahuila	A cave obligate isopod			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Isopods	
Mexiweckelia hardeni	A cave obligate amphipod			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Amphipods	
Microceramus texanus	Texas urocoptid			G2	S2*	Woodland	Terrestrial - Mollusks - Land Snails	
Millerelix gracilis	Edwards Plateau liptooth			G2G3	S2?*	Woodland	Terrestrial - Mollusks - Land Snails	
Myrmecoderus laevipennis	A narrow-waisted bark beetle			G1*	S1*	Forest, Woodland	Terrestrial - Insect - Beetles	
Nectopsyche texana	A caddisfly			G1G3	S2?*	Riparian, Riverine	Aquatic - Insects - Caddisflies	
Tayshaneta anopica	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Tayshaneta bullis	A cave obligate spider			G1G2*	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Tayshaneta concinna	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Tayshaneta devia	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Tayshaneta microps	Government Canyon Bat Cave spider	LE		G1G2	S1	Caves/Karst	Karst - Arachnid - Spiders	

Tayshaneta myopica	Tooth Cave spider	LE		G1G2	S1	Caves/Karst	Karst - Arachnid - Spiders	
Tayshaneta valverde	A cave obligate spider			G1G2	S1*	Caves/Karst	Karst - Arachnid - Spiders	
Neotrichia juani	A caddisfly			G1	S1*	Riparian, Riverine	Aquatic - Insects - Caddisflies	
Nitocrellopsis texana	A cave obligate copepod			G1*	S1*	Caves/Karst	Karst - Crustaceans - Copepods	
Oncopodura fenestra	A cave obligate springtail			G2G3	S2?*	Caves/Karst	Karst - Sprintails	
Oxyelophila callista	A snout moth			G1?*	S1?*	Woodland	Aquatic - Insects - Moths	
Oxyethira ulmeri	A caddisfly			G2G3	S2?*	Riparian, Riverine	Aquatic - Insects - Caddisflies	
Palaemonetes antrorum	A cave obligate shrimp			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Decapods	
Palaemonetes texanus	Texas river shrimp			G1G2*	S1?*	Riverine	Aquatic - Crustaceans - Shrimp	
Parabogidiella americana	A cave obligate amphipod			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Amphipods	
Paraholsingerius smaragdinus	A cave obligate amphipod			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Amphipods	
Paralimnetis texana	Pointytop finger clam shrimp			G1	S1*	Riparian, Riverine	Aquatic - Crustaceans - Clam/Fairy Shrimp	
Paramexiweckelia ruffoi	A cave obligate amphipod			G1G2	S1?*	Caves/Karst	Karst - Crustaceans - Amphipods	
Patera leatherwoodi	Pedernales oval			G1	S1*	Woodland	Terrestrial - Mollusks - Land Snails	
Perdita dolanensis	A mining bee			G1*	S1*	Grassland, Shrubland	Terrestrial - Insect - Bee/Wasp/Ant	
Petrophila daemonalis	A snout moth			G1?*	S1?*	Grassland, Shrubland	Aquatic - Insects - Moths	
Phreatodrobia conica	Hueco cavesnail			G1	S1*	Caves/Karst	Karst - Mollusks - Freshwater Snails	
Phreatodrobia imitata	Mimic cavesnail			G1	S1	Caves/Karst	Karst - Mollusks - Freshwater Snails	
Phreatodrobia micra	Flattened cavesnail			G2G3	S2S3	Caves/Karst	Karst - Mollusks - Freshwater Snails	
Phreatodrobia nugax	Nymph trumpet			G1G2	S1*	Caves/Karst	Karst - Mollusks - Freshwater Snails	
Phreatodrobia plana	Disc cavesnail			G2	S2*	Caves/Karst	Karst - Mollusks - Freshwater Snails	
Phreatodrobia punctata	High-hat cavesnail			G2	S2*	Caves/Karst	Karst - Mollusks - Freshwater Snails	
Phreatodrobia rotunda	Beaked cavesnail			G1G2	S1*	Caves/Karst	Karst - Mollusks - Freshwater Snails	
Plauditus texanus	A mayfly			G2G3	S1?*	Riparian, Riverine	Aquatic - Insects - Mayflies	

Pogonomyrmex comanche	Comanche harvester ant			G2G3*	S2*	Barren/Sparse Vegetation	Terrestrial - Insect - Bee/Wasp/Ant; ecoregions added	
Procloeon distinctum	A mayfly			G1G3	S2?*	Riverine, Riparian	Aquatic - Insects - Mayflies	
Protandrena maurula	A mining bee			G1G2*	S1S2*	Grassland, Shrubland	Terrestrial - Insect - Bee/Wasp/Ant	
Protoptila arca	A caddisfly			G1	S1	Riverine, Riparian	Aquatic - Insects - Caddisflies	
Pygarctia lorula	A tiger moth			G2G3	S2?*	Savanna/Open Woodland	Terrestrial - Insect - Butterflies/Moths	
Quadrula aurea	Golden orb		T	G1	S2*	Riverine	Aquatic - Freshwater - Mollusks; new state rank and threatened state status	Y
Quadrula houstonensis	Smooth pimpleback		T	G2	S1S2*	Riverine	Aquatic - Freshwater - Mollusks; new state rank and threatened state status	Y
Quadrula mitchelli	False Spike		T	GH	SH	Riverine	Aquatic - Freshwater - Mollusks; new state rank and threatened state status	
Quadrula petrina	Texas pimpleback		T	G2	S1*	Riverine	Aquatic - Freshwater - Mollusks; new state rank and threatened state status	Y
Rhadine austinica	A cave obligate beetle			G1G2	S1*	Caves/Karst	Karst - Insect - Beetles	
Rhadine bullis	A cave obligate beetle			G2*	S2	Caves/Karst	Karst - Insect - Beetles	
Rhadine exilis	A cave obligate beetle	LE		G1	S1	Caves/Karst	Karst - Insect - Beetles	
Rhadine infernalis	A cave obligate beetle	LE		G2G3	S1	Caves/Karst	Karst - Insect - Beetles	
Rhadine insolata	A cave obligate beetle			G1G2	S1*	Caves/Karst	Karst - Insect - Beetles	
Rhadine noctivaga	A cave obligate beetle			G1G2	S1*	Caves/Karst	Karst - Insect - Beetles	
Rhadine persephone	Tooth Cave ground beetle	LE		G1G2	S1	Caves/Karst	Karst - Insect - Beetles	
Rhadine reyesi	A cave obligate beetle			G1G2*	S1S2*	Caves/Karst	Karst - Insect - Beetles	
Rhadine russelli	A cave obligate beetle			G1G2	S1*	Caves/Karst	Karst - Insect - Beetles	
Rhadine speca	A cave obligate beetle			G2*	S2*	Caves/Karst	Karst - Insect - Beetles	
Rhadine subterranea	A cave obligate beetle			G2*	S2*	Caves/Karst	Karst - Insect - Beetles	
Seborgia relicta	A cave obligate amphipod			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Amphipods	

Speocirolana hardeni	A cave obligate isopod			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Isopods	
Speodesmus echinourus	A cave olbigate millipede			G2G3	S2?*	Caves/Karst	Karst - Millipede	
Speodesmus falcatus	A cave olbigate millipede			G2 *	S2*	Caves/Karst	Karst - Millipede	
Speodesmus ivyi	A cave olbigate millipede			G2 *	S2*	Caves/Karst	Karst - Millipede	
Speodesmus reddelli	A cave olbigate millipede			G2 *	S2*	Caves/Karst	Karst - Millipede	
Sphinx eremitoides	Sage sphinx			G1G2	S1?*	Grassland	Terrestrial - Insect - Butterflies/Moths	
Streptocephalus linderi	Spinyfinger fairy shrimp			G2	S2*	Riverine, Riparian	Aquatic - Crustaceans - Clam/Fairy Shrimp	
Stygobromus balconis	A cave obligate amphipod			G2G3	S1	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygobromus dejectus	Cascade Cave amphipod			G1G2	S1	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygobromus flagellatus	Ezell's Cave amphipod			G2G3	S1	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygobromus hadenoecus	Devil's Sinkhole amphipod			G1G2	S1	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygobromus limbus	Border Cave amphipod			G1G2	S1*	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygobromus longipes	Long-legged Cave amphipod			G2G3	S1	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygobromus n. sp.	Neel's Cave amphipod			G1G2*	S1*	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygobromus n. sp.	Devils River Cave amphipod			G1G2*	S1*	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygobromus n. sp.	Fessenden Cave amphipod			G1G2*	S1*	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygobromus n. sp.	Lost Maples Cave amphipod			G1G2*	S1*	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygobromus n. sp.	San Gabriel Cave amphipod			G1G2*	S1*	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygobromus pecki	Peck's Cave amphipod	LE	E	G1G2	S1	Caves/Karst	Karst - Crustaceans - Amphipods	

Stygobromus reddelli	Reddell stygobromid			G1G2	S1	Caves/Karst	Karst	
Stygobromus russelli	A cave obligate amphipod			G1G2*	S1*	Caves/Karst	Karst - Crustaceans - Amphipods	
Stygoparnus comalensis	Comal Springs dryopid beetle	LE		G1G2	S1	Caves/Karst	Karst - Insect - Beetles	
Stygopyrgus bartonensis	Barton cavesnail			G1	S1	Caves/Karst	Karst - Mollusks - Freshwater Snails	
Tartarocreagris altimana	A cave obligate pseudoscorpion			G1G2*	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tartarocreagris amblyopa	A cave obligate pseudoscorpion			G1G2*	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tartarocreagris attenuata	A cave obligate pseudoscorpion			G1G2*	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tartarocreagris domina	A cave obligate pseudoscorpion			G1G2*	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tartarocreagris grubbsi	A cave obligate pseudoscorpion			G1G2*	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tartarocreagris hoodensis	A cave obligate pseudoscorpion			G1G2*	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tartarocreagris infernalis	A cave obligate pseudoscorpion			G2G3	S2?*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tartarocreagris intermedia	A cave obligate pseudoscorpion			G1G2	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tartarocreagris proserpina	A cave obligate pseudoscorpion			G1G2*	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tartarocreagris reddelli	A cave obligate pseudoscorpion			G1G2*	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tartarocreagris reyesi	A cave obligate pseudoscorpion			G1G2*	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tartarocreagris texana	Tooth Cave Pseudoscorpion	LE		G1G2	S1	Caves/Karst	Karst - Arachnids - Pseudoscorpions	

Tethysbaena texana	A cave obligate crustacean			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Thermosbaenaceans	
Texamaurops reddelli	Kretschmarr Cave Mold Beetle	LE		G2G3	S1	Caves/Karst	Karst - Insect - Beetles	
Texanobathynella bowmani	A bathynellid			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Bathynellaceans	
Texapyrgus longleyi	Striated Hydrobe			G1	S1	Freshwater Wetland	Aquatic - Freshwater - Snails	
Texella brevidenta	A cave obligate harvestman			G1G2	S1*	Caves/Karst	Karst - Arachnids - Harvestman	
Texella brevistyla	A cave obligate harvestman			G1G2	S1*	Caves/Karst	Karst - Arachnids - Harvestman	
Texella cokendolpheri	Cokendolpher Cave Harvestman	LE		G1G2	S1	Caves/Karst	Karst - Arachnids - Harvestman	
Texella diplospina	A cave obligate harvestman			G1G2	S1*	Caves/Karst	Karst - Arachnids - Harvestman	
Texella grubbsi	A cave obligate harvestman			G1G2	S1*	Caves/Karst	Karst - Arachnids - Harvestman	
Texella hardeni	A cave obligate harvestman			G1G2	S1*	Caves/Karst	Karst - Arachnids - Harvestman	
Texella mulaiki	A cave obligate harvestman			G2G3	S2*	Caves/Karst	Karst - Arachnids - Harvestman	
Texella reddelli	Reddell harvestman	LE		G2G3	S2*	Caves/Karst	Karst - Arachnids - Harvestman	
Texella renkesae	A cave obligate harvestman			G1G2	S1*	Caves/Karst	Karst - Arachnids - Harvestman	
Texella reyesi	Bone Cave harvestman	LE		G2G3	S2*	Caves/Karst	Karst - Arachnids - Harvestman	
Texella spinoperca	A cave obligate harvestman			G1G2*	S1*	Caves/Karst	Karst - Arachnids - Harvestman	
Texiweckelia texensis	A cave obligate amphipod			G2G3	S2?*	Caves/Karst	Karst - Crustaceans - Amphipods	

Truncilla macrodon	Texas fawnsfoot		T	G2Q	S1*	Riverine	Aquatic - Freshwater - Mollusks; new state rank and threatened state status	Y
Tyrannochthonius muchmoreorum	A cave obligate pseudoscorpion					Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Tyrannochthonius troglodytes	A cave obligate pseudoscorpion			G1G2	S1*	Caves/Karst	Karst - Arachnids - Pseudoscorpions	
Xiphocentron messapus	A caddisfly			G1G3	S2?*	Riparian, Riverine	Aquatic - Insects - Caddisflies	
PLANTS						J.M. Poole, W.R. Carr, D.M. Price and J.R. Singhurst. 2007. Rare Plants of Texas. Texas A&M University Press, College Station. D.S. Correll and M.C Johnston. 1979. Manual of the Vascular Plants of Texas. The University of Texas at Dallas, Richardson. M.C. Johnston. 1990. The Vascular Plants of Texas: A List Up-dating the Manual of the Vascular Plants of Texas, 2nd Edition. Marshall C. Johnston, Austin. F.W. Gould. 1975. The Grasses of Texas. Texas A & M University Press, College Station. S.D. Jones, J.K. Wipff, and P.M. Montgomery. 1997. Vascular Plants of Texas: A Comprehensive Checklist including Synonymy; Bibliography, and Index. University of Texas Press, Austin. R.A. Vines. 2004. Trees, Shrubs and Woody Vines of the Southwest. Blackburn Press.		
Agalinis densiflora	Osage Plains false foxglove			G3	S2	Savanna/Open Woodland - Outcrops	Terrestrial	N
Amorpha roemeriana	Texas amorpha			G3	S3	Woodland	Terrestrial	Y
Argythamnia aphoroides	Hill Country wild-mercury			G2G3	S2S3	Savanna/Open Woodland	Terrestrial	Y
Astragalus mollissimus var. coryi	Cory's woolly locoweed			G5T3	S3	Grassland (limestone substrates)	Terrestrial	Y
Astragalus reflexus	Texas milk vetch			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Astragalus wrightii	Wright's milkvetch			G3	S3	Grassland; Savanna/Open Woodland	Terrestrial	Y
Bauhinia lunarioides	Anacacho orchid			G3	S1	Shrubland	Terrestrial	N
Berberis swaseyi	Texas barberry			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Brazoria enquistii	Enquist's sandmint			G2	S2	Riparian (sandy banks and streamsides) with Savanna/Open Woodland matrix	Terrestrial	Y
Brickellia dentata	gravelbar brickellbush			G3G4	S3S4	Riparian	Terrestrial	Y
Brickellia eupatorioides var. gracillima	narrowleaf brickellbush			G5T3	S3	Riparian	Terrestrial	Y
Campanula reverchonii	Basin bellflower			G2	S2	Barren/Sparse Vegetation (granite gravels and outcrops)	Terrestrial	Y

Cardamine macrocarpa var. texana	Texas largeseed bittercress			G3T2	S2	Woodland (oak-juniper)	Terrestrial	N
Carex edwardsiana	canyon sedge			G3G4S3S4	S3S4	Woodland (slopes above Riparian)	Wetland	Y
Chaetopappa effusa	spreading leastdaisy			G3G4	S3S4	Woodland	Terrestrial	Y
Clematis texensis	scarlet leather-flower			G3G4	S3S4	Woodland	Terrestrial	Y
Colubrina stricta	Comal snakewood			G2	S1	Shrubland	Terrestrial	N
Crataegus turnerorum	Turners' hawthorn			G3Q	S3	Savanna/Open Woodland	Terrestrial	Y
Croton alabamensis var. texensis	Texabama croton			G3T2	S2	Woodland	Terrestrial	Y
Cuscuta exaltata	tree dodder			G3	S3	Woodland	Terrestrial	N
Dalea hallii	Hall's prairie-clover			G3	S3	Savanna/Open Woodland; Grassland	Terrestrial	Y
Dalea sabinalis	Sabinal prairie-clover			GH	SH	Grassland; Savanna/Open Woodland	Terrestrial	Y
Desmanthus reticulatus	net-leaf bundleflower			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Desmodium lindheimeri	Lindheimer's tickseed			G3G4	S1	Woodland	Terrestrial	N
Donrichardsia macroneuron	Don Richard's spring moss			G1	S1	Freshwater Wetland (springs)	Aquatic	Y
Echinocereus coccineus var. paucispinus	Texas claret-cup cactus			G5T3	S3	Shrublands; Desert Scrub; Grasslands; Woodlands	Terrestrial	N
Ephedra coryi	Cory's ephedra			G3	S3	Barren/Sparse Vegetation (inland sand dunes); Grasslands	Terrestrial	N
Eriocaulon koernickianum	small-headed pipewort			G2	S1	Freshwater Wetland (bogs)	Wetland	N
Eriogonum nealleyi	Irion County wild-buckwheat			G2	S2	Savanna/Open Woodland; Grassland	Terrestrial	Y
Eriogonum tenellum var. ramosissimum	Basin wild-buckwheat			G5T3	S3	Barren/Sparse Vegetation (granite gravels and outcrops)	Terrestrial	Y
Euphorbia peplidion	low spurge			G3	S3	Savanna/Open Woodland	Wetland	Y
Festuca versuta	Texas fescue			G3	S3	Woodland	Terrestrial	N

Galactia watsoniana	Watson's milk-pea			G1	S1	Woodland (canyons)	Terrestrial	Y
Gilia ludens	South Texas gilia			G3	S3	Shrubland	Terrestrial	Y
Glossopetalon texense	Texas greasebush			G1	S1	Savanna/Open Woodland; Barren/Sparse Vegetation (limestone cliffs, ledges, or outcrops)	Terrestrial	Y
Hesperaloe parviflora	red yucca			G3	S3	Savanna/Open Woodland	Terrestrial	N
Hexalectris nitida	Glass Mountains coral-root			G3	S3	Woodland	Terrestrial	N
Hexalectris warnockii	Warnock's coral-root			G2G3	S2	Woodland	Terrestrial	N
Houstonia parviflora	Greenman's bluet			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Isoetes lithophila	rock quillwort			G2	S2	Freshwater Wetland (vernal pools)	Aquatic	Y
Isoetes piedmontana	Piedmont quillwort			G3	S1	Freshwater Wetland (vernal pools)	Aquatic	N
Lythrum ovalifolium	Plateau loosestrife			G3G4	S3S4	Riparian; Freshwater Wetlands (seeps)	Wetland	N
Matelea edwardsensis	Plateau milkvine			G3	S3	Woodland (canyons)	Terrestrial	Y
Matelea sagittifolia	arrowleaf milkvine			G3	S3	Shrubland; Woodland	Terrestrial	N
Monarda punctata var. stanfieldii	Stanfield's beebalm			G5T3	S3	Savanna/Open Woodland	Terrestrial	Y
Muhlenbergia villiflora var. villosa	villous muhly			G5T3	S2	Barren/Sparse Vegetation (gypseous soils); Shrubland	Terrestrial	N
Nesaea longipes	longstalk heimia			G2G3	S2	Freshwater Wetland (springs, cienegas)	Wetland	N
Oenothera cordata	heartleaf evening-primrose			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Onosmodium helleri	Heller's marbleseed			G3	S3	Woodland	Terrestrial	Y
Packera texensis	Llano butterweed			G2	S2	Savanna/Open Woodland (on granite gravels)	Terrestrial	Y
Pediomelum cyphocalyx	turnip-root scurfpea			G3G4	S3S4	Grassland	Terrestrial	Y
Penstemon guadalupensis	Guadalupe beardtongue			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Penstemon triflorus subsp. integrifolius	Heller's beardtongue			G3T3	S2	Savanna/Open Woodland; Barren/Sparse Vegetation (limestone cliffs, ledges, or outcrops)	Terrestrial	N
Penstemon triflorus subsp. triflorus	threeflower penstemon			G3T3	S3	Savanna/Open Woodland; Barren/Sparse Vegetation (limestone cliffs, ledges, or outcrops)	Terrestrial	Y

Phaseolus texensis	canyon bean			G2	S2	Woodland (canyons)	Terrestrial	Y
Philadelphus ernestii	canyon mock-orange			G3	S3	Woodland (canyons on limestone outcrops or boulders)	Terrestrial	N
Phoradendron hawksworthii	Hawksworth's mistletoe			G3	S3	Woodland	Terrestrial	N
Physaria engelmannii	Engelmann's bladderpod			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Physostegia correllii	Correll's false dragon-head			G2	S2	Riparian; Riverine; Freshwater Wetland	Aquatic	N
Polygala palmeri	Palmer's milkwort			G3	S2	Shrubland	Terrestrial	N
Pomaria brachycarpa	broadpod rushpea			G2	S2	Savanna/Open Woodland	Terrestrial	Y
Prenanthes carrii	canyon rattlesnake-root			G2	S2	Woodland (canyons)	Wetland	Y
Prunus minutiflora	Texas almond			G3G4	S3S4	Savanna/Open Woodland	Terrestrial	N
Prunus texana	Texas peachbush			G3G4	S3S4	Savanna/Open Woodland; Grassland	Terrestrial	Y
Salvia pentstemonoides	big red sage			G1	S1	Barren/Sparse Vegetation (limestone outcrops, boulders, and cliffs); Woodland (canyons)	Wetland	Y
Sclerocactus brevihamatus subsp. tobuschii	Tobusch fishhook cactus	LE	E	G4T3	S3	Savanna/Open Woodland	Terrestrial	Y
Selenia jonesii	Jones' selenia			G3	S3	Grassland	Wetland	Y
Seymeria texana	Texas seymeria			G3	S3	Woodland	Terrestrial	Y
Shinnersia rivularis	springrun whitehead			G2G3	S1	Riverine (riffles)	Aquatic	N
Spigelia texana	Florida pinkroot			G3	S3	Woodland (canyons); Freshwater Wetland (Bottomland Forest)	Terrestrial	Y
Streptanthus bracteatus	bracted twistflower			G1G2	S1S2	Woodland; Savanna/Open Woodland	Terrestrial	Y
Streptanthus platycarpus	broadpod twistflower			G3	S3	Savanna/Open Woodland	Terrestrial	N
Styrax platanifolius subsp. platanifolius	sycamore-leaf snowbell			G3T3	S3	Woodland	Terrestrial	Y
Styrax platanifolius subsp. stellatus	hairy sycamore-leaf snowbell			G3T3	S3	Woodland	Terrestrial	Y
Styrax platanifolius subsp. texanus	Texas snowbells	LE	E	G3T1	S1	Barren/Sparse Vegetation (limestone cliffs and ledges); Riparian; with Woodland or Shrubland matrix	Terrestrial	Y

Tradescantia pedicellata	granite spiderwort			G2Q	S2	Savanna/Open Woodland	Terrestrial	Y
Tragia nigricans	darkstem noseburn			G3	S3	Woodland	Terrestrial	Y
Tridens buckleyanus	Buckley tridens			G3G4	S3S4	Woodland	Terrestrial	Y
Valerianella stenocarpa	bigflower cornsalad			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Valerianella texana	Edwards Plateau cornsalad			G2	S2	Savanna/Open Woodland (igneous or metamorphic gravels)	Wetland	Y
Zizania texana	Texas wild rice	LE	E	G1	S1	Riverine (spring-fed, clear, thermally constant, moderate current, sand to gravel substrate)	Aquatic	Y

SPECIES OF GREATEST CONSERVATION NEED: TEXAS BLACKLAND PRAIRIES ECOREGION

Scientific Name	Common Name	Status		Abundance Ranking		General Habitat Type(s) in Texas These are VERY broad habitat types as a starting place	Other Notes	Endemic in Texas
		Federal	State	Global	State Code	State of the practice resources are listed in each taxa line for more detailed information		
MAMMALS						W.B. Davis and D.J. Schmidly. 1997 and 1994. Mammals of Texas (online and in print). Texas Tech University (1997) and Texas Parks and Wildlife Department (1994). http://www.nsrl.ttu.edu/tmot1/Default.htm (accessed 2011)		
Blarina hylophaga plumblea	Elliot's short-tailed shrew			G5T1Q	S1	Savanna/Open Woodland		N
Geomys attwateri	Attwater's pocket gopher			G4	S4	Shrubland		Y
Lutra canadensis	River otter			G5	S4	Riparian	Appendix II, CITES	N
Mustela frenata	Long-tailed weasel			G5	S5	Forest, Woodland, Desert Scrub, Shrubland, Savanna/Open Woodland	Statewide	N
Myotis austroriparius	Southeastern myotis			G3G4	S3	Caves/Karst, Forest, Riparian		N
Myotis velifer	Cave myotis			G5	S4	Caves/Karst,		N
Puma concolor	Mountain lion			G5	S2	Forest, Woodland, Desert Scrub, Shrubland, Savanna/Open Woodland, Riparian	Statewide	N
Spilogale putorius	Eastern spotted skunk			G4T	S4	Savanna/Open Woodland, Grassland		N
Sylvilagus aquaticus	Swamp rabbit			G5	S5	Riparian, Freshwater Wetland		N
Tadarida brasiliensis	Brazilian free-tailed bat			G5	S5	Cave/Karst, Artificial Refugia	Statewide	N
Taxidea taxus	American badger			G5	S5	Grassland, Desert scrub, Woodland, Savanna/Open Woodland, Forest		N
Ursus americanus	Black bear	SAT	T	G5	S3	Forest, Woodland, Savanna/Open Woodland, Desert Scrub, Shrubland	see also Louisiana black bear; may overlap wi	N

BIRDS						The Birds of North America Online (A. Poole, Ed.). 2005 (with current updates by species). Retrieved from The Birds of North America Online database: http://bna.birds.cornell.edu/BNA/ (accessed 2011). Supported by information from the Cornell Lab of Ornithology and the American Ornithologists' Union (http://www.aou.org/).		BIRDS ONLY: instead of endemism these numbers are for taxonomic sorting
Anas acuta	Northern Pintail			G5	S3B,S5N	Lacustrine, freshwater wetland, saltwater wetland, coastal, marine	Winter	2
Colinus virginianus	Northern Bobwhite			G5	S4B	Grassland, Shrubland, Savanna/Open Woodland	deleted for CHIH	4
Tympanuchus cupido	Greater Prairie-Chicken (Interior)			G4	S1B	Grassland	Year-round	6
Meleagris gallopavo	Wild Turkey			G5	S5B	Shrubland, Savanna/Open Woodland, Forest, Riparian, Agricultural	Year-round, added *merriami* for CHIH	8
Ixobrychus exilis	Least Bittern			G5	S4B	Lacustrine, Freshwater Wetland, Saltwater Wetland, Estuary	Breeding	11
Egretta thula	Snowy Egret			G5	S5B	Riparian, Riverine, Lacustrine, Freshwater Wetland, Saltwater Wetland, Estuary, Coastal, Cultural Aquatic	Breeding	12
Egretta caerulea	Little Blue Heron			G5	S5B	Riparian, Riverine, Lacustrine, Freshwater Wetland, Saltwater Wetland, Estuary, Coastal, Cultural Aquatic	Breeding	13
Butorides virescens	Green Heron			G5	S5B	Riparian, Riverine, Lacustrine, Freshwater Wetland, Cultural Aquatic	Breeding	16
Mycteria americana	Wood Stork		T	G4	SHB,S2N	Riverine, Freshwater wetland	Migrant	18
Ictinia mississippiensis	Mississippi Kite			G5	S4B	Woodland, Forest, Riparian, Developed:Urban/Suburban/Rural	Breeding	20
Haliaeetus leucocephalus	Bald Eagle			G5	S3B,S3N	Riparian, Lacustrine, Freshwater Wetland, Saltwater Wetland	Year-round, added CRTB	22
Circus cyaneus	Northern Harrier			G5	S2B,S3N	Grassland, Shrubland	Year-round	23
Buteo lineatus	Red-shouldered Hawk			G5	S4B	Woodland, Forest, Riparian, Freshwater Wetland	Year-round	26
Pluvialis dominica	American Golden-Plover			G5	S3	Grassland, Freshwater Wetland, Agricultural	Migrant	39
Charadrius montanus	Mountain Plover	PT		G3	S2	Agricultural, Grassland	Winter	43
Scolopax minor	American Woodcock			G5	S2B,S3N	Woodland, Forest, Riparian	Winter (some breeding during that time)	51
Sternula antillarum	Least Tern	LE*	E*	G4	S3B	Riverine, Lacustrine, Freshwater Wetland, Saltwater Wetland, Estuary, Coastal, Marine, Developed: Industrial	Year-round; subspecies *athalassos*	54
Asio flammeus	Short-eared Owl			G5	S4N	Grassland, Shrubland, Agricultural	Winter	65
Caprimulgus carolinensis	Chuck-will's-widow			G5	S3S4B	Woodland, Forest, Riparian	Breeding	66
Melanerpes erythrocephalus	Red-headed Woodpecker			G5	S3B	Savanna/Open Woodland, Woodland, Forest, Riparian, Developed: Urban/Suburban/Rural	Year-round	67

Dryocopus pileatus	Pileated Woodpecker			G5	S4B	Savanna/Open Woodland, Woodland, Forest, Riparian, Developed: Urban/Suburban/Rural	Year-round	69
Tyrannus forficatus	Scissor-tailed Flycatcher			G5	S3B	Desert Scrub, Grassland, Shrubland, Agricultural, Developed	Breeding	71
Lanius ludovicianus	Loggerhead Shrike			G4	S4B	Desert Scrub, Grassland, Shrubland, Savanna/Open Woodland, Agricultural, Developed	Year-round	73
Vireo bellii	Bell's Vireo			G5	S3B	Desert scrub, Shrubland, Riparian	Breeding	74
Poecile carolinensis	Carolina Chickadee			G5	S5B	Woodland, Forest, Riparian, Developed: Urban/Suburban/Rural	Year-round	76
Thryomanes bewickii (bewickii)	Bewick's Wren			G5	S5B	Shrubland, Savanna/Open Woodland, Woodland, Developed: Urban/Suburban/Rural	Year-round, red-backed form only	77
Cistothorus platensis	Sedge Wren			G5	S4	Grassland, Freshwater Wetland	Winter	78
Hylocichla mustelina	Wood Thrush			G5	S4B	Woodland, Forest, Riparian	Breeding	79
Anthus spragueii	Sprague's Pipit	C		G4	S3N	Barren/Sparse Vegetation, Grassland, Shrubland, Agricultural	Winter	80
Dendroica dominica	Yellow-throated Warbler			G5	S4B	Woodland, Forest, Riparian	Breeding	84
Protonotaria citrea	Prothonotary Warbler			G5	S3B	Woodland, Forest, Riparian, Lacustrine, Freshwater Wetland	Breeding	86
Limnothlypis swainsonii	Swainson's Warbler			G4	S3B	Woodland, Forest, Riparian	Breeding	88
Seiurus motacilla	Louisiana Waterthrush			G5	S3B	Woodland, Forest, Riparian	Breeding	89
Oporornis formosus	Kentucky Warbler			G5	S3B	Woodland, Forest	Breeding	90
Spizella pusilla	Field Sparrow			G5	S5B	Grassland, Shrubland, Savanna/Open Woodland	Year-round	96
Ammodramus savannarum	Grasshopper Sparrow			G5	S3B	Grassland, Agricultural	Year-round	97
Chondestes grammacus	Lark Sparrow			G5	S4B	Grassland, Shrubland, Savanna/Open Woodland	Year-round	98
Ammodramus henslowii	Henslow's Sparrow			G4	S2S3N,SX	Grassland, Savanna/Open Woodland	Winter	100
Ammodramus leconteii	Le Conte's Sparrow					Grassland	Winter	101
Zonotrichia querula	Harris's Sparrow			G5	S4	Shrubland, Agricultural	Winter	103
Calcarius mccownii	McCown's Longspur			G4	S4	Grassland, Agricultural	Winter, TBPR (northern), ECPL (northern)	104
Calcarius pictus	Smith's Longspur					Grassland, Agricultural	Winter	105
Piranga rubra	Summer Tanager			G5	S5B	Savanna/Open Woodland, Woodland, Forest, Riparian, Developed: Urban/Suburban/Rural	Breeding	106
Passerina ciris	Painted Bunting			G5	S4B	Shrubland, Agricultural	Breeding	107

Spiza americana	Dickcissel			G5	S4B	Grassland, Agricultural	Breeding	108
Sturnella magna	Eastern Meadowlark			G5	S5B	Grassland, Shrubland, Savanna/Open Woodland	Year-round; subspecies *lilliana* added for CHI	109
Euphagus carolinus	Rusty Blackbird			G4	S3	Woodland, Forest, Riparian, Lacustrine, Freshwater Wetland	Winter	110
Icterus spurius	Orchard Oriole			G5	S4B	Shrubland, Savanna/Open Woodland, Woodland, Riparian	Breeding	111
REPTILES AND AMPHIBIANS						J.E. Werler and J.R. Dixon. 2000. Texas Snakes: Identification, Distribution, and Natural History. University of Texas Press, Austin. 519 pgs. J.R. Dixon. 1987. Amphibians and Reptiles of Texas. Texas A&M University Press, College Station. 434 pp.		
Anaxyrus (Bufo) woodhousii	Woodhouse's toad			G5	SU	woodland, forest, freshwater wetland		N
Apalone mutica	smooth softshell turtle					riparian, riverine, lacustrine, freshwater wetland	added	N
Apalone spinifera	spiny softshell turtle					riparian, riverine, lacustrine, freshwater wetland	added, not AZNM	N
Cheylydra serpentina	Common snapping turtle					riparina, riverine	added	N
Crotalus atrox	Western diamondback rattlesnake				S4	barren/sparse vegetation, desert scrub, grassland, shrubland, savanna, woodland, caves/karst		N
Crotalus horridus	Timber (Canebrake) Rattlesnake		T	G4	S4	woodland, forest, riparian		N
Graptemys caglei	Cagle's map turtle		T	G3	S1	riparian, riverine		Y
Graptemys versa	Texas map turtle			G4	SU	riparian, riverine		Y
Heterodon nasicus	Western hognosed snake					desert scrub, grassland, shrubland	added	N
Macrochelys temminckii	alligator snapping turtle		T	G3G4	S3	riparian, riverine, cultural aquatic	added	N
Ophisaurus attenuatus	western slender glass lizard					grassland, savanna	added	N
Phrynosoma cornutum	Texas horned lizard		T	G4G5	S4	desert scrub, grassland, savanna		N
Pseudacris streckeri	Strecker's Chorus Frog			G5	S3	grassland, savanna, woodland, riparian, cultural aquatic, freshwater wetland		N
Sistrurus catenatus	massasauga					grassland, barren/sparse vegetation, shrubland, coastal,	added	N
Terrapene carolina	Eastern box turtle			G5	S3	grasslands, savanna, woodland		N

Terrapene ornata	Ornate box turtle			G5	S3	grassland, barren/sparse vegetation, deset scrub, savanna, woodland		N
Thamnophis sirtalis annectans	Texas Garter Snake (Eastern/ Texas/ New Mexico)			G5	S2	riparian, around lacustrine and cultural aquatic sites		Y
Trachemys scripta	Red-eared slider					riparian, riverine, lacustrine, freshwater wetland, cultural aquatic	added	N
FRESHWATER FISHES						C. Thomas, T.H. Bonner and B.G. Whiteside. 2007. Freshwater Fishes of Texas: A Field Guide. Sponsored by The River Systems Institute at Texas State University, published by Texas A&M University Press. *Editor's Note: All freshwater fishes life history information in this table was sourced directly from the online version; citations are embedded in the online version at http://www.bio.txstate.edu/~tbonner/txfishes/*	Range in Texas, as known	
Anguilla rostrata	American eel			G4	S5	streams and reservoirs in drainages connected to marine environments	Originally found in large rivers from the Red R	N
Atractosteus spatula	alligator gar					near surface habitats in slack water and backwater habitats of rivers. Preferred pool, pool-bank snag, pool-channel snag, pool-snag complex, pool-edge, and pool-vegetation habitat	Red River (from the mouth upstream to and i	N
Cycleptus elongatus	Blue sucker		T	G3G4	S3	large, deep rivers, and deeper zones of lakes	Red River (from the mouth upstream to and i	N
Etheostoma fonticola	Fountain darter	LE	E	G1	S1	Thermally constant (21-24 °C) springs and the upper San Marcos (Hays Co.) and Comal (Comal Co.) rivers, usually in dense beds of *Vallisneria, Elodia, Ludwigia* and other aquatic plants; substrate normally mucky	upper San Marcos (Hays Co.) and Comal (Com	Y
Macryhbopsis storeriana	Silver chub					Broad rivers with low gradient which flow through old mature valley; bottoms gravel to silt, but more common over silt or mud, turbid water with very soft sand/silt substrate Normally inhabits pools, will move to riffle if siltation is heavy; when large streams very turbid or depositing unusually large amounts of silt, will temporarily migrate into clearer streams of higher gradients; when waters were very clear individuals move to deeper water	Red River and the lower Brazos River; Brazos	N
Micropterus treculii	Guadalupe bass			G3	S3	small lentic environments; commonly taken in flowing water	Endemic to the streams of the northern and e	Y
Notropis atrocaudalis	Blackspot shiner					more abundant near headwaters; runs and pools over all types of substrates, generally avoiding areas of backwater and swiftest currents	Red River (from the mouth upstream to and i	N
Notropis bairdi	Red River shiner					turbid waters of broad, shallow channels of main stream, over bottom mostly of silt and shifting sand; streambeds with widely fluctuating flows subject to high summer temperatures, high rates of evaporation, and high concentrations of dissolved solids; tolerant of high salinities	Red River, from the mouth upstream to and i	N
Notropis buccula	Small eye shiner	C		G2Q	S2	turbid waters of broad, sandy channels of main stream, over substrate consisting mostly of shifting sand; broad condition tolerances (turbidity, salinity, oxygen).	Brazos River; historically as far south as Hemp	Y
Notropis chalybaeus	Ironcolor shiner					small to medium sized streams that drain pine woodlands; acid, tannin-stained, non-turbid sluggish Coastal Plain streams and rivers of low to moderate gradient; often at the upstream ends of pools, with a moderate to sluggish current, and sand, mud, silt, or detritus substrata; usually associated with aquatic vegetation; in the San Marcos River (Hays Co.), a disjunct population is restricted to clear, spring-fed waters with abundant aquatic vegetation	Red River (from the mouth upstream to and i	N
Notropis oxyrhynchus	Sharpnose shiner	C		G3	S3	Moderate current velocities and depths, sand bottom	Brazos River drainage; Red River drainage, wh	Y
Notropis potteri	Chub shiner		T	G4	S3	turbid, flowing water with silt or sand substrate; tolerant of high salinities	Brazos River, Colorado River, San Jacinto Rive	N

Notropis shumardi	Silverband shiner					Large rivers, smaller tributaries and oxbow lakes that frequently reconnect to Brazos River mainstem; main channel with moderate to swift current velocities and moderate to deep depths; associated with turbid water over silt, sand, and gravel; tolerant of high turbidity	Red River (from the mouth upstream to and i	N
Percina apristis	Guadalupe darter					riffles; most common under or around boulders in the main current; moderately turbid water; absent in collections from the clearest waters tributary to the Guadalupe, namely spring heads and the main river west of Kerrville	Guadalupe River and its tributaries, the San M	Y
Polyodon spathula	Paddlefish		T	G4	S3	Large river systems and tributaries; deepwater channel habitats; low-gradient areas of moderate to large-sized rivers, sluggish pools, backwaters, bayous, and oxbows with abundant zooplankton; large reservoirs if connected to/can access free-flowing streams in the spring for spawning	Historically occurred in Texas in every major r	N
Satan eurystomus	Widemouth blindcat		T	G1	S1	Karst: Subterranean waters	Restricted to 5 artesian wells penetrating the	Y
Trogloglanis pattersoni	Toothless blindcat		T	G1	S1	Karst: Subterranean waters	Restricted to 5 artesian wells penetrating the	Y
INVERTEBRATES						www.bugguide.net – good tool for identification and taxonomic information. www.texasento.net – compilation of information on insects in Texas www.odonatacentral.org – resource for identification and distribution of damselflies and dragonflies www.butterfliesandmoths.org – resource for identification and distribution of Lepidoptera www.texasmussels.wordpress.com – resource for information on freshwater mussels in Texas Howells, R. G., R. W. Neck and H. D. Murray. 1996. Freshwater Mussels of Texas. Texas Parks and Wildlife Press, Austin. Burlakova, L. E., A. Y.Karatayev, V. A. Karatayev, M. E. May, D. L. Bennett and M. J. Cook. 2011. Biogeography and conservation of freshwater mussels (Bivalvia:Unionidae) in Texas: patterns of diversity and threats. Diversity andDistributions: 1-15.		
Bombus pensylvanicus	American bumblebee			GU	SU*	Grassland, Savanna/Open Woodland	Terrestrial - Insect - Bee/Wasp/Ant	
Chimarra holzenthali	Holzenthal's Philopotamid caddisfly			G1G2	S1	Riparian, Riverine	Aquatic - Insects - Caddisflies; added TBPR, ECPL	
Cotinis boylei	A scarab beetle			G2*	S2*	Grassland, Shrubland, Woodland	Terrestrial - Insect - Beetles	
Nicrophorus americanus	American Burying Beetle	LE		G1	S1	Grassland, Savanna/Open Woodland	Terrestrial - Insect - Beetles	
Potamilus amphichaenus	Texas heelsplitter		T	G1G2	S1	Riverine	Aquatic - Freshwater - Mollusks; new state rank and threatened state status	
Procambarus regalis	Regal burrowing crayfish			G2G3	S2?*	Freshwater Wetland, Grassland	Aquatic - Crustaceans - Crayfish	
Procambarus steigmani	Parkhill prairie crayfish			G1G2	S1S2*	Freshwater Wetland, Grassland	Aquatic - Crustaceans - Crayfish	
Pseudocentroptiloides morihari	A mayfly			G2G3	S2?*	Riverine, Riparian	Aquatic - Insects - Mayflies	

Sphinx eremitoides	Sage sphinx			G1G2	S1?*	Grassland	Terrestrial - Insect - Butterflies/Moths	
Susperatus tonkawa	A mayfly			G1	S1*	Riparian, Riverine	Aquatic - Insects - Mayflies	
PLANTS						J.M. Poole, W.R. Carr, D.M. Price and J.R. Singhurst. 2007. Rare Plants of Texas. Texas A&M University Press, College Station. D.S. Correll and M.C Johnston. 1979. Manual of the Vascular Plants of Texas. The University of Texas at Dallas, Richardson. M.C. Johnston. 1990. The Vascular Plants of Texas: A List Up-dating the Manual of the Vascular Plants of Texas, 2nd Edition. Marshall C. Johnston, Austin. F.W. Gould. 1975. The Grasses of Texas. Texas A & M University Press, College Station. S.D. Jones, J.K. Wipff, and P.M. Montgomery. 1997. Vascular Plants of Texas: A Comprehensive Checklist including Synonymy; Bibliography, and Index. University of Texas Press, Austin. R.A. Vines. 2004. Trees, Shrubs and Woody Vines of the Southwest. Blackburn Press.		
Agalinis densiflora	Osage Plains false foxglove			G3	S2	Savanna/Open Woodland - Outcrops	Terrestrial	N
Astragalus reflexus	Texas milk vetch			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Calopogon oklahomensis	Oklahoma grass pink			G3	S1S2	Savanna/Open Woodland; Grassland; Freshwater Wetland	Terrestrial	N
Carex edwardsiana	canyon sedge			G3G4S3S4	S3S4	Woodland (slopes above Riparian)	Wetland	Y
Carex shinnersii	Shinner's sedge			G3?	S2	Grassland	Wetland	N
Crataegus dallasiana	Dallas hawthorn			G3Q	S3	Riparian (creeks in the Blackland Prairie)	Terrestrial	Y
Cuscuta exaltata	tree dodder			G3	S3	Woodland	Terrestrial	N
Dalea hallii	Hall's prairie-clover			G3	S3	Savanna/Open Woodland; Grassland	Terrestrial	Y
Echinacea atrorubens	Topeka purple-coneflower			G3	S3	Savanna/Open Woodland	Terrestrial	N
Hexalectris nitida	Glass Mountains coral-root			G3	S3	Woodland	Terrestrial	N
Hexalectris warnockii	Warnock's coral-root			G2G3	S2	Woodland	Terrestrial	N
Hymenoxys pygmea	Pygmy prairie dawn			G1	S1	Barren/Sparse Vegetation with Grassland matrix (saline prairie)	currently being described	Y
Liatris glandulosa	glandular gay-feather			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Paronychia setacea	bristle nailwort			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Phlox oklahomensis	Oklahoma phlox			G3	SH	Savanna/Open Woodland	Terrestrial	N

Physaria engelmannii	Engelmann's bladderpod			G3	S3	Savanna/Open Woodland	Terrestrial	Y
Polygonella parksii	Parks' jointweed			G2	S2	Savanna/Open Woodland (sandhills); Grassland	Terrestrial	Y
Prunus texana	Texas peachbush			G3G4	S3S4	Savanna/Open Woodland; Grassland	Terrestrial	Y
Thalictrum texanum	Texas meadow-rue			G2	S2	Savanna/Open Woodland; Riparian (bottomland forest)	Terrestrial	Y
Zizania texana	Texas wild rice	LE	E	G1	S1	Riverine (spring-fed, clear, thermally constant, moderate current, sand to gravel substrate)	Aquatic	Y

Texas Conservation Action Plan 2011: Status and Rank Key for use with SGCN and Rare Communities List

Note: Table is formatted 8-1/2” x 11”, landscape orientation

RANK	DEFINITION
STATE or FEDERAL LISTING STATUS	
LE	Federally endangered species or population.
LT	Federally threatened species or population.
C	Federal Candidate
SAT	Treated as threatened due to similarity of appearance to a species which is federally listed such that enforcement personnel have difficulty in attempting to differentiate between the listed and unlisted species.
PT	Proposed Threatened
PDL	Proposed Dowlisting/Proposed Delisting
E	State endangered species or population.
T	State threatened species or population.
CONSERVATION (Vulnerability or Rarity) RANKING	
(G) GLOBAL Conservation Status Rank	
GX	Presumed Extinct (species) — Not located despite intensive searches and virtually no likelihood of rediscovery.
	Eliminated (ecological communities) — Eliminated throughout its range, with no restoration potential due to extinction of dominant or characteristic species.
GH	Possibly Extinct (species) — Missing; known from only historical occurrences but still some hope of rediscovery.
	Presumed Eliminated — (Historic, ecological communities)-Presumed eliminated throughout its range, with no or virtually no likelihood that it will be rediscovered, but with the potential for restoration, for example, American Chestnut Forest.
G1	Critically Imperiled — At very high risk of extinction due to extreme rarity (often 5 or fewer populations), very steep declines, or other factors.
G2	Imperiled — At high risk of extinction due to very restricted range, very few populations (often 20 or fewer), steep declines, or other factors.
G3	Vulnerable — At moderate risk of extinction due to a restricted range, relatively few populations (often 80 or fewer), recent and widespread declines, or other factors.
G4	Apparently Secure — Uncommon but not rare; some cause for long-term concern due to declines or other factors.
G5	Secure — Common; widespread and abundant.
(S) Subnational or STATE Conservation Status Rank	
SX	Presumed Extirpated — Species or community is believed to be extirpated from the nation or state/province. Not located despite intensive searches of historical sites and other appropriate habitat, and virtually no likelihood that it will be rediscovered.
SH	Possibly Extirpated (Historical) — Species or community occurred historically in the nation or state/province, and there is some possibility that it may be rediscovered. Its presence may not have been verified in the past 20-40 years. A species or community could become NH or SH without such a 20-40 year delay if the only known occurrences in a nation or state/province were destroyed or if it had been extensively and unsuccessfully looked for. The NH or SH rank is reserved for species or communities for which some effort has been made to relocate occurrences, rather than simply using this status for all elements not known from verified extant occurrences.
S1	Critically Imperiled — Critically imperiled in the nation or state/province because of extreme rarity (often 5 or fewer occurrences) or because of some factor(s) such as very steep declines making it especially vulnerable to extirpation from the state/province.
S2	Imperiled — Imperiled in the nation or state/province because of rarity due to very restricted range, very few populations (often 20 or fewer), steep declines, or other factors making it very vulnerable to extirpation from the nation or state/province.

Texas Conservation Action Plan 2011: Status and Rank Key for use with SGCN and Rare Communities List

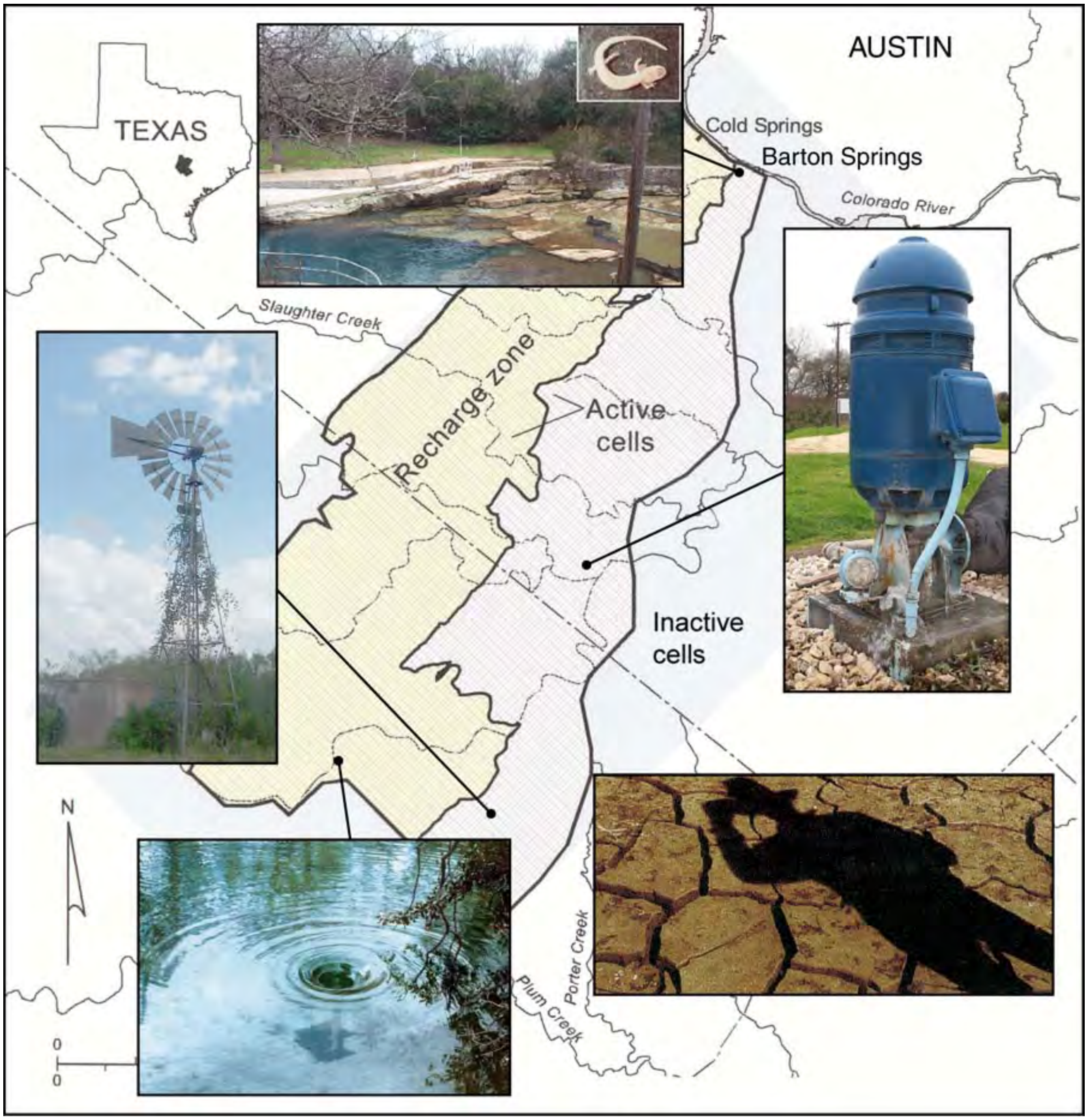
RANK	DEFINITION
S3	Vulnerable — Vulnerable in the nation or state/province due to a restricted range, relatively few populations (often 80 or fewer), recent and widespread declines, or other factors making it vulnerable to extirpation.
S4	Apparently Secure — Uncommon but not rare; some cause for long-term concern due to declines or other factors.
S5	Secure — Common, widespread, and abundant in the nation or state/province.
SNR	Unranked — Nation or state/province conservation status not yet assessed.
SU	Unrankable — Currently unrankable due to lack of information or due to substantially conflicting information about status or trends.
SNA	Secure — Common, widespread, and abundant in the nation or state/province.
Rank Qualifiers	
?	Inexact Numeric Rank—Denotes inexact numeric rank (e.g., G2?)
Q	Questionable taxonomy—Taxonomic distinctiveness of this entity at the current level is questionable; resolution of this uncertainty may result in change from a species to a subspecies or hybrid, or the inclusion of this taxon in another taxon, with the resulting taxon having a lower-priority conservation priority.
Infraspecific Taxon Conservation Status Ranks	
Infraspecific taxa refer to subspecies, varieties and other designations below the level of the species. Infraspecific taxon status ranks (T-ranks) apply to plants and animal species only; these T-ranks do not apply to ecological communities.	
T#	Infraspecific Taxon (trinomial)—The status of infraspecific taxa (subspecies or varieties) are indicated by a "T-rank" following the species' global rank. Rules for assigning T-ranks follow the same principles outlined above for global conservation status ranks. For example, the global rank of a critically imperiled subspecies of an otherwise widespread and common species would be G5T1. A T-rank cannot imply the subspecies or variety is more abundant than the species as a whole-for example, a G1T2 cannot occur. A vertebrate animal population, such as those listed as distinct population segments under under the U.S. Endangered Species Act, may be considered an infraspecific taxon and assigned a T-rank; in such cases a Q is used after the T-rank to denote the taxon's informal taxonomic status. At this time, the T rank is not used for ecological communities.
Variant Ranks	
G#G# or S#S#	Range Rank—A numeric range rank (e.g., G2G3 or S2S3) is used to indicate the range of uncertainty in the status of a species or community. Ranges cannot skip more than one rank (e.g., GU should be used rather than G1G4).
GU	Unrankable—-Currently unrankable due to lack of information or due to substantially conflicting information about status or trends. Whenever possible, the most likely rank is assigned and the question mark qualifier is added (e.g., G2?) to express uncertainty, or a range rank (e.g., G2G3) is used to delineate the limits (range) of uncertainty.
GNR	Unranked—Global rank not yet assessed.
Not Provided	Species is known to occur in this nation or state/province. Contact the relevant natural heritage program for assigned conservation status.
Breeding Status Qualifiers	
B	Breeding—Conservation status refers to the breeding population of the species in the nation or state/province.
N	Nonbreeding—Conservation status refers to the non-breeding population of the species in the nation or state/province.

APPENDIX B

The District's Sustainable Yield Study

Note: The District conducted a sustainable yield study for the Barton Springs segment of the Edwards Aquifer in 2003-2004, as a precursor to the analyses performed as part of the District Habitat Conservation Plan. The body of the main study report, including both text and figures, is included on the following pages as Appendix B, and also in its entirely on the District website at http://www.bseacd.org/publications/reports/. Other links on this webpage may also be of interest to those needing additional information about groundwater availability modeling in general and the modeling that was initially performed by TWDB for this segment and modified in the Sustainable Yield Study.

EVALUATION OF SUSTAINABLE YIELD OF THE BARTON SPRINGS SEGMENT OF THE EDWARDS AQUIFER, HAYS AND TRAVIS COUNTIES, CENTRAL TEXAS



Barton Springs/Edwards Aquifer Conservation District

October 2004

Cover Illustration

Background image of the numerical model area was modified from Scanlon et al. (2001). Photographs (clockwise from the top) include: Barton Springs Pool with low water level during cleaning and image of the endangered Barton Springs Salamander, photograph of spring by Brian A. Smith; turbine pump in the Creedmoor-Maha well field, photograph by Brian B. Hunt; mudcracks and farmer’s shadow during a drought, photograph by Mike Rayner (‘The Age’); whirpool formed above Cripple Crawfish Cave in Onion Creek, photograph by David Johns; windmill that serves as the District’s Mountain City observation well for drought declaration, photograph by Brian B. Hunt. Cover illustration arranged by Brian B. Hunt.

EVALUATION OF SUSTAINABLE YIELD OF THE BARTON SPRINGS SEGMENT OF THE EDWARDS AQUIFER, HAYS AND TRAVIS COUNTIES, CENTRAL TEXAS

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10/28/04

Brian A. Smith, Ph.D., P.G.
Senior Hydrogeologist, Assessment Program Manager

STATE OF TEXAS
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Brian B. Hunt, P.G.
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Barton Springs/Edwards Aquifer Conservation District
October 2004

EVALUATION OF SUSTAINABLE YIELD OF THE BARTON SPRINGS SEGMENT OF THE EDWARDS AQUIFER, HAYS AND TRAVIS COUNTIES, CENTRAL TEXAS

Barton Springs/Edwards Aquifer Conservation District
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Edited by Board Subcommittee on Sustainable Yield
Dr. Robert D. Larsen
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Technical Editing
Lana Dieterich, Bureau of Economic Geology, The University of Texas at Austin

October 2004

STATE OF TEXAS §
§ **RESOLUTION # 102804-01**
COUNTY OF TRAVIS §

A RESOLUTION OF THE BOARD OF DIRECTORS, BARTON SPRINGS EDWARDS AQUIFER CONSERVATION DISTRICT, ACCEPTING AND ENDORSING THE REPORT ENTITLED *EVALUATION OF SUSTAINABLE YIELD OF THE BARTON SPRINGS SEGMENT OF THE EDWARDS AQUIFER, HAYS AND TRAVIS COUNTIES, CENTRAL TEXAS*, BEING A SCIENTIFIC STUDY PREPARED BY DISTRICT STAFF

WHEREAS, the Barton Springs Edwards Aquifer Conservation District (the District) is a Groundwater Conservation District created by an act of the 70th Legislature and subject to various requirements of State Law governing groundwater districts, including Texas Water Code Chapter 36; and

WHEREAS, the District was established for the purpose of providing for the conservation, preservation, protection, recharging and prevention of waste of groundwater and of groundwater reservoirs in the Barton Springs segment of the Edwards Aquifer (Aquifer), and to control subsidence caused by withdrawal of groundwater from those groundwater reservoirs or their subdivisions; and

WHEREAS, the Aquifer is either a sole source or primary source of drinking water for approximately 44,000 people living and working in the central part of this state, and is a vital resource to the general economy and welfare of the State of Texas; and

WHEREAS, the District's Management Plan defines sustainable yield as the amount of water that can be pumped for beneficial use from the Aquifer under a reoccurrence of the drought of record conditions, after considering adequate water levels in water wells and degradation of water quality that could result from low water levels and low spring discharge; and

WHEREAS, the Board of Directors in 2003 instructed staff to develop and conduct a scientific investigation relative to determining the sustainable yield of the Aquifer and revising the Texas Water Development Board's currently approved Groundwater Availability Model for the Aquifer; and

WHEREAS, staff has developed and completed a report responsive to all charges assigned by the Board of Directors; and

WHEREAS, the report was subjected to an independent peer-review process by members of the Groundwater Model Advisory Team, who included, Renee Barker, Senior Hydrogeologist, United States Geological Survey; Nico Hauwert, Hydrogeologist, City of Austin and Doctoral Candidate, University of Texas at Austin; David Johns, Senior Hydrogeologist, City of Austin; Dr. Robert Mace, Director Groundwater

Resources Division, Texas Water Development Board; Dr. Bridget Scanlon, Senior Research Scientist, Bureau of Economic Geology, University of Texas at Austin; Dr. Jack Sharp, Chevron Centennial Professor in Geology, University of Texas at Austin; Raymond Slade, United States Geological Survey (retired) and Consulting Hydrologist; Eric Strom, Assistant District Chief, United States Geological Survey;

NOW, THEREFORE BE IT RESOLVED by the Board of Directors of the Barton Springs Edwards Aquifer Conservation District, that:

SECTION I

The Board of Directors accepts and endorses the report prepared by staff entitled, *Evaluation of Sustainable Yield of the Barton Springs Segment of the Edwards Aquifer, Hays and Travis Counties, Central Texas*.

SECTION II

Furthermore, the Board of Directors declares that the information presented in the report is the best science and information currently available for evaluating the sustainable yield of the Barton Springs segment of the Edwards Aquifer.

The motion passed with 5 ayes, and 0 nays.

PASSED AND APPROVED THIS THE 28th DAY OF OCTOBER, 2004.

Robert D. Larsen

Dr. Robert D. Larsen, Board President

Jack Goodman

Jack Goodman, Board Vice-President

David R Carpenter

David Carpenter, Board Member

Chuck Murphy

Chuck Murphy, Board Member

ATTEST:

Craig Smith

Craig Smith, Board Secretary

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PREFACE

A statutory mandate charges the Barton Springs/Edwards Aquifer Conservation District (District) with the responsibility of conserving, protecting, and enhancing groundwater resources of the Barton Springs segment of the Edwards Aquifer. Part of this responsibility is to determine the amount of groundwater available for use in the aquifer. The District considers the amount of groundwater available for use as the "sustainable yield" that is defined in Section 1.2 (Concepts and Definitions of Sustainable Yield). So that this amount may be readily determined, Texas Water Code (§ 36.1071(h)) requires the District to use results of a groundwater availability model (GAM) in conjunction with other studies or information of the aquifer. Additionally, to ensure that future water needs are met during times of severe drought, the regional water planning process (§ 16.053(a)) requires water planning to be based on drought-of-record conditions.

To fulfill these mandates, at the May 22, 2003, board meeting, the District's Board of Directors charged the Assessment Program staff with conducting an evaluation of sustainable yield of the Barton Springs segment of the Edwards Aquifer. Assessment Program staff made 11 presentations to the District's board and 2 board workshops were held during the evaluation process. Results of the evaluation were presented to the board on February 5, 2004. The purpose of this report is to present the results of that evaluation and to provide a scientific foundation for establishing sustainable-yield policies by the District for resource management.

This report is based on research conducted by many scientists and represents decades of work. Numerical modeling presented herein expands on that knowledge, specifically building on the research and modeling of Slade et al. (1985), Wanakule (1989), Barrett and Charbeneau (1996), and Scanlon et al. (2001). To assist in the evaluation of sustainable yield, the District's Assessment Program staff assembled a Groundwater Model Advisory Team (GMAT) consisting of expert scientists from the Austin area. GMAT met monthly between September 2003 and February 2004 and provided critical input and comments throughout the modeling and sustainable-yield evaluation process. GMAT is made up of:

Rene Barker, Senior Hydrogeologist, U.S. Geological Survey

Nico Hauwert, Hydrogeologist, City of Austin; Ph.D. candidate, The University of Texas at Austin

David Johns, Senior Hydrogeologist, City of Austin

Dr. Robert Mace, Director, Groundwater Resources Division, Texas Water Development Board

Dr. Bridget Scanlon, Senior Research Scientist, Bureau of Economic Geology, The University of Texas at Austin

Dr. Jack Sharp, Chevron Centennial Professor in Geology, The University of Texas at Austin

Raymond Slade, U.S. Geological Survey, retired, and Consulting Hydrologist

Eric Strom, Assistant District Chief, U.S. Geological Survey

Technical meetings were held on September 10, 2003, and March 24, 2004, for the District to receive input from a broad group of technical specialists (Appendix C). From March through April 2004 results of these studies were presented to various stakeholder groups, including the Lower Colorado River Authority (LCRA), U.S. Fish and Wildlife Service (USFWS), District permittees, news media, environmental groups, and representatives from the City of Kyle.

It is the authors' professional opinion, and the consensus of GMAT members, that the information presented herein is the best science and information currently available for evaluating sustainable yield of the Barton Springs segment of the Edwards Aquifer.

EVALUATION OF SUSTAINABLE YIELD OF THE BARTON SPRINGS SEGMENT OF THE EDWARDS AQUIFER, HAYS AND TRAVIS COUNTIES, CENTRAL TEXAS

Brian A. Smith, Ph.D., P.G. and Brian B. Hunt, P.G.

EXECUTIVE SUMMARY

The combined effects of drought and substantial pumping can result in a decline in water levels and spring flow in an aquifer. This report evaluates potential impacts on groundwater availability in the Barton Springs segment of the Edwards Aquifer (Barton Springs aquifer) during a recurrence of drought-of-record (1950's) conditions and various rates of pumping. A numerical groundwater model and hydrogeologic data were the primary tools used in this evaluation.

The Barton Springs aquifer is an important groundwater resource for municipal, industrial, domestic, recreational, and ecological needs. Approximately 50,000 people depend on water from the Barton Springs aquifer as their sole source of drinking water. Additionally, various spring outlets at Barton Springs are the only known habitats of the endangered Barton Springs salamander. The amount of groundwater available to meet current and future needs is limited, however.

A statutory mandate charges the Barton Springs/Edwards Aquifer Conservation District (District) with the responsibility of conserving, protecting, and enhancing groundwater resources of the Barton Springs aquifer. Part of this responsibility is to determine the amount of groundwater available for use in the aquifer, referred to as "sustainable yield" by the District. State law requires water planning for drought conditions and use of groundwater modeling information in conjunction with other studies or data about the aquifer. The purpose of this report is to provide scientific foundation and documentation for policy makers' use so that future water needs are met during times of severe drought.

The Barton Springs aquifer is located within parts of Travis and Hays Counties in Central Texas. It lies along the Balcones Fault Zone and is generally bounded to the north by the Colorado River, to the south by the southern groundwater divide near the City of

Kyle, to the east by the interface between the fresh- and saline-water zones, and to the west by the Balcones Fault.

A numerical model was developed for the Barton Springs aquifer (Scanlon et al., 2001; Appendix A). However, the model was constructed to match water levels and spring flow from a period wetter than that of the 1950's drought. Because the model was calibrated to a relatively wet period, it overestimates spring flow and underpredicts water-level elevations compared with measurements taken during the 1950's drought of record. The model was recalibrated so that simulated and measured spring-flow and water-level data from the 1950's drought matched better. The recalibrated model was then used to predict spring-flow and water-level declines under 1950's drought conditions and various future pumping scenarios. Hydrogeological data, such as saturated-thickness maps, potentiometric-surface maps, and well-construction and yield data, were evaluated alongside the model results so that impacts to water-supply wells under 1950's drought conditions and various rates of pumping could be estimated.

Results of the evaluations indicate that water levels and spring flow are significantly impacted by 1950's drought conditions and projected pumping. The model indicates that 10 cubic feet per second (cfs) of pumping, combined with 1950's drought conditions, produces a mean monthly spring flow of about 1 cfs. According to a minimum daily discharge of 9.6 cfs, such as that measured in 1956, spring flow could temporarily cease for periods less than 1 month. At 15 cfs of pumping, spring flow would cease for at least 4 months. Simulations indicate that a given pumping rate applied under 1950's drought conditions would diminish Barton Springs spring flow by an amount equivalent to the pumping rate. As many as 19% of all water-supply wells in the District may be negatively impacted under 1950's drought conditions and a pumping rate of 10 cfs. Negative impacts might include wells going dry, water levels dropping below pumps, or intermittent yield due to low water levels. Finally, under 1950's drought conditions and high rates of pumping, potential for saline water to flow from the saline-water zone into the freshwater aquifer would increase, impacting water-supply wells and endangered species.

Information presented herein is based on the best science and information currently available for evaluating sustainable yield of the Barton Springs segment of the

Edwards Aquifer. Results of this sustainable-yield evaluation will be considered in District sustainable-yield policies for resource management.

1.0 INTRODUCTION

The Barton Springs segment of the Edwards Aquifer (Barton Springs aquifer) is a part of a prolific karst aquifer on which approximately 50,000 people depend as their sole source of drinking water. As part of the Barton Springs/Edwards Aquifer Conservation District's (District's) role of managing groundwater extraction from the Barton Springs aquifer, the District has conducted groundwater modeling of the aquifer to help determine the amount of groundwater available for pumping from the aquifer. The principal tool for this evaluation has been a groundwater availability model developed for the Lower Colorado Regional Water Planning Group (LCRWPG) and the Texas Water Development Board (TWDB). Modifications were made to the model to evaluate the amount of spring flow at Barton Springs and potential impacts to water-supply wells during a recurrence of 1950's drought-of-record conditions using various rates of projected pumping. Aquifer conditions from the 1950's were used in this evaluation because the regional water-planning process ((Texas Water Code, § 16.053(a)) requires that water planning be based on drought-of-record conditions.

The model indicates that under 1950's drought conditions and current (2004) pumping rates of about 10 cubic feet per second (cfs), flow from Barton Springs would decrease to less than 1 cfs or cease altogether. Low flows or a lack of flow from the springs is likely to have a negative impact on Barton Springs as a recreational resource and on the endangered salamanders that live in the springs. An analysis of hydrogeologic data and model-simulated water-level drawdown due to pumping shows that, under 1950's drought conditions and current (2004), permitted pumping rates, as many as 19% of the water-supply wells in the District would be dry or experience a reduction in yield. Results of these model simulations will be used by the District to establish policies with the objective of minimizing impacts of high rates of pumping during a recurrence of 1950's drought conditions.

1.1 Purpose and Approach

The purpose of this study was to evaluate impacts of pumping and 1950's drought conditions on spring flow and water levels in wells in the Barton Springs aquifer. The evaluation was based on modification of a Groundwater Availability Model (GAM) developed for the Barton Springs aquifer by Scanlon et al. (2001) (hereafter referred to as the 2001 GAM). That model evaluated long-term groundwater availability in response to future pumping and potential future droughts. A GAM first developed in 2000 established the model framework (Scanlon et al., 2000). Modifications were made to the 2000 GAM to meet standards set by TWDB for the Barton Springs GAM. The 2001 GAM, the foundation for numerical modeling in this study, was recalibrated to better simulate 1950's drought conditions.

The approach to evaluating sustainable yield of the Barton Springs aquifer consisted of:

I. Numerical Modeling (Section 2)

- The 2001 GAM was recalibrated (hereafter referred to as the *recalibrated GAM*) by changing hydraulic conductivity and storage values to better match spring-flow and water-level data from the 1950's drought;
- The recalibrated GAM was then used to predict spring-flow and water-level declines under 1950's drought conditions and various rates of projected future pumping.

II. Water-Supply-Well Impacts (Section 3)

- A potentiometric map of water levels measured during the 1950's drought was superimposed on simulated drawdown maps for various rates of pumping to create a series of saturated-thickness maps.
- Well yield and construction data were evaluated using the potentiometric and saturated thickness maps to estimate the number of wells that might be negatively impacted under various simulated pumping rates. Negative impacts might include wells going dry, water levels dropping below the pumps, or intermittent yield due to low water levels.

1.2 Concepts and Definitions of Sustainable Yield

One commonly used definition of safe yield of an aquifer is “the amount of water which can be withdrawn from it [the aquifer] annually without producing an undesired result” (Todd, 1959). The potential for “undesired results” from excessive pumping of an aquifer is an important concept that the District considers in its role of protecting and enhancing groundwater resources of the Barton Springs aquifer. The term *sustainable yield* is used more commonly today to acknowledge limits to aquifer pumping that need to be considered in the management of an aquifer in order to minimize or eliminate undesired results (Sophocleous, 1997). The District’s task is to determine quantitatively the undesired results and what policies can be developed to minimize them.

The District defines sustainable yield as: *the amount of water that can be pumped for beneficial use from the aquifer under drought-of-record conditions after considering adequate water levels in water-supply wells and degradation of water quality that could result from low water levels and low spring discharge* (Barton Springs/Edwards Aquifer Conservation District, 2003). During periods of severe drought the District is concerned about sufficient yield from water-supply wells, quality of groundwater, and quantity and quality of groundwater discharging from Barton Springs. Low-water-level conditions brought about by 1950’s drought conditions combined with high rates of future pumping could cause Barton Springs and some water-supply wells to undergo water-quality degradation because of migration of saline water from the saline-water zone into the freshwater part of the aquifer.

2.0 SETTING

The Barton Springs aquifer is an important groundwater resource for municipal, industrial, domestic, recreational, and ecological needs. Approximately 50,000 people depend on water from the Barton Springs aquifer as their sole source of drinking water, and the various spring outlets at Barton Springs are the only known habitats for the endangered Barton Springs salamander. The following sections provide the geologic and hydrogeologic framework needed for evaluating sustainable yield.

2.1 Study Area

The Barton Springs aquifer constitutes the study area. Located within parts of Travis and Hays Counties in Central Texas, the aquifer lies within the Balcones Fault Zone and is generally bounded to the north by the Colorado River, to the south by the southern groundwater divide near the City of Kyle, to the east by the interface between the fresh- and saline-water zones, and to the west by the Balcones Fault (Figure 2-1).

2.2 Previous Aquifer Studies

Previous investigations in the Barton Springs aquifer have concentrated primarily on characterizing the geology and hydrogeology of the Edwards Aquifer system. Brune and Duffin (1983) discussed the availability of groundwater during a drought in terms of spring flow and recognized that withdrawals (pumping) equal to, or greater than, the lowest recorded spring-flow measurement of 9.6 cfs (March 29, 1956) would dry up all spring flow at Barton Springs. Similarly, Guyton and Associates (1979) reported a one-to-one relationship of pumping to spring flow at Comal and San Marcos Springs in the San Antonio segment of the Edwards Aquifer (San Antonio aquifer). Senger and Kreitler (1984) discussed the hydrogeology and hydrochemistry of the aquifer.

Slade et al. (1986) presented a series of potentiometric maps, including two that represented drought conditions from 1956 and 1978. Slade et al. (1985) used a numerical groundwater-flow model calibrated to average aquifer conditions in order to simulate the effects of pumping on groundwater availability. Transient-model simulations were calibrated to a limited period (164 days) under average flow conditions and did not focus on 1950's drought conditions or the effects on spring flow. Results of their future simulations, with increased projected demand (pumping of 12.3 cfs), indicate that water levels would decline more than 100 ft in the vicinity of Kyle and that significant portions of the western aquifer would be completely dewatered.

A groundwater-flow model was developed by Wanakule (1989) to be used as an aquifer-management tool for the Barton Springs aquifer. This study identified dewatering of parts of the aquifer and decreasing spring flow as major issues to be considered in any aquifer-management scenarios.

Barrett and Charbeneau (1996) developed a lumped-parameter model of the Barton Springs aquifer that divided the aquifer into five cells, each representing a surface drainage basin associated with creeks flowing across the recharge zone. The lumped-parameter model was calibrated to 1989 through 1994 conditions. Although this model was more simplistic than the finite-difference model prepared by Slade et al. (1985), it did not simulate water levels, but showed a good match between simulated and measured spring flow for the period of simulation of 1989 through 1998. However, the lumped-parameter model appears to overpredict spring flow slightly during the 1996 drought period, when compared with measured values.

Sharp and Banner (1997) discussed hydrogeology and critical issues with regard to the Edwards Aquifer as a resource, such as endangered species and legal, political, and economic management problems. Sharp and Banner pointed out that demand on groundwater in 1996 exceeded historical availability during the droughts between 1947 and 1956 and that continued demand at or above this level would cause considerable hardship on the region when severe drought conditions recur.

The 2000 and 2001 GAMs were developed to evaluate groundwater availability and predict water levels and spring flow in response to increased pumpage and 1950's drought conditions (Scanlon et al., 2000, 2001). The 2001 GAM reduced a bias in the 2000 GAM that overpredicted spring flow during 1950's drought conditions by about 10 cfs. Good agreement was found between measured and simulated flow at Barton Springs and between measured and simulated water levels (Scanlon et al., 2001). Results of the simulations indicated that under average recharge conditions, with future pumpage conditions of 19 cfs,, water-level drawdown is small (less than 35 ft). Water-level declines are large (up to 270 ft) under future pumpage (19 cfs) and drought conditions.

The 2001 GAM predicts that spring flow would cease at a pumping rate of 15 cfs under drought-of-record conditions. However, both the 2000 and 2001 GAMs were calibrated to data from the 1990's, a period wetter than that of the 1950's drought. Because the model was calibrated to a wetter period, the 2001 GAM overestimated spring flow and generally underpredicted head elevations compared with those of measured 1950's drought conditions (Smith and Hunt, 2004). Results of the 2000 GAM, corrected for an apparent 10 cfs bias during 1950's drought conditions, predicts that spring flow will decline to rates of 4 cfs at a pumping rate of 6.3 cfs under drought-of-record conditions. The 2001 GAM model, uncorrected for an estimated bias of 2 cfs (Section 3.1—Purpose and Approach of Modeling), showed drying of Barton Springs at 15 cfs of pumpage combined with 1950's drought conditions. Both models indicate that during drought conditions, spring flow declined in direct proportion to increases in pumpage. Therefore, when corrected for estimated bias, both models indicate that under 1950's drought conditions, Barton Springs begins to experience drying at pumping rates of about 10 to 11 cfs.

Scanlon et al. (2003) demonstrated that equivalent porous media models are capable of simulating regional groundwater flow and spring discharge in a karst aquifer.

2.3 Geology

The Edwards Aquifer is composed of the Cretaceous-age Edwards Group (Kainer and Person Formations) and the Georgetown Formation (Figure 2-2; Figures 6 and 7 in Appendix A). Sediments making up the Edwards Group accumulated on the Comanche Shelf as shallow marine, intertidal, and supratidal deposits. The Georgetown Formation, disconformably overlying the Edwards Group, was deposited in a more openly circulated, shallow-marine environment (Rose, 1972).

The prolific Edwards Aquifer evolved over millions of years as the result of numerous geologic processes such as deposition, tectonism, erosion, and diagenesis. The formation of the aquifer was influenced significantly by fracturing and faulting associated with the Balcones Fault Zone (BFZ) and dissolution of limestone and dolomite units by infiltrating meteoric water (Sharp, 1990; Barker et al., 1994; Sharp and Banner, 1997).

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; Barton Springs/Edwards Aquifer Conservation District, 2002). The limestone units generally step down to the east, primarily because of faulting. Most faults trend to the northeast and are downthrown to the southeast, with total offset of about 1,100 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).

2.4 Hydrogeology

2.4.1 Aquifer Boundaries

The areal extent of the Barton Springs aquifer is about 155 mi^2. Approximately 80% of the aquifer is unconfined; the remainder is confined (Slade et al., 1985). The aquifer is bounded on the north by the Colorado River, the regional base level and location of spring discharge (Slade et al., 1986) (Figure 2-1). The east boundary is the interface between the fresh-water zone and the saline-water or "bad-water" zone of the aquifer, characterized by a sharp increase in dissolved constituents (more than 1,000 mg/L total dissolved solids) and a decrease in permeability (Flores, 1990). The west boundary of the aquifer is defined by the western limit of Edwards Aquifer hydrogeologic units and the BFZ (Slagle et al., 1986; Small et al., 1996) and is limited locally by saturated thickness of the aquifer.

The southern hydrologic divide between the Barton Springs aquifer and the San Antonio segment of the Edwards Aquifer (San Antonio aquifer) is estimated to occur between Onion Creek and the Blanco River, according to potentiometric-surface elevations and recent dye-tracing information (LBG-Guyton Associates, 1994; Hauwert et. al, 2004).

2.4.2 Recharge

2.4.2.1 Surface Recharge

Estimates of recharge based primarily on 3 years of continuous flow data from five of the six major creeks show that as much as 85% of the water that recharges the Barton Springs aquifer occurs within six major creek channels (Slade et al., 1986). The remaining recharge is attributed to upland areas, which include tributary streams. Recent investigations have demonstrated that most recharge infiltrates via discrete features, such as caves, sinkholes, fractures, and solution cavities within stream channels (Barton Springs/Edwards Aquifer Conservation District and City of Austin, 2001). Additional flow and recharge data are currently being collected by the USGS, City of Austin, the District, and The University of Texas at Austin to verify and further refine quantification of sources of recharge to the Barton Springs aquifer. The recharge zone is about 90 mi^2. East of the recharge zone, the aquifer is overlain by less permeable clay and limestone units, which hydraulically confine the aquifer farther east in the confined, or artesian, zone (Figure 2-1).

2.4.2.2 Subsurface Recharge

The amount of 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 surface discharge (Slade et al., 1985). Leakage from the saline-water zone is probably minimal, although the leakage does influence water quality at Barton Springs during low-spring-flow conditions (Senger and Kreitler, 1984; Slade et al., 1986). On the basis of a geochemical evaluation, Hauwert et al. (2004) found that the contribution to spring flow from the saline-water zone to Barton Springs under low-flow conditions could be about 3.5% of the discharge.

Subsurface flow into the Barton Springs aquifer from adjacent aquifers such as the San Antonio aquifer and the Trinity Aquifer is limited when compared with surface recharge (Slade et al., 1985). Hauwert et al. (2004) indicated that flow across the south boundary is probably insignificant under the conditions tested. However, the potential exists for such leakage during severe drought conditions, which was not tested in that study. As part of the sustainable-yield evaluation, an analysis of the southern groundwater divide was conducted to evaluate the potential for flow across that boundary (Appendix B).

Flow (or leakage) from the Trinity Aquifer into the Barton Springs aquifer is thought to be relatively insignificant. In fact, estimates based on water quality at Barton Springs suggest that less than 1% of flow to the springs is from the Trinity Aquifer (Hauwert et al., 2004). Although leakage from the Trinity Aquifer is thought to be insignificant compared with total recharge rates, leakage may nevertheless locally impact water quality and influence water levels (Slade et al., 1986). A groundwater model of the Trinity Aquifer includes lateral groundwater leakage into the Edwards Aquifer in the San Antonio area in order for the model to simulate observed hydrogeologic conditions (Mace et al., 2000). However, where the Trinity Aquifer is in contact with the Barton Springs aquifer, the Trinity model indicates little or no lateral flow into the Barton Springs aquifer. Upward "leakage" from the Trinity Aquifer into the Edwards Aquifer is also thought to be limited and to occur locally along high-permeability fault zones (Slade et al., 1986). The District investigated the local vertical flow potential between the Edwards and (upper-middle) Trinity Aquifers using a nested well pair in the west part of the recharge zone. Results of that local investigation support the idea of limited vertical leakage from the Trinity to the Edwards Aquifer, demonstrating that actual potential for vertical flow is from the Edwards to the Trinity in the vicinity of the nested wells.

2.4.3 Discharge

Discharge from the aquifer is primarily from spring flow and pumpage from wells in the study area. Amount of subsurface discharge occurring through adjacent aquifers is unknown, although it is thought to be relatively small on the basis of a water-budget analysis for surface recharge and surface discharge (Slade et al., 1985).

2.4.3.1 Spring Flow

The largest natural discharge point of the Barton Springs aquifer is Barton Springs, located in Barton Creek about ¼ mi upstream of its confluence with the Colorado River (Figure 2-1). Barton Springs consists of four major outlets, the largest discharging directly into Barton Springs pool, a major recreational attraction of the City of Austin.

Long-term mean discharge from Barton Springs is 53 cfs (Figure 26 in Appendix A). The lowest instantaneous spring-flow measurement of 9.6 cfs was made on March 29, 1956 (Baker et al., 1986; Brune, 2002). The lowest monthly mean spring flow of 11 cfs was reported at the end of the 7-yr drought-of-record (1950's drought) during July and August of 1956 (Slade et al., 1986). Comal Springs in the San Antonio aquifer ceased flowing for about 4 months in 1956 during that drought.

Additional springs with small discharge are present along Town Lake. The largest of these is Cold Springs, which is located on the south bank of the Colorado River about 1.5 mi upstream of the mouth of Barton Creek. Measurements of spring flow from Cold Springs are limited and imprecise but range from 2.6 to 6.8 cfs (Brune, 2002; Hauwert et al., in press).

The aqueous chemistry of groundwater discharging from the springs varies with aquifer conditions, the most substantial decrease in water quality occurring under low-flow conditions. Increases in chloride, sodium, sulfate, and strontium concentrations are reported for low-flow conditions that result from an influx from the saline-water zone and the underlying Trinity Aquifer (Senger and Kreitler, 1984). Additionally, under low-flow conditions, nutrients (primarily nitrates) increase in concentration (City of Austin, 1997).

2.4.3.2 Pumpage

Water-supply wells in the Barton Springs aquifer include about 970 active wells that pump water for public, domestic, industrial, commercial, irrigation, and agricultural uses. About 10% of these wells have annual pumping permits issued by the District, which have so far totaled about 2.3 billion gallons (7,060 acre-ft per year, 9.75 cfs) of water in 2004. Most permitted pumpage is for public-supply and industrial purposes. Nonpermitted pumpage, such as agricultural and domestic supply, is estimated to be less than 10% of the permitted pumpage volume, or about 200 million gallons per year. The most significant volumes of permitted pumping occur in the southeast part of the aquifer (Figure 28 in Appendix A). Combined, these pumping volumes are about 2.5 billion gallons per year (7,818 acre-ft per year) and equate to a mean pumping rate of about 10.8 cfs for 2004 (Figure 2-3).

Scanlon et al. (2001) estimated that pumping would increase linearly from 9.3 cfs in 2000 to 19.6 cfs by the year 2050. Future pumping projections are described in Appendix A (Scanlon et al., 2001). These rates are rough estimates that are based on projections from LCRWPG and the Capital Area Metropolitan Planning Organization (CAMPO).

2.4.4 Groundwater Storage and Flow

The Edwards Aquifer is geologically and hydraulically heterogeneous and anisotropic, both of which strongly influence groundwater flow and storage (Slade et al., 1985; Maclay and Small, 1986; Hovorka et al., 1996; Hovorka et al., 1998). Karst aquifers, such as the Barton Springs aquifer, are commonly described as triple porosity (and permeability) systems consisting of matrix, fracture, and conduit porosity (Ford and Williams, 1992; Quinlan et al., 1996; Palmer et al., 1999). Most storage of water in the Edwards Aquifer is within the matrix porosity (Hovorka et al., 1998); therefore, volumetrically, flow through the aquifer is dominantly diffuse. However, groundwater dye-tracing studies demonstrate that significant components of groundwater flow are rapid and influenced by conduits (Hauwert et al., 2002). Hydraulic conductivity values from aquifer tests range from 0.40 to 75.3 ft/day and are log-normally distributed (Figure 27 in Appendix A). Storativity values range from 0.05 to 0.00078, reflecting unconfined to confined aquifer conditions, respectively (Scanlon et al., 2001). Heterogeneity of the aquifer is further expressed in terms of well yields, which range from less than 10 gallons per minute (gpm) to greater than 1,000 gpm. Well yields in the confined part of the Edwards Aquifer are often limited more by pump size than by aquifer properties (Schindel et al., 2004). Pump setting and well depth can also limit well yields.

The Edwards Aquifer is dynamic, with rapid fluctuations in spring flow, water levels (Figures 14 and 15 in Appendix A), and storage, reflecting changes in recharge (climatic conditions) and pumpage (demand). Water-level measurements and groundwater dye-tracing studies provide insight into groundwater-flow paths from source areas (recharge locations) to wells and springs. Groundwater generally flows west to east across the recharge zone, converging with preferential groundwater-flow paths subparallel to major faulting, and then flowing north toward Barton Springs. Although regional groundwater flow in the aquifer occurs largely under diffuse conditions, preferential flow paths were traced along troughs in the potentiometric surface, indicating zones of high permeability. Rates of groundwater flow along preferential flow paths, determined from dye tracing, can be as fast as 4 to 7 mi/day under high-flow conditions or about 1 mi/day under low-flow conditions (Hauwert et al., 2002).

2.4.5 1950's Drought

The worst drought on record for central and other parts of Texas occurred from 1950 through 1956 and is referred to as the "1950's drought" (Lowry, 1959). The mean annual precipitation of 23.1 inches during the 7-yr drought was about two-thirds of the long-term annual precipitation of 33.5 inches (Figure 4a in Appendix A). Mean annual precipitation during the last 3 years of the drought was 16.5 inches, about half the long-term average precipitation (Scanlon et al., 2001). During the 1950's drought, spring flow reached historic lows at Barton Springs and ceased at Comal Springs.

2.4.6 Trinity Aquifer

The Edwards Aquifer overlies the Trinity Aquifer system in the BFZ (Figure 2-2). Along the west part of the study area, where the Edwards Aquifer is thin, water-supply wells commonly penetrate the lower Edwards units and are completed in the Upper Trinity Aquifer. The Upper Trinity Aquifer comprises the Upper Glen Rose Formation, which satisfies, almost exclusively, domestic and livestock needs with very small (less than 5 gpm) to small (5–20 gpm) yields of highly mineralized water (relative to the Edwards Aquifer) in the Central Texas Hill Country west of the BFZ (DeCook, 1960; Ashworth, 1983; Muller and McCoy, 1987). The Upper Trinity Aquifer, consistently about 350 to 400 ft thick in Hays County, has hydraulic properties (storage and hydraulic conductivity) substantially lower than those of the Edwards Aquifer (Ashworth, 1983; Barker et al., 1994). Seasonal variations in heads in the Upper Trinity Aquifer are most dramatic in wells less than 250 ft deep. These aspects make the Upper Trinity Aquifer more susceptible than the Edwards Aquifer to the effects of drought (Barker et al., 1994).

3.0 NUMERICAL GROUNDWATER MODELING

A numerical model was developed for the Barton Springs aquifer (Scanlon et al., 2001; Appendix A) as an aquifer-management tool to help evaluate the effects of pumping on the aquifer. The numerical model was developed by The University of Texas at Austin, Bureau of Economic Geology, and the District for the Groundwater Availability Model (GAM) initiative of TWDB. GAM models are part of an effort to develop state-of-the-art, publicly available, numerical groundwater-flow models for major and minor aquifers in Texas. The 2001 GAM was recalibrated to better match spring-flow and water-level data from the 1950's drought and was used to predict spring-flow and water-level declines under 1950's drought conditions and various rates of pumping.

3.1 Purpose and Approach of Modeling

The District reviewed the 2001 GAM (Scanlon et al., 2001) to evaluate its effectiveness as a tool for helping determine groundwater availability during conditions similar to those of the 1950's drought. The District conducted extensive reviews and analyses of hydrogeologic data collected by numerous individuals and organizations over many years. The Groundwater Model Advisory Team (see Preface), a team of scientists from the Austin area, assisted the District in reviewing the data and the model.

After reviewing the results of the 2001 GAM, the team decided that the model could not simulate spring-flow or water-level conditions of the 1950's drought as well as it could simulate conditions of the 1990's. The 2001 GAM indicated that monthly mean spring flow under 1950's drought conditions with no pumping would be 13.7 cfs. The lowest monthly mean measured flow from the springs was 11 cfs in July and August 1956 (Slade et al., 1986). Subtracting a pumping rate of 0.66 cfs from 13.7 cfs gives a discrepancy of about 2 cfs between the 2001 GAM simulated results and mean measured values of spring flow. Because the 2001 and recalibrated GAMs are based on stress periods of 1 month, they may not be able to simulate conditions equivalent to those represented by instantaneous spring-flow measurements. This limitation of resolution of the models precludes a direct comparison of the model results for lowest spring flow with the lowest instantaneous measurements at Barton Springs of 9.6 cfs (Figure 3-1).

The 2001 GAM underpredicted water levels by as much as 150 ft in some parts of the aquifer relative to actual water-level measurements from the 1950's. Table 3-1 shows data representing the lowest water levels measured in nine wells during the 1950's drought and the amount of water-level adjustments necessary for model results to match measured water levels. Because of the discrepancy between measured and simulated values for spring flow and water levels of 1950's drought conditions, the District decided to recalibrate the 2001 GAM to emphasize conditions during the 1950's drought. The recalibrated model is hereafter referred to as the recalibrated GAM. The following approaches were taken in recalibrating the model:

- Hydraulic conductivity and storage values were modified from values used in the 2001 GAM to provide a better match between simulated and measured heads and simulated and measured spring flow. All other model parameters were unchanged.
- Pumping rates were set at 0.66, 10, 15, and 19 cfs for each simulation to represent 1950's pumping, current pumping, and two future-pumping scenarios, respectively.

3.2 Previous Work: 2001 GAM

A GAM was developed for the Barton Springs segment of the Edwards Aquifer by The University of Texas at Austin, Bureau of Economic Geology (BEG), and the District on behalf of the LCRWPG and TWDB (Scanlon et al., 2001). The conceptual model, design, and boundaries are described in Appendix A (Scanlon et al., 2001), and parts of the report are described only briefly here.

The GAM is a two-dimensional (one-layer), finite-difference model based on the U.S. Geological Survey's (USGS's) MODFLOW code (Harbaugh and McDonald, 1996). Processing MODFLOW for Windows (PMWIN) v. 5.1.7 was used as a pre- and postprocessor for running MODFLOW (Chiang and Kinzelbach, 2001). The model consists of a single layer with 120 rows, 120 columns, and 7,043 active rectangular cells 1,000 ft long and 500 ft wide (Figure 29 in Appendix A).

The north boundary of the model is the Colorado River, which is the regional base level (Slade et al., 1986). The east boundary is the bad-water line that is thought to have minimal contribution via leakage (Senger and Kreitler, 1984; Slade et al., 1986; Hauwert et al., 2004). The south boundary is a hydrologic divide along Onion Creek in the recharge zone and between the cities of Buda and Kyle in the confined part of the aquifer (LBG-Guyton Associates, 1994). The west boundary is the Mount Bonnell fault, which acts as a hydrologic barrier to flow (Senger and Kreitler, 1984). All boundaries are simulated as no-flow boundaries in the model, as described earlier in Section 2.4.2.2 (Subsurface Recharge).

Ten zones of hydraulic conductivity resulted from steady-state calibration, with values ranging from 1 to 1,236 ft/day (Figure 30 in Appendix A). Recharge values were distributed to stream cells across the recharge zone on the basis of recharge estimates from flow-loss studies. Interstream recharge was set at 15% of the total recharge (Slade et al., 1986). For 7-yr drought-of-record simulations, recharge was assumed to equal discharge (1950 through 1956).

As required by TWDB for its GAM contracts, the model was run in five 10-yr periods to simulate aquifer conditions from 2001 through 2050. Each 10-yr period simulated 3 years of average flow conditions, followed by 7 years of drought conditions, which mimicked the drought of the 1950's. Monthly stress periods were used for transient simulations, resulting in a total of 120 stress periods for a 10-yr simulation. Recharge and pumpage were set for each stress period. Pumping rates were increased linearly over that period, with pumping at the end of 2050 (19 cfs) representing 2.1 times the pumping rate at the beginning of 2001.

Transient simulations of the 2001 GAM were calibrated to conditions from 1989 through 1998. Simulated values for spring flow during this period, plotted with measured spring-flow values, are shown in Figure 36 in Appendix A. Spring flows ranged from 17 cfs in August 1997 to about 123 cfs in 1992. For this calibration period, peak spring-flow values might have been higher than those shown in Figure 36 in Appendix A for 1992 because floodwaters overtopping the upstream pool dam may have distorted accurate measurement of spring flow.

Pumping from permitted wells was assigned to cells on the basis of pumping records at the District. Estimates of exempt well pumping were calculated from countywide estimates and assigned equally to all active cells. During each simulation, pumping rates changed monthly as a result of seasonal demand.

The Drain package of MODFLOW represents Barton Springs and Cold Springs, with a high drain-conductance value to allow unrestricted discharge. To estimate spring flow from Barton Springs, spring flow output from the model was reduced 6% to account for flow discharging from Cold Springs.

3.2.1 2001 GAM Simulations

Good agreement was found in the 2001 GAM between measured and simulated flow at Barton Springs and between measured and simulated water levels (Scanlon et al., 2001). The root mean square (RMS) error between measured and simulated discharge for the transient model is 12 cfs, which represents 11% of the range in discharge measured at Barton Springs (1989 through 1998). Spring flow during periods of high flow (more than 100 cfs of spring flow) is overpredicted by the 2001 GAM (Figure 36 in Appendix A). The 2001 GAM generally reproduced water levels monitored continuously in wells throughout the study area (Figures 38 and 39 in Appendix A). The RMS error of 29 ft represents 11% of the water-level drop in the model area during low-flow conditions (March and April 1994) (Figure 40 in Appendix A).

Results of the simulations indicated that under average recharge and future pumpage conditions (19 cfs) water-level drawdown is small (less than 35 ft). Water-level declines are large (as much as 270 ft) under future pumpage (19 cfs) and when combined with 1950's drought conditions. Predicted spring flow is 0 cfs in response to pumping 19 cfs under 1950's drought conditions.

3.3 Transient-Model Recalibration

Incremental changes were made through trial and error to specific yield, specific storage, and hydraulic conductivity values to recalibrate the transient portion of the 2001 GAM to 1950's drought conditions. The recalibrated GAM was run with the adjusted parameters, and model output was reviewed for spring-flow and water-level responses to parameter changes. Between model runs, changes were made to one parameter at a time. Further adjustments were made to parameters until simulated spring flow and water-level values were deemed to agree adequately with measured values from the 1950's drought.

By the end of recalibration, specific yield was decreased from 0.005 to 0.0021, and specific storage was decreased from 1.0×10^{-6} to 5.0×10^{-7}. Revised hydraulic conductivity values range from 0.3 to 740 ft/day (Table 3-2 and Figure 3-2), compared with a range of 1 to 1,236 ft/day in the 2001 GAM. Hydraulic conductivity and storage values for the aquifer under 1950's drought conditions were expected to be lower because of differences between the shallow part of the aquifer, where dissolution of the limestone and conduit development would be greater than at greater depths in the aquifer (Ogden et al., 1986; Maclay, 1995; Small et al., 1996). Additionally, specific-capacity tests have been performed in one well in the Barton Springs aquifer during high- and low-flow conditions. Results indicated that hydraulic parameters were lower under low-flow conditions (Raymond Slade, personal communication).

3.3.1 Water Levels

Nine wells were identified as having an adequate number of water-level measurements from the 1950's to recalibrate the 2001 GAM to low-flow conditions. An additional well measurement from the 1978 drought was added to this data set for better geographic coverage. Table 3-1 shows the lowest measured values for water levels in 10 wells with 1950's water-level data, plus simulated water-level values from the 2001 GAM and from the recalibrated GAM. The RMS error between measured water levels and simulated water levels in the 10 wells was improved to 6% using the recalibrated GAM, compared with 25% using the 2001 GAM. TWDB contract requirements request less than a 10% RMS error in water levels for the steady-state model. Water levels from the end of simulated 1950's drought conditions are plotted against measured values from the 1950's drought in Figure 3-3. In addition to a lower RMS error for results of the recalibrated model, the coefficient of determination (R^2) value of 0.94, using linear regression procedures, indicates a good match between simulated and measured values. The R^2 value for a perfect fit between data sets would be 1.0. For this same time period, R^2 value of the 2001 GAM results is 0.64.

The recalibrated GAM provides a good match between simulated water levels and measured water levels during periods of lowest flow, particularly during July and August 1956 (Figure 3-4). The simulation of 1950's drought conditions includes periods when recharge increases to near-average conditions, such as in 1953, which brought the aquifer briefly out of severe drought. During these periods, simulated water-level elevations in the recalibrated GAM are overpredicted when compared with measured values. This overprediction of water levels during these periods may be due to the inability of the model to simulate high rates of conduit flow during high water-level conditions. However, the recalibrated GAM succeeds in adequately simulating periods of low flow, such as during 1952 and 1954 through 1956 (Figure 3-4).

3.3.2 Spring Flow

Simulated and measured monthly mean spring-discharge values from the 1950's drought show good agreement in both the 2001 and recalibrated GAMs (Figure 3-5a), with very good agreement for periods when spring flow is below 20 cfs in the recalibrated GAM (Figure 3-5b). In the recalibrated GAM, RMS error between measured and simulated discharge for the entire 1950's drought is 13.8 cfs, which represents 23% of the range of measured discharge fluctuations. The 2001 GAM data set has an RMS error of 12.4 cfs, which represents 21% of the range of measured discharge for the same period. However, for periods of low flow below 18 cfs, the recalibrated GAM data set has a better match to measured values than the 2001 GAM, achieving an RMS of 6.0 cfs, or 10% of the range of measured discharge. The 2001 GAM achieves an RMS of 9.7 cfs, or 16% of the range of measured discharge for the same low flow period.

Amount of pumping estimated for the 1950's of 0.66 cfs (an annual rate of 478 acre-ft/yr) was incorporated into the recalibrated GAM (Brune and Duffin, 1983). The 2001 GAM indicated that spring flow under 1950's drought conditions with no pumping would be 13.7 cfs. The lowest monthly mean flow from the springs was 11 cfs from four flow measurements in July and August 1956 (Slade et al., 1986). The lowest daily flow measurement ever recorded was 9.6 cfs, which occurred on March 29, 1956 (Brune, 2002). Subtracting a pumping rate of 0.66 cfs from 13.7 cfs gives a discrepancy of about 2 cfs between 2001 GAM simulated results and measured values of spring flow. The recalibrated GAM was able to produce a spring-flow value of 11 cfs, matching the lowest monthly mean for measured spring flow.

3.3.3 Sensitivity Analyses

Following TWDB requirements for GAM contracts, sensitivity analyses were conducted on the recalibrated GAM to assess the impact of varying certain aquifer parameters, such as recharge, specific yield, and specific storage, on simulated spring flow and water levels in various wells. Because of convergence problems with the 2001 GAM for adjustments of some parameters, only those analyses that were reported in the 2001 GAM report (Scanlon et al., 2001) were tested during evaluation of the recalibrated model. Results of these sensitivity analyses are presented in Figures 3-6 through 3-9. Sensitivity analyses were not conducted to test responses to variations in pumping because the scenarios for future conditions use various pumping rates. Of the parameters tested, changes in recharge had the most significant impacts on spring flow and water levels. Changes to specific yield and specific storage had similar impacts on spring flow, although water levels are more sensitive to changes in specific storage than specific yield. By changing specific storage from 5.0×10^{-7} to 5.0×10^{-6}, range of simulated water levels was reduced considerably. Spring flows were not impacted significantly by increasing specific storage and specific yield by a factor of 10, but lower end spring-flow values increased slightly. Because concerns about the aquifer are primarily for low-flow conditions, small changes in spring flow under these conditions are significant.

3.4 Predictions

3.4.1 Pumping

Pumping data for each simulation incorporated changes in pumping due to seasonal demand, as originally constructed in the 2001 GAM. The 2001 GAM considered impacts to spring flow and water levels over a 50-yr period, with steadily increasing pumpage. Because a drought similar to that of the 1950’s could occur at any time in the future, the recalibrated GAM simulates 1950’s drought conditions under pumping rates mentioned earlier. The purpose of this approach is to avoid any implication that any particular set of aquifer conditions or impacts might occur at a particular future date.

3.4.2 Impacts to Spring Flow and Water Levels

For effects of specific pumping rates on water levels and spring flow under 1950's drought conditions to be determined, pumping rates of 0.66, 5, 10, 15, and 19 cfs were evaluated in the recalibrated GAM. At a pumping rate of 0.66 cfs, the model predicts flow at Barton Springs to be 11 cfs, which is the same as the measured monthly mean flow (Figure 3-10), but 1.4 cfs more than an instantaneous flow measurement of 9.6 cfs reported for March 29, 1956. At 5 cfs of pumping (not shown in Figure 3-10), simulated spring flow decreases to a monthly mean of about 6.5 cfs. At 10 cfs of pumping, which is the estimated amount of pumpage in 2004, the model predicts that spring flow will be about 1 cfs averaged over 1 month. According to a minimum daily discharge of 9.6 cfs measured in 1956, spring flow may temporarily cease for periods less than 1 month. At a pumping rate of 15 cfs, simulated spring flow will be 0 for at least 4 months. Model simulations suggest a nearly one-to-one relationship between pumpage and spring flow. This relationship is in agreement with the conceptual model of previous investigators (Brune and Duffin, 1983) and historical water-balance analysis (Sharp and Banner, 1997).

To illustrate the impacts to spring flow from the combined effects of 1950's drought conditions and pumping, two potentiometric surface maps were prepared comparing the effects of 19 cfs pumping during both average flow conditions and 1950's drought conditions (Figure 3-11). The equipotential lines for average flow conditions with 19 cfs of pumping show that groundwater flow in the west part of the aquifer is primarily from west to east. Near the boundary between recharge and confined zones, flow turns to the northeast, toward the springs. This pattern of flow matches well with potentiometric surface maps prepared from measured water levels in as many as 175 wells across the aquifer. Under 1950's drought conditions with 19 cfs of pumping, flow in the west part of the aquifer is again from west to east. However, near the boundary between the recharge and confined zones, flow is to the southeast. This is the area in which primary pumping wells are concentrated (Figure 28 in Scanlon et al., 2001). Potentiometric surface lines show that flow is converging on a broad area north and south of Buda. Under these conditions there is no flow from the springs, and water levels are about 18 ft below the elevation of Barton Springs. Section 4.0 (Impacts to Water Levels and Water-Supply Wells from 1950's Drought Conditions and Pumping) discusses in detail potential impacts to water-supply wells due to pumping at various rates under 1950's drought conditions.

Under low-flow conditions, additional gains and losses of groundwater could affect availability of usable groundwater for wells and flow at Barton Springs. Other potential sources include the Trinity Aquifer, part of the Edwards Aquifer south of the southern groundwater divide, the saline-water zone, cross-aquifer flow via poorly constructed wells, and urban leakage (water and wastewater). The volume of contributing flows from Trinity leakage, the saline-water zone, and gains and losses in groundwater from the San Antonio aquifer appears to be less than 1% of the total spring flow during droughts (Hauwert et al., 2004). Additionally, during periods of drought, water levels in the Trinity and San Antonio aquifers will also be low, with a low potential for substantial flow from these sources. However, the quality of water from the saline-water zone, the Trinity Aquifer, or infrastructure leakage may be poor and significantly degrade water in the Barton Springs aquifer, potentially rendering it unsuitable for drinking or for endangered species. Future studies are required to quantify these influences.

Although these factors that could potentially affect spring flow were not specifically simulated in the 2001 and recalibrated GAMs, simulation results can be compared with historic measured values of Barton Springs flow to examine whether the sum of recharge sources was accurately assessed. Because discharge is assumed to equal discharge for the 1950's drought, the 2001 and recalibrated GAMs indirectly account for these potential additions of water at spring-flow rates as low as 11 cfs. Furthermore, pumpage increases within the Trinity Aquifer source area west of the Barton Springs aquifer can be expected to reduce contributions that were experienced in the 1950's.

3.5 Qualifications and Data Needs

All models have limitations on how they simulate a real system. Because this model simulates a karst aquifer that consists of diffuse, fracture, and conduit flow of groundwater, its limitations are associated primarily with its ability to simulate conduit flow. The 2001 and recalibrated GAMs use zones of high hydraulic conductivity near the springs to approximate conduit flow. This works well for simulating potentiometric maps, spring flow, and regional groundwater flow, but it is unsuitable for simulating travel times (Scanlon et al., 2003).

The 1950's simulation period contains times when rainfall and recharge increase to near-average conditions, such as in 1953, bringing the aquifer briefly out of severe drought. During these periods, simulated water-level elevations are overpredicted when compared with measured values, owing to the dynamic nature of the karst system and the inability of MODFLOW to explicitly simulate conduit flow. It is recommended that the District evaluate the potential of new groundwater models, as they become available, that can incorporate conduit flow. In the future, a karst groundwater modeling initiative at the Southwest Research Institute may provide such a model (Ron Green, personal communication). Another option may be a revision to the modeling pre- and postprocessor, Groundwater Vistas, which will allow for variable hydraulic conductivities as a function of saturated thickness (Robert Mace, personal communication).

Any future groundwater model in the Barton Springs aquifer will be limited by the number of surface and subsurface recharge data available. The 2001 GAM uses streamflow and stream-loss data to estimate surface recharge for the transient period of 1989 through 1998. Future scenarios were based on 1950's drought conditions for which no recharge data are available. To estimate recharge, the 2001 GAM had spring discharge equal to recharge, and the recalibrated GAM incorporates this same assumption. Recharge may be slightly overestimated during low recharge periods because some of the water being discharged may be coming from aquifer storage rather than directly from recharge (Scanlon et al., 2001). The District, City of Austin, and the Texas Commission on Environmental Quality (TCEQ) are currently funding USGS flow stations on all major upstream and downstream locations of the recharge zone in order to gauge recharge.

Additional studies are needed to better characterize the potential for flow in or out of the aquifer at its boundaries. These areas include:

(1) Southern groundwater divide. The groundwater model currently being developed for the San Antonio aquifer could be used to quantify the amount of water that might flow between Barton Springs and San Antonio aquifers under various

aquifer conditions. This model incorporates the Barton Springs aquifer within the model area. A water flux could be determined for a line of cells near the groundwater divide. Simulated water levels from the San Antonio model could be used to establish a time-varying specified-head boundary for the Barton Springs model (Appendix B). Additional groundwater dye tracing coupled with detailed potentiometric map studies may also provide further insight into flow along the boundaries.

(2) *Edwards-Trinity connection*. Additional monitor well pairs could be installed to measure head differences between Edwards and Trinity Aquifers. An effective method for determining vertical hydraulic gradients between aquifers would be to install one or more multiport monitoring wells. Such a well would be completed with multiple zones in both the Edwards and Trinity Aquifers that could indicate the potential for flow between different hydrogeologic units. Synoptic water-level data could be collected from wells in areas for which both Edwards and Trinity wells are available to compare potentiometric surfaces between aquifers. Potential impacts on water quality at Barton Springs and in water-supply wells due to flow from the Trinity into the Edwards Aquifer are poorly understood. Losses and gains of water via interaquifer flow due to poorly constructed wells are also unknown.

(3) *Saline-water line*. Additional studies are needed to determine potential for migration of saline water into the freshwater part of the aquifer and potential impacts on water quality at Barton Springs and in water-supply wells near the saline-water line.

(4) *Influence of urban recharge*. Studies currently being conducted at The University of Texas at Austin suggest that a significant amount of subsurface recharge due to losses from water-supply, storm-water, and sewer lines could be occurring. During periods of severe drought (1950's drought conditions), the amount of water available from urban recharge might make up a significant part of recharge to the aquifer. Potential impacts on water quality at Barton Springs and in water-supply wells from urban recharge are poorly understood. As those studies are completed, results could be incorporated in the District's modeling.

3.6 Major Findings

- The recalibrated GAM provides a better match between simulated and measured spring-flow and water-level values under 1950’s drought conditions than does the 2001 GAM.

- Recalibrated GAM simulations indicate that for each 1 cfs of groundwater pumped from the aquifer under 1950’s drought conditions, discharge from Barton Springs will diminish by about 1 cfs.

- The recalibrated GAM simulates a mean monthly spring flow of about 1 cfs, with the present (2004) pumping rate of 10 cfs under 1950’s drought conditions. According to a minimum daily discharge of 9.6 cfs measured in 1956, spring flow may temporarily cease for periods of less than 1 month. At 15 cfs of pumping, spring flow will cease for at least 4 months.

- Simulations of 1950’s drought conditions with present (2004) and future rates of pumping indicate that significantly lower water levels will occur in most parts of the aquifer, resulting in an increased potential for flow from sources with poor water quality, such as the saline-water zone.

4.0 IMPACTS TO WATER LEVELS AND WATER-SUPPLY WELLS FROM 1950'S DROUGHT CONDITIONS AND PUMPING

The combined effects of drought and significant pumping can result in a decline in water levels and spring flow in an aquifer. Municipal water supplies in some areas of Texas declined or were exhausted completely during the 1950's drought (Lowry, 1959). Declining water levels due to drought and pumping will have negative effects on water-supply wells in a variety of ways, including increased energy costs, deterioration of water quality, water levels declining below pumps or well bores, and well yields that decline below usable rates (Bartolino and Cunningham, 2003). For the Barton Springs aquifer, these effects will profoundly impact wells that partly penetrate the aquifer and where dewatering of the aquifer occurs. Earlier discussion stated that current demand on groundwater in the Edwards Aquifer may exceed the historical availability during the 1950's drought and would cause considerable hardship on the region when severe drought conditions recur (Sharp and Banner, 1997).

To assess these potential hardships, this section describes methods used to characterize and quantify impacts to water-supply wells under 1950's drought conditions with increasing demand on groundwater. Hydrogeological, structural, and well data were used, along with results from the recalibrated GAM to estimate potential impacts to water-supply wells due to 1950's drought conditions and increasing rates of pumping. Results of this study indicate that water levels are significantly impacted by 1950's drought conditions alone and that even greater impact occurs when effects of pumping are combined with 1950's drought conditions.

4.1 Methods

About 970 active water-supply wells are in the District that pump water from the Barton Springs aquifer for public, domestic, industrial, commercial, irrigation, and agricultural purposes. Pumping from the Barton Springs aquifer under 1950's drought conditions could negatively impact many of these wells. In general terms, *negative impacts* to wells occur when instantaneous demand from a well is not met. The number of wells that could be negatively impacted by low water levels was evaluated using two methods:

- Saturated aquifer thickness analysis: assessing the number of wells having low specific capacity that are located in areas having less than 100 ft of saturated aquifer thickness in the unconfined zone and
- Saturated borehole thickness analysis: assessing the total number of wells throughout the study area that partly penetrate the aquifer, resulting in less than 25 ft of saturated borehole.

Each of these methods requires evaluation of changes in saturation of the aquifer and well boreholes using measured and model-simulated data. Data sets used in the evaluation, including structure-contour maps, potentiometric maps, simulated drawdown, and well information, are described in the subsections following.

A small number of the same wells may be included within each evaluation. However, attempts to eliminate duplicate counts of wells do not appear possible because one is a broad, percentage-based evaluation and the other is a well-by-well evaluation.

4.1.1 Data Sets

An evaluation of saturated aquifer thickness and saturated borehole thickness relies heavily on several key data sets and maps described in the subsections following. Contouring of all surfaces was done using the grid-based graphics program Surfer® in the UTM-feet coordinate system (NAD 83). Kriging was used for generating contour surfaces because it produced the most realistic contours. Grid size of cells was about 1,200 × 1,500 ft, according to distribution and density of data sets within Surfer®.

4.1.1.1 Structure-Contour Maps

The primary data set (245 wells) for the structure-contour surface of the bottom of the aquifer was derived from driller's descriptions, geophysical logs, geotechnical logs, and core data (Figure 4-1). Geologic contacts and geologic maps (Small et al., 1996) were also used for control. Faulting was not incorporated into the gridding process; limited faulting incorporated into the gridding process did not appear to have a profound effect on contour shapes owing to the relatively high density of data. The top of the basal nodular member of the Kainer Formation was used as the effective bottom of the aquifer in this study. This member is about 50 ft thick in the study area and, despite localized karst development where exposed at the surface, it appears to have low permeability and storage compared with that of the rest of the Edwards Group (Small et al., 1996). These hydraulic characteristics of the basal nodular are evident from a few widely spaced well-drilling observations. In contrast, at many localities where the basal nodular is exposed at the surface, the unit characteristically contains light-toned, recrystallized rock having abundant springs and solution cavities that suggest a high permeability. Furthermore, in many driller's and geophysical logs, the top of the basal nodular member can be distinguished more readily than the top of the Glen Rose Formation. For the purposes of estimating the bottom of the aquifer, the top of the basal nodular was assumed to be the base of the Edwards Aquifer, even though the basal nodular is clearly a part of the Edwards Aquifer. In many areas elevation of the bottom of the aquifer was derived by applying known total aquifer thickness and unit thicknesses from well-defined, stratigraphic control points.

To characterize change in thickness of the aquifer as it relates to groundwater availability, an isopach (thickness) map of the lithologic units in the recharge and confined zones was created (Figure 4-2).

4.1.1.2 Potentiometric Maps

For a potentiometric map representing 1950's drought conditions to be constructed, water-level data since 1937 were collected from the TWDB database and reports and USGS reports (Follet, 1956; DeCook, 1960; Slade et al., 1986). Limited water-level data from the 1950 through 1957 drought period exist. A composite potentiometric-surface map was constructed using July and August 1956 water-level data as the base data set. Additional 1950's water-level data were adjusted in elevation to better match the July and August 1956 period when possible, and additional water-level data from low-spring-flow periods were used. The final data set used to construct the composite potentiometric-surface map representing 1950's drought conditions has about 50 control points within the District boundaries (Table 4-1; Figure 4-3).

The composite potentiometric-surface map generally contains a steep west-east gradient along the west (unconfined) part of the aquifer. The gradient decreases toward the confined part of the aquifer, and direction of flow changes from W-E to SW-NE, which is similar to other potentiometric-surface maps that were constructed with many more data points. The composite potentiometric-surface map created by these procedures is similar in shape, gradient, and elevation to the 1950's map in Slade et al. (1986). However, most significant differences in the maps occur in the area of interest along the western Edwards Aquifer, with some elevations being more than 50 ft higher in elevation in the Slade et al. (1986) map. The map constructed in this study contains more control data in this area, which may account for these differences.

4.1.1.3 Simulated Drawdown

The recalibrated GAM was used to simulate drawdown in 41 wells at pumping rates of 5, 10, 15, and 19 cfs (Table 4-2). Some of these wells also have historical water-level data. Simulated drawdown was calculated as the difference in water levels between simulated 1950's drought conditions (with 0.66 cfs pumping) and simulated 1950's drought conditions for each pumping scenario listed earlier. Data were gridded and contoured to create drawdown surfaces. Figure 4-4 is an example of the drawdown contour map with 10 cfs pumping. Each of these simulated drawdown surfaces was subtracted from the potentiometric map representing measured 1950's drought conditions. Resulting potentiometric maps were created to quantify impacts under drought with pumping scenarios described earlier. Figure 4-5 is an example of a potentiometric map representing combined effects of 1950's drought and 10 cfs of pumping.

4.1.1.4 Well Data

Specific capacity is defined as well production per unit decline in head and is a function of the aquifer and well setting and pumping rate and duration (Mace et al., 2000). In this study, specific-capacity data throughout the aquifer were used to characterize the percentage and magnitude of drawdown in wells from pumping. Specific-capacity data were assembled from well schedules and pumping-test reports and reviewed to improve data quality. A total of 168 measurements were compiled from various hydrologic conditions, 29 of which are from long-term aquifer pumping tests, and they have a broad distribution of values. No attempts were made to normalize the specific-capacity data to aquifer thickness (unit specific capacity). The data show heterogeneity distributed across the aquifer; however, the lowest values are located primarily within the western, unconfined area of the aquifer and along the saline-water zone on the east side of the aquifer (Figure 4-6a and 4-6b).

Wells drilled to produce water in the Edwards Aquifer range in depth from 40 to 800 ft, with an average well depth of about 400 ft. Distribution of well depths is not systematic across the aquifer. A District review of wells reported to have "gone dry" or that had yield problems during a drought revealed that cable-tool drilling, a drilling technology largely unused today, was responsible for many shallow-penetrating wells.

4.1.2 Saturated Aquifer Thickness Analysis

Maps of saturated aquifer thickness were created from three types of data: (1) the structure contour of the bottom of the aquifer, (2) potentiometric maps representing measured 1950's drought conditions, and (3) simulated drawdown for various pumping rates. Saturated-thickness maps in the unconfined zone were created using the following mathematical relationship at each grid node:

$$b_{wt} = (H_t - s) - A_b \qquad (1)$$

where b_{wt} is saturated thickness of the water-table aquifer (in feet), H_t is the total measured hydraulic head representing 1950's drought conditions in feet above mean sea level (msl), s is the hydraulic head loss due to pumping (in feet), and A_b is the elevation of the bottom of the aquifer in feet above msl.

For purposes of this evaluation, 100 ft of saturated aquifer thickness was defined as sufficient to derive adequate water supplies for wells in the unconfined aquifer. This number is a reasonable thickness based on distribution of wells on nondrought saturated-thickness maps and amount of drawdown that occurs for low-yield wells along the west part of the aquifer. Specific-capacity data were compiled and mapped to determine range and distribution of well yields in the unconfined aquifer (Figure 4-6a and 4-1b). In the unconfined zone, 13% of 113 specific-capacity values were less than or equal to 0.17 gallons per minute per foot (gpm/ft). These wells have more than 100 ft of drawdown for a constant pumping rate of 15.9 gallons per minute (gpm). From 184 measurements, average pumping rate for domestic supply wells was determined to be 15.9 gpm.

According to this general approach, those wells will most likely experience problems producing water because drawdown in the borehole will exceed the saturated thickness of the aquifer under these conditions. For example, under 1950's drought conditions with minimal pumping (0.66 cfs), it is estimated that 230 wells may have less than 100 ft of saturated aquifer thickness, and it is estimated that of that total number, 13%, or 30 wells, will experience yield problems. It is assumed that all wells in this analysis penetrate the entire thickness of the aquifer because these wells are generally in the thinnest part of the aquifer.

4.1.3 Saturated Borehole Thickness Analysis

Quantification of the number of wells that would be impacted by combined effects of lower head and partial penetration of the aquifer by a well requires three types of data: (1) location and elevation of the bottom of the well borehole, (2) a corresponding potentiometric surface elevation representing 1950's drought conditions, and (3) drawdown from pumping scenarios. The saturated borehole for each well was determined using the following mathematical relationship:

$$b_s = H_t - W_b \qquad (2)$$

where b_s is saturated borehole thickness (in feet), H_t is total hydraulic head (in feet above msl), and W_b is elevation of the bottom of the borehole (in feet above msl). Hydraulic head for each well having sufficient depth and location information (614 wells) was determined from residuals on potentiometric surface maps in Surfer®.

As in the saturated-thickness evaluation, it is recognized that a negative impact to a well would likely occur before the saturated thickness of a well borehole reached 0 from drought and regional pumping. For this part of the evaluation, 25 ft of saturated borehole was defined as sufficient for deriving adequate water supplies. This number results from recognition that well pumps are generally not set at the bottom of the borehole and the confined part of the aquifer generally has specific-capacity values that are higher than those of the unconfined zone. Therefore, wells in this area would experience less drawdown. For example, under 1950's drought conditions with minimal pumping (0.66 cfs), it is estimated that 43 of the 970 water-supply wells in the District may have less than 25 ft saturated borehole thickness and will therefore have problems with yield.

4.2 Results

The saturated thickness of the aquifer is shown in Figure 4-7 under 1950's drought conditions and minimal pumping (0.66 cfs). The cross-sectional expression of this surface is shown in Figure 2-2. A significant part of the unconfined aquifer in the recharge zone is likely to have little to no water available for water-supply wells under 1950's drought conditions. Figure 4-8 is a composite map of the 100-ft saturated-thickness contour lines under 1950's drought conditions with various pumping scenarios (0.66, 5, 10, 15, and 19 cfs). This figure shows effective drawdown of the aquifer with each scenario of increased pumping under 1950's drought conditions as the 100-ft saturated-thickness contour line moves east with higher rates of pumping. The most significant decrease in saturated thickness occurs along the southwest part of the unconfined aquifer, with the greatest shift in contours between high flow and 1950's drought conditions (Figure 4-8). Drawdown of water levels is small in the north part of the aquifer near the springs and the Colorado River, although even small changes in water levels in this area are associated with significant changes in spring flow. Table 4-3 lists the number of wells located west of the saturated aquifer contour line, which indicates that they have less than 100 ft of saturated aquifer thickness available. For given demand (15.9 gpm) and well yield (Sc= 0.17 gpm/ft), these wells will most likely have insufficient yield as a result of drawdown of the aquifer from 1950's drought conditions and increased pumping. Under 1950's drought conditions and minimal pumping (0.66 cfs), it is estimated that 230 wells may have less than 100 ft of saturated aquifer thickness, and it is estimated that of that total number, 13%, or 30 wells, will experience yield problems.

Under 1950's drought conditions and increased demand, water levels in the confined zone decrease. Although saturated thickness of the aquifer is not severely impacted in the confined zone under these scenarios, decreases in water levels under 1950's drought conditions and increased pumping shift the boundary of unconfined to confined conditions to the east (Figure 2-2). Under 1950’s drought conditions and 19 cfs of pumping, nearly the entire aquifer is hydraulically unconfined.

Water-level decreases will leave some wells with less than 25 ft of saturated borehole (Table 4-4). These wells will most likely have insufficient yield owing to the dewatering of the well borehole primarily because of lower water-level values and partial penetration of the aquifer by the borehole. Under 1950’s drought conditions with minimal pumping (0.66 cfs), it is estimated that 43 of the 970 water-supply wells in the District may have less than 25 ft of saturated borehole thickness and will therefore have problems with yield.

Total number of wells estimated to be impacted by drawdown of water levels is shown in Table 4-5 and in Figure 4-9. Public water-supply systems in operation in the District at the time this report was generated were evaluated to determine whether there was likely to be any impact under 1950’s drought conditions and various rates of pumping. Only two public water-supply systems in the southwest part of the aquifer were found to have insufficient aquifer saturation under 1950’s drought conditions alone. Those two systems serve areas of Oak Forest and Ruby Ranch Subdivisions. Most other public water-supply systems are located in the highly transmissive, confined part of the aquifer and penetrate most of the aquifer thickness. Some small public-supply systems rely primarily on the Trinity Aquifer. Effects of drought and pumping on the Trinity Aquifer are beyond the scope of this investigation.

4.3 Discussion

Hydraulic properties of this karst aquifer are heterogeneous and anisotropic. Wells in the unconfined zone have lower and more variable specific-capacity values than those of the confined zone (Figure 4-6b) and are more susceptible to variations in saturated thickness (Figure 2-2). In the unconfined zone we expect transmissivity and, therefore, specific-capacity values to be lower under lower water-level conditions (drought). Therefore, the percentage of wells with more than 100 ft of drawdown would most likely increase during drought. Accordingly, results presented should represent a minimum estimate of negative impacts to wells from drought and various pumping rates that were evaluated.

Wells in the confined zone are negatively impacted by the combination of decreases in hydraulic head and partial penetration of wells into the aquifer. Many shallow wells were drilled using cable-tool technology before rotary drilling became commonplace.

A significant decrease in hydraulic head in the freshwater zone will increase the potential for flow from the bad-water zone into the freshwater zone (as shown in Figure 2-2), resulting in potential water-quality implications for water-supply wells and Barton Springs. More investigations are needed to characterize this potential.

The compounded effects of drought and significant pumping have been characterized as "negative impacts" in this report. Negative impacts do not necessarily mean that wells will "go dry." If water levels drop below the pump or bottom of the borehole, air would enter the system, causing the well to cease production.

Potential remedies to these negative impacts could include deepening the well farther into the Edwards Aquifer or into the Middle Trinity Aquifer, lowering the pump, setting a lower pumping rate, and obtaining more storage capacity. Other solutions for municipalities or large public-supply corporations include conservation; cross connections to other water sources, such as surface-water lines; desalination of saline water; or an aquifer storage and recovery facility.

Most public-supply wells are drilled to sufficient depth, are located in the confined part of the aquifer, and will not likely be impacted negatively. Generally speaking, public water-supply systems are more capable of mitigating impacts during a drought owing to their ability to control pumping rates, store water, and to cross connect with other water-supply sources.

In the unconfined zone it is common for wells to penetrate into the underlying Upper Trinity Aquifer, as illustrated by wells 5857204 and 5857609 in Figure 2-2. In general these wells penetrate less than 250 ft into the Upper Glen Rose and most likely derive their water from both the Edwards and Upper Trinity Aquifers. The Upper Trinity has negligible contribution to these hybrid wells compared with the Edwards, according to the literature (Barker et al., 1994). However, during drought conditions with high rates of pumping, the Upper Trinity may locally provide sufficient supplies to wells that penetrate through the Edwards. Accordingly, this analysis overestimates impacts on such hybrid wells. Further investigations are needed for us to understand the Trinity Aquifer system's hydraulic connection to the Edwards and its potential as a source of water.

Although the District has the most complete and comprehensive database for the study area, many wells are likely to remain undocumented. In general, these wells predate the existence of the District (pre-1987) and could represent a higher number of wells that partly penetrate the aquifer. Accordingly, our estimates would underestimate impacts of these additional wells during drought conditions and with the various pumping rates evaluated in this report.

The heterogeneity of the karst aquifer system necessitated some assumptions to quantify an "impact" to wells. Primary assumptions that have a direct bearing on the number of wells impacted include specific definitions of impact (e.g., how much saturated aquifer and borehole are sufficient for supplies?). For this study we chose 100 ft of saturated aquifer and 25 ft of saturated borehole, generally corresponding to the recharge and confined zone, respectively. We think that this approach gives a reasonable qualitative and quantitative evaluation of potential impacts. Although all measured data sets (structure, water level, specific capacity) and contour surfaces have implicit assumptions, the results of this study rely heavily on measured data for the impacts of a recurrence of 1950's drought conditions to be assessed. The only data set that uses model-simulated results is effects of pumping on drawdown.

As discussed in Section 3.0, other sources of water may not be accounted for in drawdown simulations, which might overpredict drawdown, such as influx from the saline-water zone, San Antonio and Trinity Aquifers, or recharge from urban infrastructure, such as leaking water and sewer lines. These evaluations may also underpredict drawdown by not accurately estimating pumping from exempt wells, overpumping from permitted wells, or water discharging from the Edwards into the Trinity owing to poor well construction. However, these gains and losses of water from various sources are thought to be small (Hauwert et al., 2004) and may have only a local influence on wells or springs.

Previous studies have not quantified the impacts of drought and various pumping rates. Results of this investigation should assist in policy decision-making on aquifer management and protection of water-supply wells in the District.

4.4 Major Findings

- As many as 7% of the wells in the District, including two public water-supply systems, may be negatively impacted with insufficient yield under 1950's drought conditions alone (with minimal pumping of 0.66 cfs).
- Under 1950's drought conditions and the present pumping rate of 10 cfs, as many as 19% of the wells in the District may go dry or have reduced yields. Most of these negative impacts will be due to a combination of decreased hydraulic head and partial penetration of wells into the aquifer.
- Wells in the confined part of the aquifer that partly penetrate the aquifer are susceptible to negative impacts owing to decreases in water levels during a recurrence of 1950's drought conditions, with or without pumping from other wells.
- Because of low saturated thickness of the southwest part of the unconfined aquifer and low permeability compared with other parts of the aquifer, wells in this area are the most susceptible to negative impacts under 1950's drought conditions. As pumping rates increase, so will potential impacts in this area.
- Under 1950's drought conditions and high rates of pumping, potential for saline water to flow from the saline-water zone into the freshwater aquifer will increase.

5.0 CONCLUSIONS

Results of the sustainable-yield evaluation will be considered in District sustainable-yield policies for resource management.

- The recalibrated GAM provides a better match between simulated and measured spring-flow and water-level values under 1950's drought conditions than the 2001 GAM.
- For each 1 cfs of groundwater pumped from the aquifer under 1950's drought conditions, discharge from Barton Springs will diminish by about the same rate.
- The recalibrated GAM indicates that with the present (2004) pumping rate of 10 cfs combined with 1950's drought conditions, mean monthly spring flow will be about 1 cfs. According to a minimum daily discharge of 9.6 cfs measured in 1956, spring flow may temporarily cease on a daily basis. At 15 cfs of pumping, spring flow will cease for at least 4 months.
- Under 1950's drought conditions and the present (2004) pumping rate of 10 cfs, as many as 19% of the wells in the District may be negatively impacted. Most of those negative impacts will be due to a combination of decreased head and partial penetration of wells into the aquifer.
- Because of low saturated thickness of the southwest part of the unconfined aquifer and low permeability compared with other parts of the aquifer, wells in this area are the most susceptible to negative impacts under 1950's drought conditions. As pumping rates increase, so will potential impacts in this area.

5.1 Acknowledgments

To evaluate sustainable yield and the 2001 GAM, the District assembled a Groundwater Model Advisory Team (GMAT) composed of scientists from the Austin area. GMAT members contributed a considerable amount of time to this effort and provided critical input and comments throughout the modeling and sustainable-yield evaluation process. Those members include Rene Barker (USGS, retired), Nico Hauwert (City of Austin), David Johns (City of Austin), Dr. Robert Mace (TWDB), Dr. Bridget Scanlon (BEG), Dr. Jack Sharp (UT), Raymond Slade (USGS, retired), and Eric Strom

(USGS). Technical writing and review were by Lana Dieterich (BEG). Raymond Slade, Rene Barker, David Johns, Nico Hauwert, and Dr. Robert Mace provided final input and review of this report.

A broad group of scientists and technical experts also provided valuable input during the evaluation process (Appendix C).

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7.0 GLOSSARY OF HYDROGEOLOGIC TERMS

Modified from:
Sharp, J. M., Jr., 1999, A Glossary of Hydrogeological Terms: The University of Texas at Austin, Department of Geological Sciences, 35 p.

Anisotropy – variation of a property at a point with direction.

Aquifer – consolidated or unconsolidated geologic unit (material, stratum, or formation) or set of connected units that yields a significant quantity of water of suitable quality to wells or springs in economically usable amounts.

> **Confined** (or artesian) – an aquifer that is immediately overlain by a low-permeability unit (confining layer). A confined aquifer does not have a water table.
>
> **Unconfined** (or water-table) – the upper surface of the aquifer is the water table. Water-table aquifers are directly overlain by an unsaturated zone.

Aquifer system – intercalated permeable and poorly permeable materials that comprise two or more permeable units separated by aquitards that impede vertical groundwater movement but do not affect the regional hydraulic continuity of the system.

Artesian – hydrostratigraphically confined. In the common usage, it implies the existence of flowing wells, but all flowing wells are not artesian nor do all artesian wells flow.

Attributes – nonspatial, usually alphanumeric, data that are linked to a spatial element (e.g., points depicting well locations may be linked to attribute files containing data on stratigraphy, water levels, water chemistry, etc.).

bad water line- eastern boundary of Edwards Aquifer water in the Barton Springs aquifer of the Edwards Aquifer characterized by having more than 1,000 milligrams per liter (mg/L) of total dissolved solids (Barton Springs/Edwards Aquifer Conservation District, 2003).

Baseflow – groundwater flow to a surface-water body (lake, swamp, or stream).

Bedrock – consolidated rock at various depths beneath the Earth's surface.

Boundary condition – specified conditions at the edges or surfaces of a groundwater system.

Model calibration- involves changing input parameters until the model results match field (measured) observations.

Coefficient of determination (R^2) – percentage of variation of the dependent variable that is explainable by the regression line.

Conceptual model – clear, qualitative physical description of how a hydrogeological system behaves.

Conduit – high-permeability pathway most commonly associated with dissolution features.

Cross-formational flow – vertical groundwater flow from one hydrostratigraphic unit to another.

Diagenesis – process that alters sediment with its burial; temperatures are low, definitely less than metamorphic (°C).

discharge – (1) volumetric flow rate [L^3 t^{-1}] of a stream, spring, or groundwater system; (2) water leaving a groundwater system.

> **Mean discharge** – arithmetic mean of discharges over a given time period.

Divide – topographic high (or ridge) separating surface watersheds (catchments). A groundwater divide is an elevated area, line, or ridge of the potentiometric surface separating different groundwater flow systems.

Domestic use – water used by, and connected to, a household for personal needs or for household purposes, such as drinking, bathing, heating, cooking, sanitation or cleaning, and landscape irrigation. Ancillary use may include watering of domestic animals (Barton Springs/Edwards Aquifer Conservation District, 2003).

Double (or dual) porosity – when two porosities may be associated with a hydrogeological system. An example is a porous rock with a fracture set; such a system may then have two.

Drawdown (s) – drop in head from the initial head caused by pumping from a well or set of wells.

Drought – prolonged period of low (lower than average) rainfall. For the purposes of this study, drought corresponds to a prolonged period of low recharge, water-level elevations, and spring discharge values.

Drought of record (1950's drought) – worst drought on record for Central Texas, which occurred from 1950 through 1957.

Equipotential – line connecting points of equal hydraulic potential or hydraulic head.

Exempt well – well may be exempt if it is (Barton Springs/Edwards Aquifer Conservation District, 2003):

1. used solely to supply the domestic needs of five or fewer households, and a person who is a member of each household is either the owner of the well, a person related to the owner, or a member of the owner's household within the second degree by consanguinity, or an employee of the owner, which is drilled, completed, or equipped so that it is incapable of producing more than 10,000 gallons of groundwater a day on a tract of land larger than 10 acres; or
2. used to provide water for livestock or poultry, which is drilled, completed, or equipped so that it is incapable of producing more than 10,000 gallons of groundwater a day on a tract of land larger than 10 acres.

Fault – fracture that has experienced translation or movement of the fracture walls parallel to the plane of the fracture.

Flow path – path a molecule of water takes in its movement through a porous medium.

Formation – body of rock strata that consists of a certain lithology or combination of lithologies.

Fracture – subplanar discontinuity in a rock or soil formed by mechanical stresses.

Fresh water – water with a salinity <1,000 mg/L; drinkable or potable water is implied.

Groundwater availability modeling (GAM) – initiative by the Texas Water Development Board to develop state-of-the-art, publicly available, numerical groundwater flow models for aquifers in Texas.

Groundwater – generally all water beneath the land surface. Sometimes, it is more narrowly defined as phreatic water or water beneath the water table.

Head (h) – fluid mechanical energy per unit weight of fluid, which correlates to the elevation that water will rise to in a well [L]. Also hydraulic head.

Heterogeneity – condition in which the property of a parameter or a system varies with space.

Hydraulic conductivity (K) – volume of fluid that flows through a unit area of porous medium for a unit hydraulic gradient normal to that area.

Hydraulic head (h) – elevation in a well in reference to a specific datum; the mechanical energy per unit weight of water [L].

Hydrostratigraphic unit – formation, part of a formation, or group of formations of significant lateral extent that compose a unit of reasonably distinct (similar) hydrogeologic parameters and responses.

Isopach map – map indicating, usually by means of contour lines, the varying thickness of a designated stratigraphic unit.

Karst – geologic terrain with distinctive characteristics of relief and drainage arising primarily from dissolution of rock (or soils) by natural waters. Such terrains are underlain by rocks that have undergone significant dissolution by groundwater flow.

Kriging – geostatistical method of contouring using weighted averages of surrounding data points.

Leakage – flux of fluid from or into an aquifer or reservoir. Commonly refers to cross-formational flow.

MODFLOW – finite-difference, numerical model for groundwater flow developed by the U.S. Geological Survey.

Observation (monitor) well – well that is used to measure the elevation of the water table or the potentiometric surface.

Outcrop – point at which a formation is present at the Earth's surface.
Parameter – (1) defined physical quantity with a numerical value or a value within a certain range; (2) characteristic of a population (e.g., the mean).
Permeability – ease with which a porous medium can transmit water or other fluids.
Permit or pumpage permit – authorization issued by the District allowing withdrawal of a specific amount of groundwater from a nonexempt well for a designated period of time, generally in the form of a specific number of gallons per District fiscal year. Under normal or nondrought conditions, this volume of water may be pumped at any time during the course of the fiscal year at the convenience of and based on the needs of the permittee. However, during times of District-declared drought, monthly pumpage target-reduction goals for specific drought stages are designated in the permittee's UDCP. Achieving these target-reduction goals may result in a permittee pumping less than the permittee's annual permitted pumpage volume (Barton Springs/Edwards Aquifer Conservation District, 2003).
Porosity – volume of voids divided by total volume of a porous medium.
Potential – potential energy per unit mass of fluid.
Public water supply well – well providing groundwater for public water-supply use; nonexempt well (Barton Springs/Edwards Aquifer Conservation District, 2003).
Potentiometric surface – surface of equal hydraulic heads or potentials, typically depicted by a map of equipotentials, such as a map of water-table elevations.
Precipitation – (1) water condensing from the atmosphere and falling in drops or particles (e.g., snow, hail, sleet) to the land surface; (2) formation of a solid from dissolved or suspended matter.
Pump or pumping test – one of a series of techniques to evaluate the hydraulic properties of an aquifer by observing how water levels change with space and time when water is pumped from the aquifer.
Recharge – process by which water enters the groundwater system or, more precisely, the phreatic zone.
Recharge zone – area of the aquifer in which water infiltrates the surface and enters permeable rock layers (Barton Springs/Edwards Aquifer Conservation District, 2003).
Root mean square (RMS) – statistical measure of the magnitude of a set of numbers.
Safe yield- volume of water that can be annually withdrawn from an aquifer (or groundwater basin or system) without (1) exceeding average annual recharge, (2) violating water rights, (3) creating uneconomic conditions for water use, or (4) creating undesirable side effects, such as subsidence or saline water intrusion.
Saturation – state that occurs when all pores are filled with water.
Sinkhole – closed depression in a karstic landscape.
Specific capacity – discharge of a well divided by drawdown in the well. Note that specific capacity can depend on the pumping rate.
Specific storage (Ss) – volume of water released per unit volume of aquifer for a unit decrease in hydraulic head.
Specific yield (Sy) – volume of water that a saturated porous medium can yield by gravity drainage divided by volume of the porous medium.
Spring – point(s) of natural discharge from an aquifer (Barton Springs/Edwards Aquifer Conservation District, 2003).
Storage – water contained within an aquifer or within a surface-water reservoir.
Storativity (S) – volume of water released per unit area of aquifer for a unit decline in head. In a confined aquifer, S is the specific storage (Ss) times aquifer thickness; in an unconfined aquifer, S is equal to the specific yield (Sy) or the effective porosity.
Tracer – usually a solute, suspended matter, or heat that is artificially or naturally induced to evaluate rate and direction of groundwater flow.
Transient – condition in which properties of a system vary with time.

Transmissivity (T) – discharge through a unit width of the entire saturated thickness of an aquifer for a unit hydraulic gradient normal to the unit width, sometimes termed the coefficient of transmissibility [$L^2 t^{-1}$, gpd/ft].

Transport – movement of solute, suspended matter, or heat in a porous medium, in a surface stream, or through the atmosphere.

Trinity Group aquifer – includes the Upper Member of the Glen Rose Formation, known as the Upper Trinity; the Lower Member of the Glen Rose Formation, and the Hensell Sand and Cow Creek Limestone Members of the Travis Peak Formation, known as the Middle Trinity; and the Sligo and Hosston Members of the Travis Peak Formation, known as the Lower Trinity (Barton Springs/Edwards Aquifer Conservation District, 2003).

Unconfined – refers to an aquifer that has a water table and implies direct contact from the water table to the atmosphere (through the vadose zone).

Unsaturated – condition when porosity is not completely filled with water.

Water table – a surface at or near the top of the phreatic zone (zone of saturation) where the fluid pressure is equal to atmospheric pressure. In the field this is defined by the level of water in wells that barely penetrate the phreatic (saturated) zone.

Well – any artificial excavation or borehole constructed for the purposes of exploring for or producing groundwater or for injection, monitoring, or dewatering purposes (Barton Springs/Edwards Aquifer Conservation District, 2003).

Well log – accurately kept record, made during the process of drilling, on forms prescribed by the Water Well Drillers Team, showing the depth of the well bore, thickness of the formations, and character of casing installed, together with any other data or information required by the Water Well Drillers Team; or any other special-purpose well log that may be available for a given well, such as a gamma-ray log, a temperature log, an electric log, or a caliper log (Barton Springs/Edwards Aquifer Conservation District, 2003).

Well yield – discharge of well at (nearly) steady flow [L^3t^{-1}].

Yield – generically, the amount of water pumped from a well (or bore). In Australia, there is a narrower definition—maximum sustainable pumping rate such that the drawdown in a well after 24 hours does not exceed a specified percentage (typically ~2%) of the column of water above the base of the aquifer. It assumes that the well is fully penetrating and screened over all permeable intervals of the aquifer. Units of yield are volume per time [$L^3 t^{-1}$].

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TABLES

Table 3-1. Comparison of measured and simulated water-level values and residuals from the 2001 GAM and recalibrated model.

State well number	Lowest measured elevation*	Measure date	2001 GAM simulation*	Water-level residual (ft)	Recalibrated model simulation*	Water-level residual (ft)
5842911	428	Aug-56	441.7	-13.7	435	-7
5850301	459	Aug-56	443	16	453	6
5850801	521	Jul-56	445	76	519	2
5858101	561	Aug-56	473	88	583	-22
5857903	563	Aug-56	486	77	597	-34
5850502	487	Aug-56	452	35	482	5
5850702	626	Aug-56	476	150	590	36
5850412	650	Aug-78	585	65	653	-3
5857301	595	Aug-56	492	103	598	-3
5857204	643	Dec-50	513	130	624	19

*Elevation in ft above mean sea level

Table 3-2. Comparison of hydraulic conductivity (K) for the 2001 GAM and recalibrated GAM.

Original K (ft/day) 2001 GAM	Revised K (ft/day) recalibrated GAM	% Change
3	0.3	-90%
4.5	0.8	-82%
3.5	1.7	-51%
1	0.5	-50%
93	40	-57%
93	25	-73%
100	75	-25%
39	80	+105%
320	60	-81%
320	192	-40%
1236	740	-40%
39	12	-69%

Table 4-1. Composite potentiometric data.

SWN	Measurement date	Latitude	Longitude	WL elevation (feet above msl)
58-42-607	1/1/1951	30.30139	-97.77194	434.40
58-42-809	2/16/1949	30.26583	-97.80972	421.10
58-42-901	3/7/1955	30.27583	-97.77917	421.20
58-42-903	3/15/1957	30.2633	-97.77124	424.51
58-42-910	2/1/1955	30.27695	-97.78972	428.00
58-42-924	8/1/1949	30.28667	-97.76972	443.40
58-49-802	1/26/1981	30.12825	-97.92657	802.56
58-49-904	4/10/1980	30.13611	-97.88084	594.00
58-50-101	3/19/1952	30.22583	-97.86916	670.74
58-50-104	6/25/1940	30.23611	-97.84444	527.87
58-50-105	10/4/1939	30.23417	-97.85056	581.20
58-50-201	3/9/1956	30.21958	-97.79373	432.29
58-50-205	9/5/1939	30.23111	-97.80556	430.88
58-50-208	3/1/1955	30.21861	-97.82083	458.00
58-50-218	8/1/1978	30.2425	-97.79723	441.00
58-50-301	8/31/1956	30.21035	-97.78159	459.46
58-50-406	8/11/1978	30.19674	-97.84316	532.56
58-50-411	8/18/1978	30.1867	-97.85	554.95
58-50-416*	7/9/2001	30.1766	-97.86723	539.60
58-50-502	8/31/1956	30.18694	-97.81416	486.72
58-50-511	6/30/1956	30.17159	-97.82578	478.59
58-50-701	11/29/1949	30.13722	-97.84778	515.45
58-50-702	8/31/1956	30.14778	-97.87334	626.09
58-50-704	8/14/1978	30.13694	-97.85555	524.67
58-50-7DT*	7/9/2001	30.15528	-97.86182	535.55
58-50-801	8/29/1956	30.14281	-97.81076	531.14
58-50-804	2/10/1949	30.16159	-97.82873	493.86
58-50-808	6/27/1939	30.12556	-97.79972	559.49
58-50-814	3/21/1955	30.14056	-97.79694	552.60
58-50-817	1/1/1956	30.14	-97.83222	500.00
58-50-839	8/14/1978	30.12972	-97.82166	547.64
58-50-902	11/1/1954	30.14139	-97.75777	480.00
58-57-201	12/28/1982	30.10278	-97.93694	748.40
58-57-204	12/5/1950	30.08361	-97.91805	636.60
58-57-301	8/28/1956	30.09389	-97.89139	594.80
58-57-3DB	9/15/1999	30.11445	-97.91221	666.51
58-57-502	5/24/1978	30.06635	-97.94447	675.52
58-57-5JM	3/31/1952	30.04722	-97.95139	710.07
58-57-902	8/29/1956	30.00833	-97.895	567.37
58-57-903	8/28/1956	30.0385	-97.88617	560.14
58-57-905	1/3/1951	30.02667	-97.90361	559.70
58-57-9LN	3/27/1952	30.02583	-97.87833	557.10
58-58-101	8/28/1956	30.08358	-97.84264	562.03
58-58-104	10/24/1950	30.10417	-97.84861	549.10

Table 4-1 continued

SWN	Measurement date	Latitude	Longitude	WL elevation (feet above msl)
58-58-301	8/29/1956	30.09194	-97.78917	554.39
58-58-4JH	3/27/1952	30.06694	-97.85861	570.98
58-58-4PR	11/8/1950	30.04972	-97.86777	566.33
58-58-502	1/9/1951	30.05083	-97.80722	554.40
58-58-7LN	2/26/1952	30.02972	-97.85472	551.87
67-01-3CC	3/26/1952	29.97111	-97.89222	574.50
67-01-3OG	3/26/1952	29.98228	-97.89149	574.30
67-01-3WL	8/31/1954	29.98917	-97.89139	574.00
67-01-6EN	3/26/1952	29.93083	-97.90444	570.91
67-01-807	2/2/1940	29.90083	-97.91917	570.89
67-01-809	11/14/1950	29.91195	-97.92861	574.60
67-02-101	3/26/1952	29.98139	-97.865	568.30

**Water level adjusted 34 ft from well 5850702*

Table 4-2. Simulated drawdown in wells under 1950's drought conditions and various pumping scenarios.

SWN	Water-level drawdown (ft)			
	5 cfs	10 cfs	15 cfs	19 cfs
5842914	1	2	3	16
5842915	2	5	7	21
5849802	5	11	16	20
5849935	26	29	31	30
5850211	5	12	17	26
5850212	6	13	19	34
5850215	6	13	19	33
5850216	4	9	14	28
5850222	7	17	25	40
5850301	7	15	22	38
5850406	14	31	44	56
5850408	13	27	37	45
5850412	11	23	31	38
5850413	14	28	38	46
5850501	21	47	70	96
5850502	16	35	52	74
5850511	21	47	70	95
5850520	8	18	27	43
5850701	32	75	112	151
5850702	32	55	74	87
5850704	33	76	114	151
5850801	29	67	101	135
5857201	11	23	30	35
5857204	38	84	113	128
5857301	42	97	145	187
5857502	25	43	47	49
5857602	38	82	107	114
5857903	48	115	183	246
5858101	48	113	178	241
5858102	43	101	156	211
5858104	43	100	155	209
5858123	41	96	148	200
5858406	48	115	182	246
5858704	49	115	184	245
58501NF	9	20	29	31
58502B2	4	10	15	29
58572R2	36	77	104	119
58573BW	19	41	54	64
58573JD	41	95	141	179
58573SW	16	33	44	52

Table 4-3. Saturated aquifer thickness analysis under 1950's drought conditions and various rates of pumping.

Pumping rate (cfs)	0.66*	5	10	15	19
Total number wells west of the 100-ft saturated-thickness contour	230	267	291	330	408
Number of wells with high probability of insufficient yield**	30	35	38	43	53

**1950's drought pumping;*

***Based on 13% of wells with low specific capacity (Sc=0.17; Q=15.9 gpm)*

Table 4-4. Saturated borehole analysis under 1950's drought conditions and various rates of pumping.

Pumping rate	0.66*	5	10	15	19
Number of wells with high probability of insufficient yield**	43	74	151	216	347

**1950's drought pumping;*

***Based on wells with <25 ft saturated thickness*

Table 4-5. Total impact to wells under 1950's drought and various rates of pumping.

Pumping rate	0.66*	5	10	15	19
Total number of Impacted wells	73	109	189	259	400
Percentage of total wells (n=971)	7	11	19	27	41

**1950's drought pumping*

FIGURES

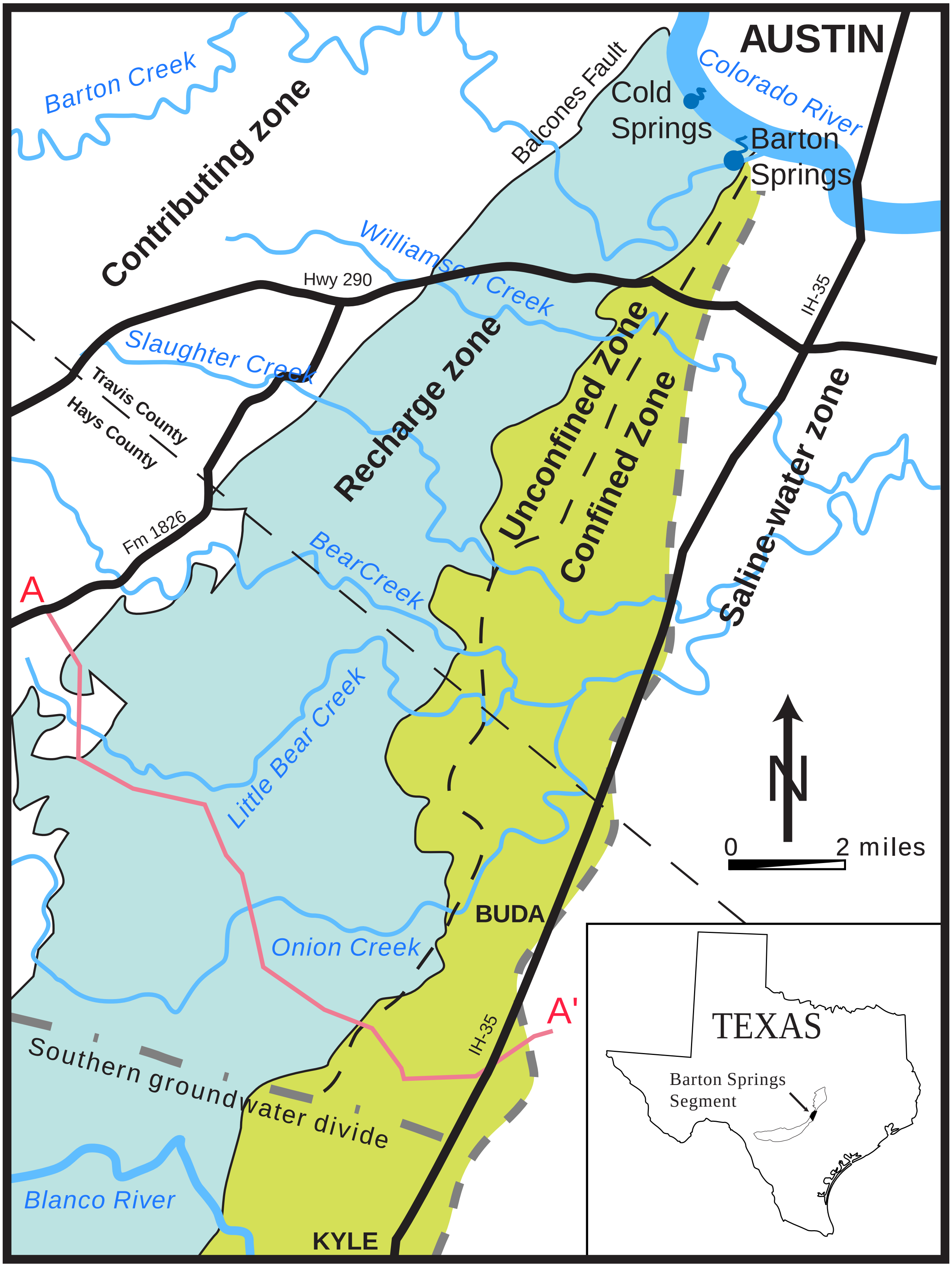

Figure 2-1. Location map of the study area. Note: shaded area is the Edwards Aquifer.

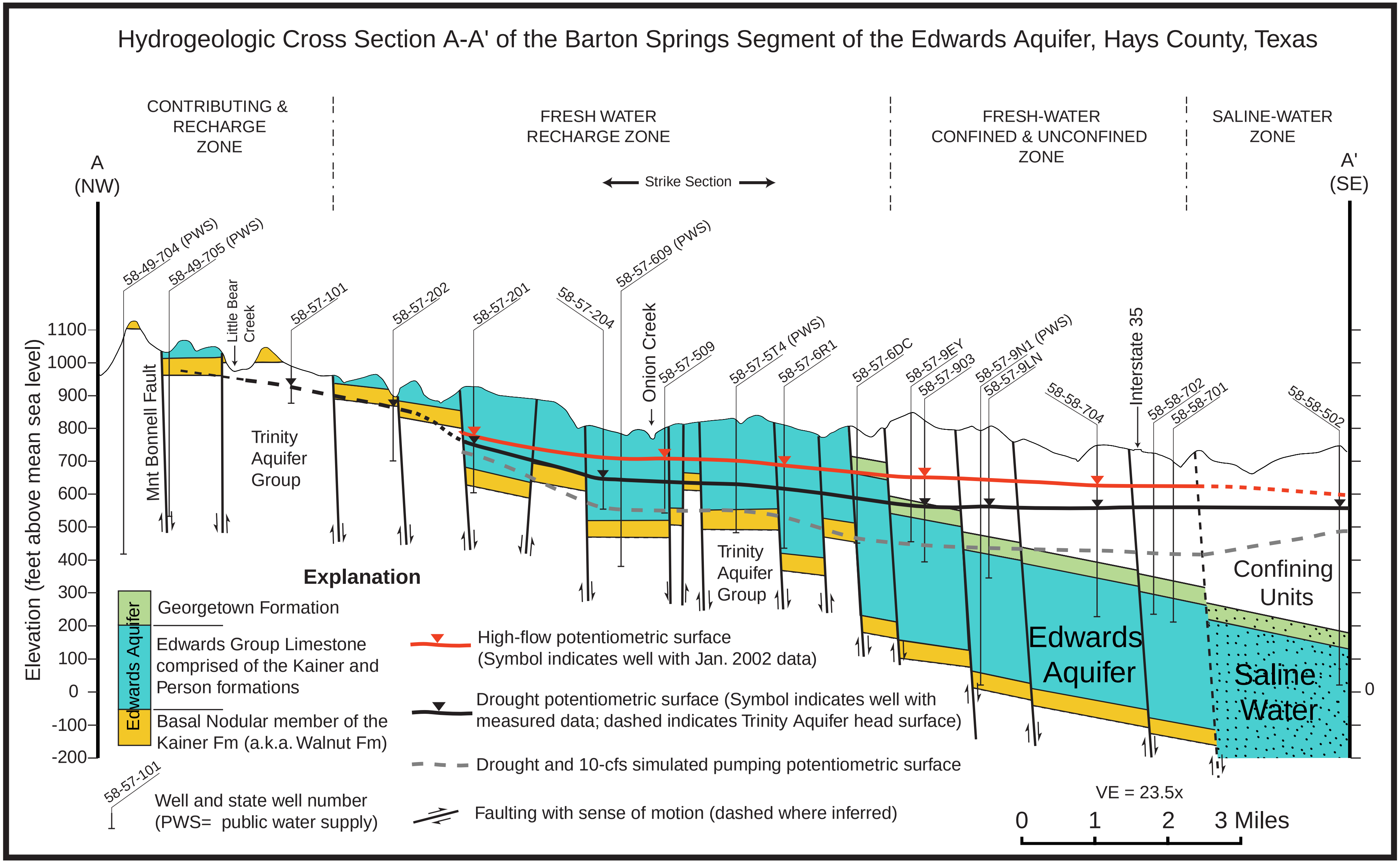
Hydrogeologic Cross Section A-A' of the Barton Springs Segment of the Edwards Aquifer, Hays County, Texas

Figure 2-2. Cross section of the Barton Springs and Trinity Aquifers in Hays County (see Figure 2-1).

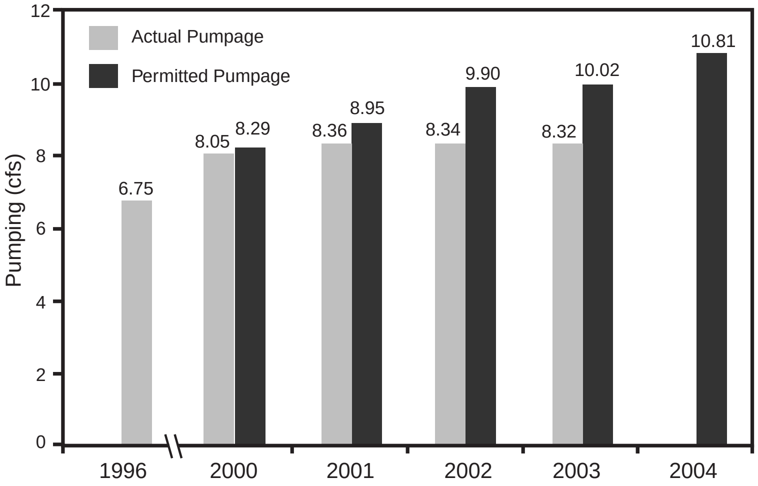

Figure 2-3. Histogram of permitted and actual pumping from the Barton Springs aquifer.

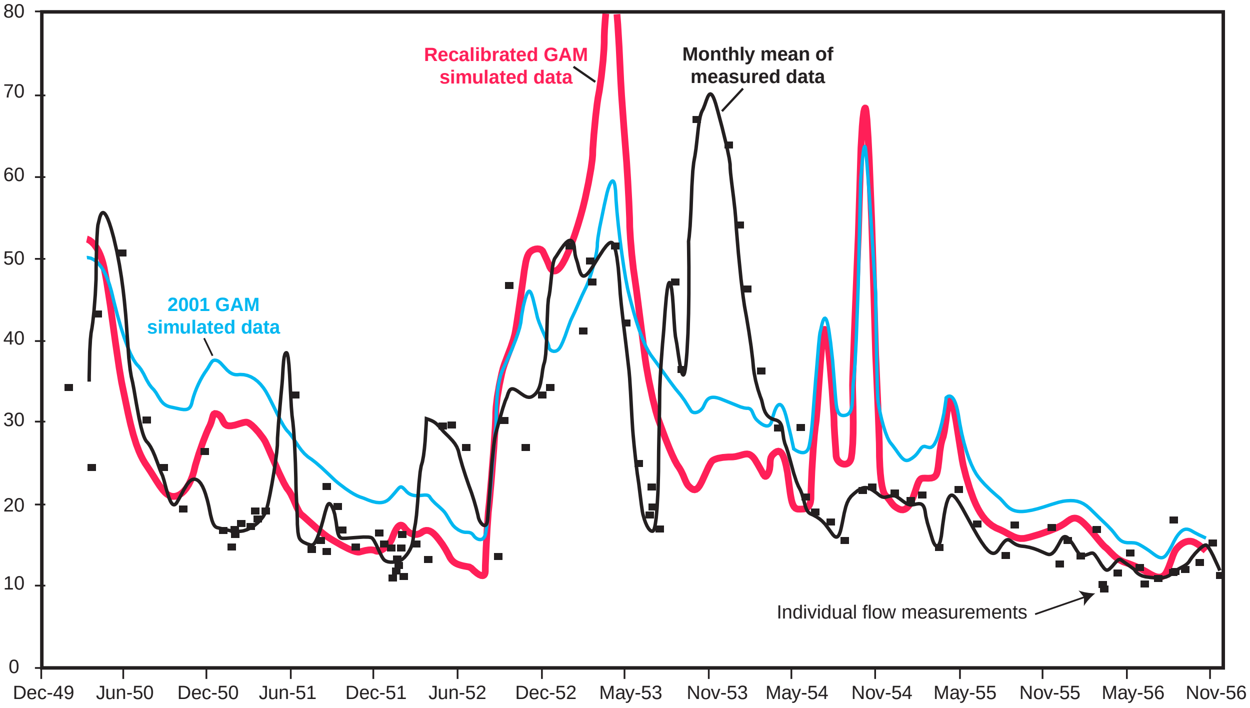

Figure 3-1. Hydrograph of simulated and measured spring flow dishcarge from 1950's drought. Note: lowest individual measured value (arrow) 9.6 cfs. Both simulations were run with 0.66 cfs pumping.

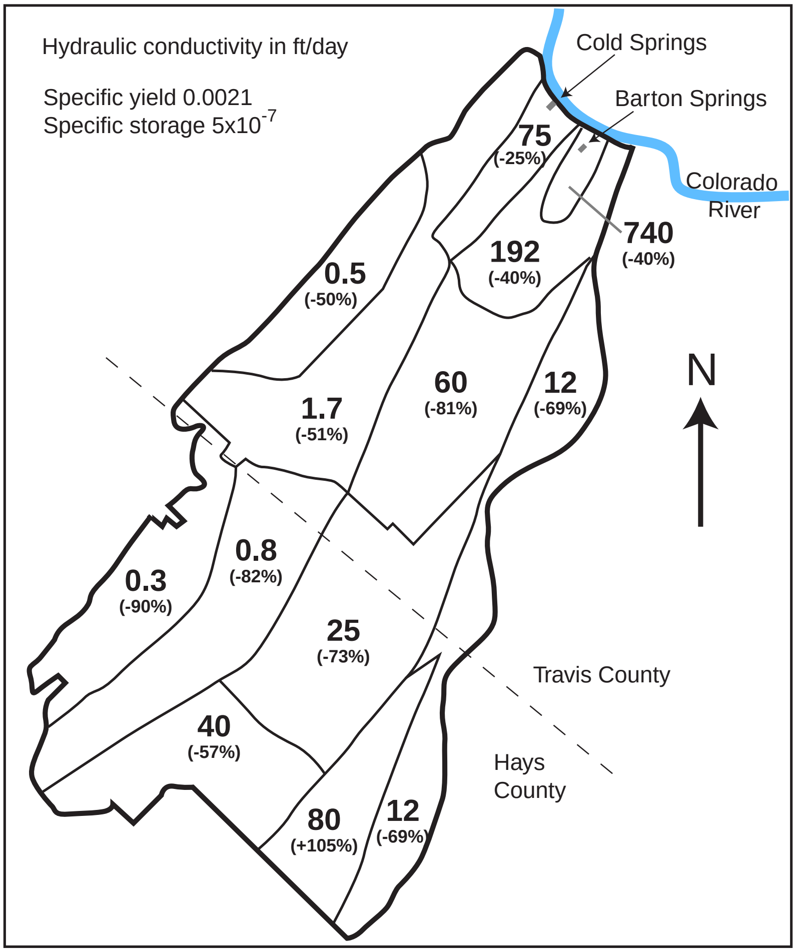

Figure 3-2. Map of zonal distribuion of hydraulic conductivity (ft/day) in the recalibrated GAM model. Note: percent change from 2001 GAM values shown in parentheses (see Table 3-2).

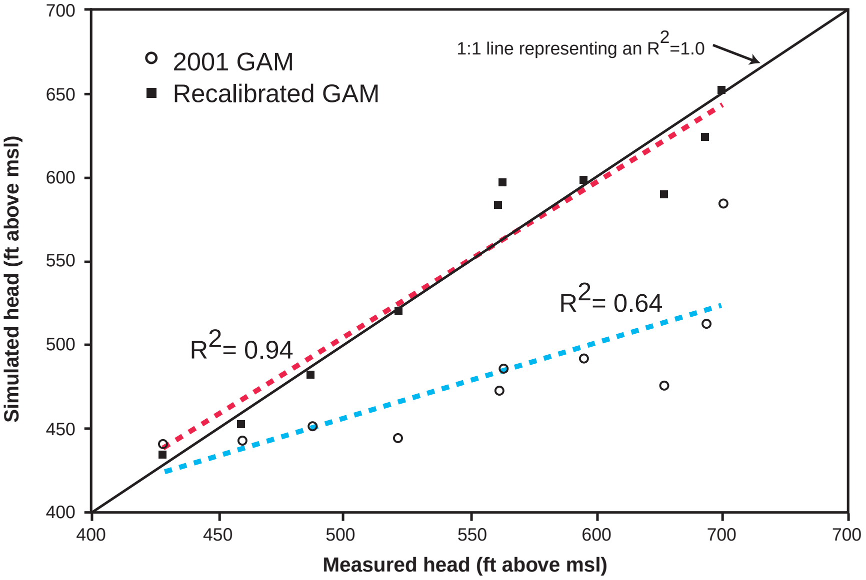

Figure 3-3. Scatter plot of the simulated results from the 2001 GAM and recalibrated GAM plotted against measured low-flow 1950's water levels. See Table 3-1.

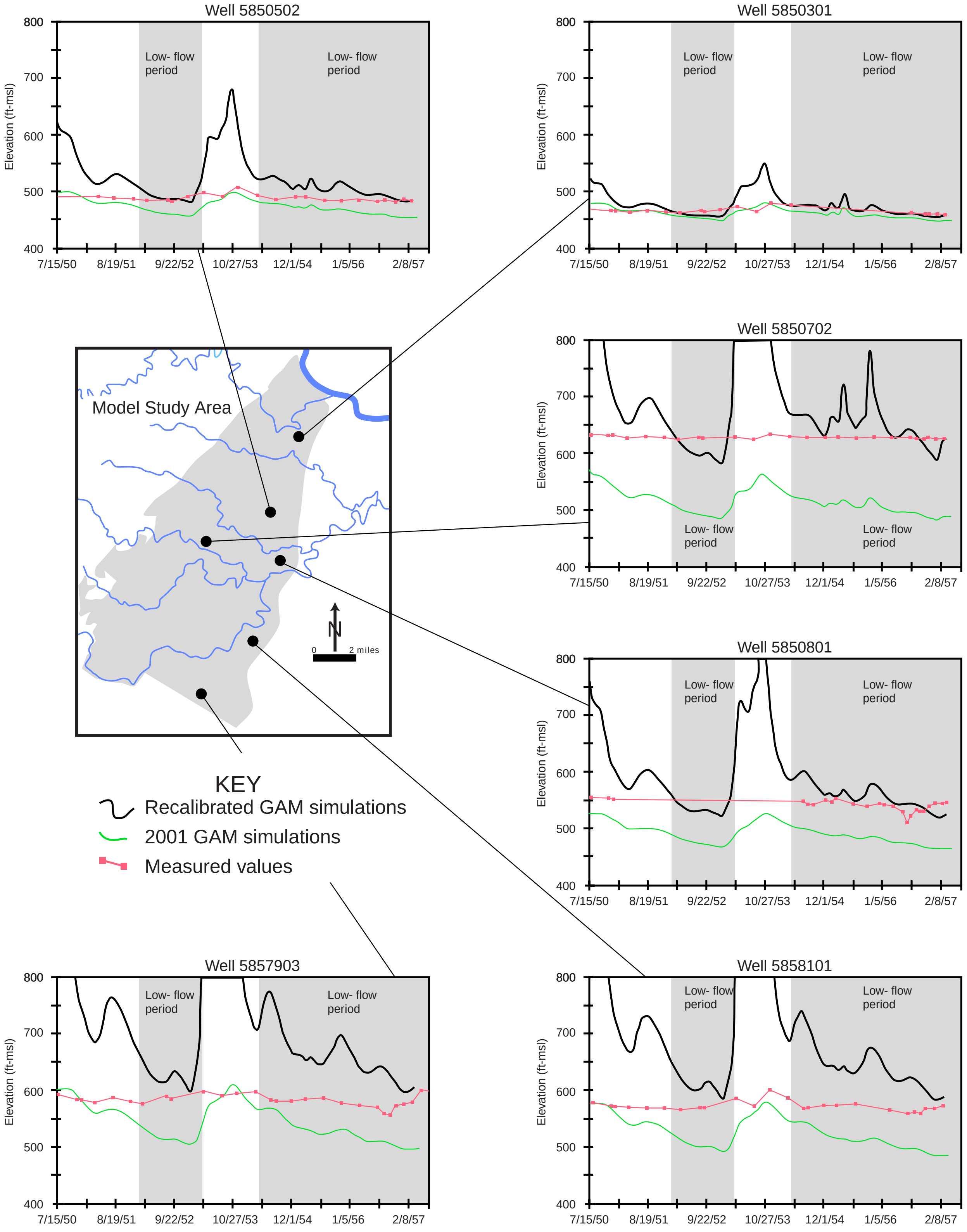

Figure 3-4. Comparison of simulated and measured water-level elevation hydrographs from the study area. Recalibration of the GAM was to the low-flow periods (shaded area) of the 1950's drought.

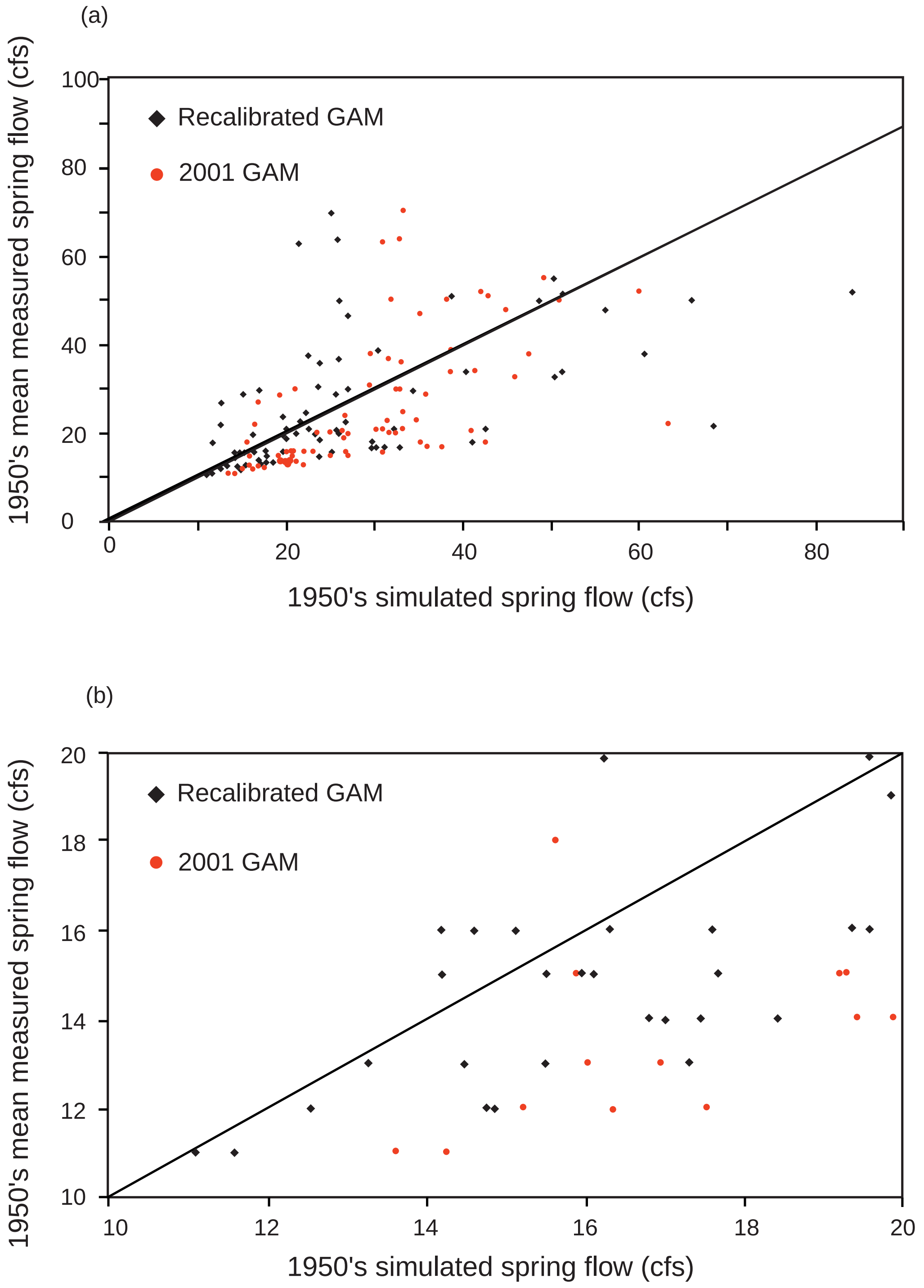

Figure 3-5. Scatter plot of spring-flow simulations from the 2001 and the recalibrated GAMs and mean of measured spring-flow values for (a) all flow conditions and (b) low-flow conditions.

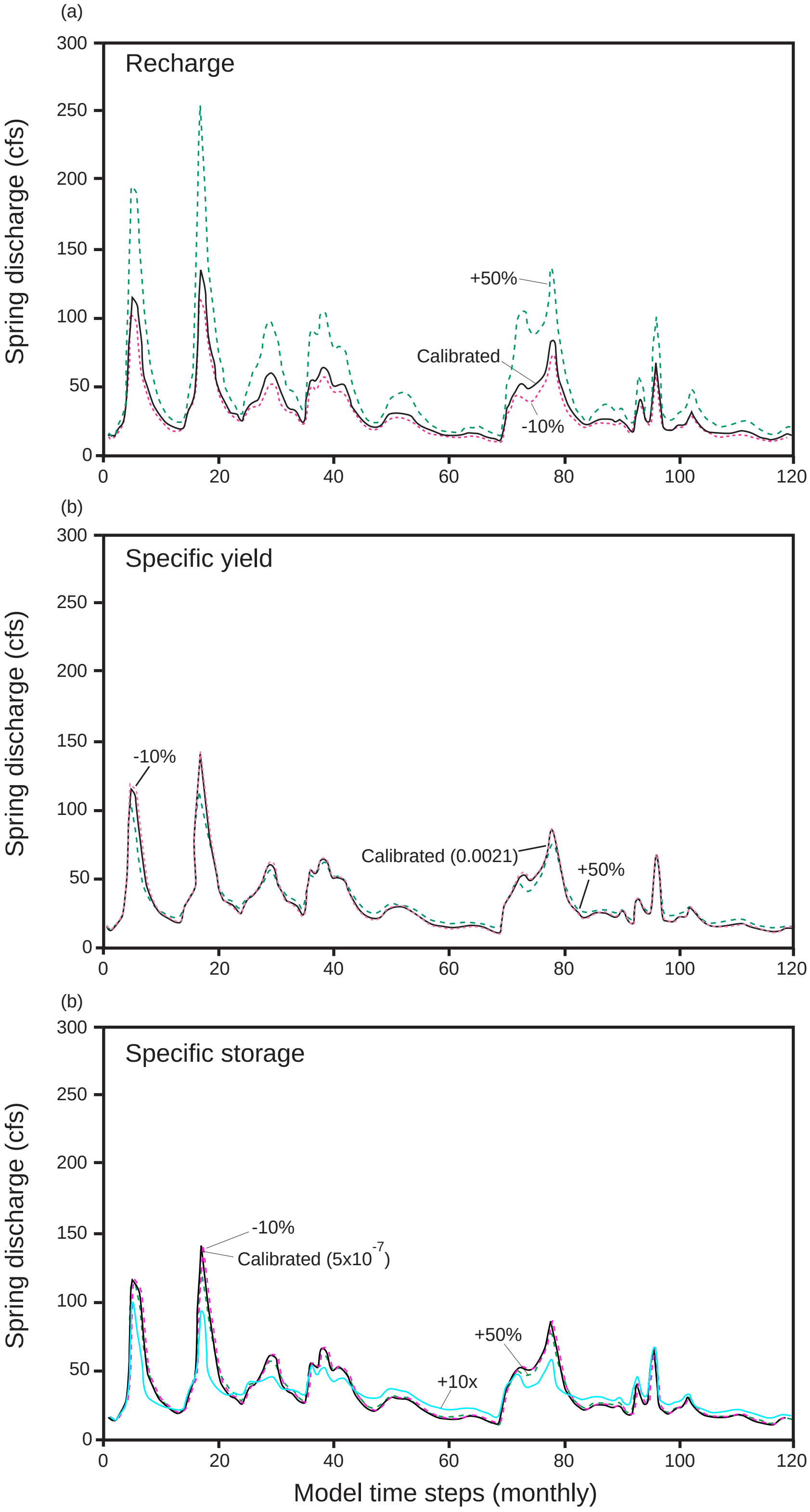

Figure 3-6. Sensitivity of transient simulated spring discharge to (a) recharge, (b) specific yield, and (c) specific storage.

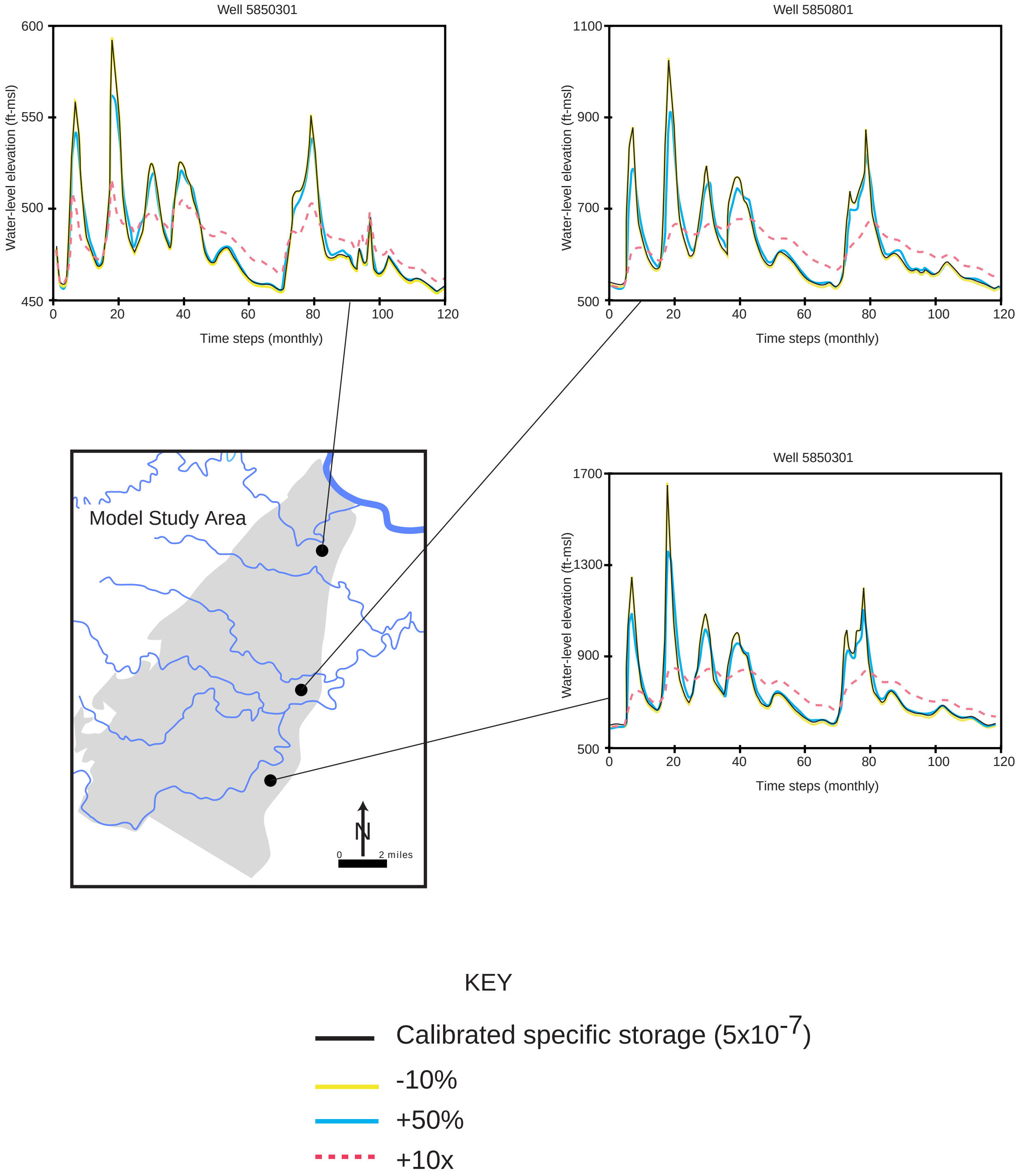

Figure 3-7. Sensitivity of transient calibration water levels to specific storage.

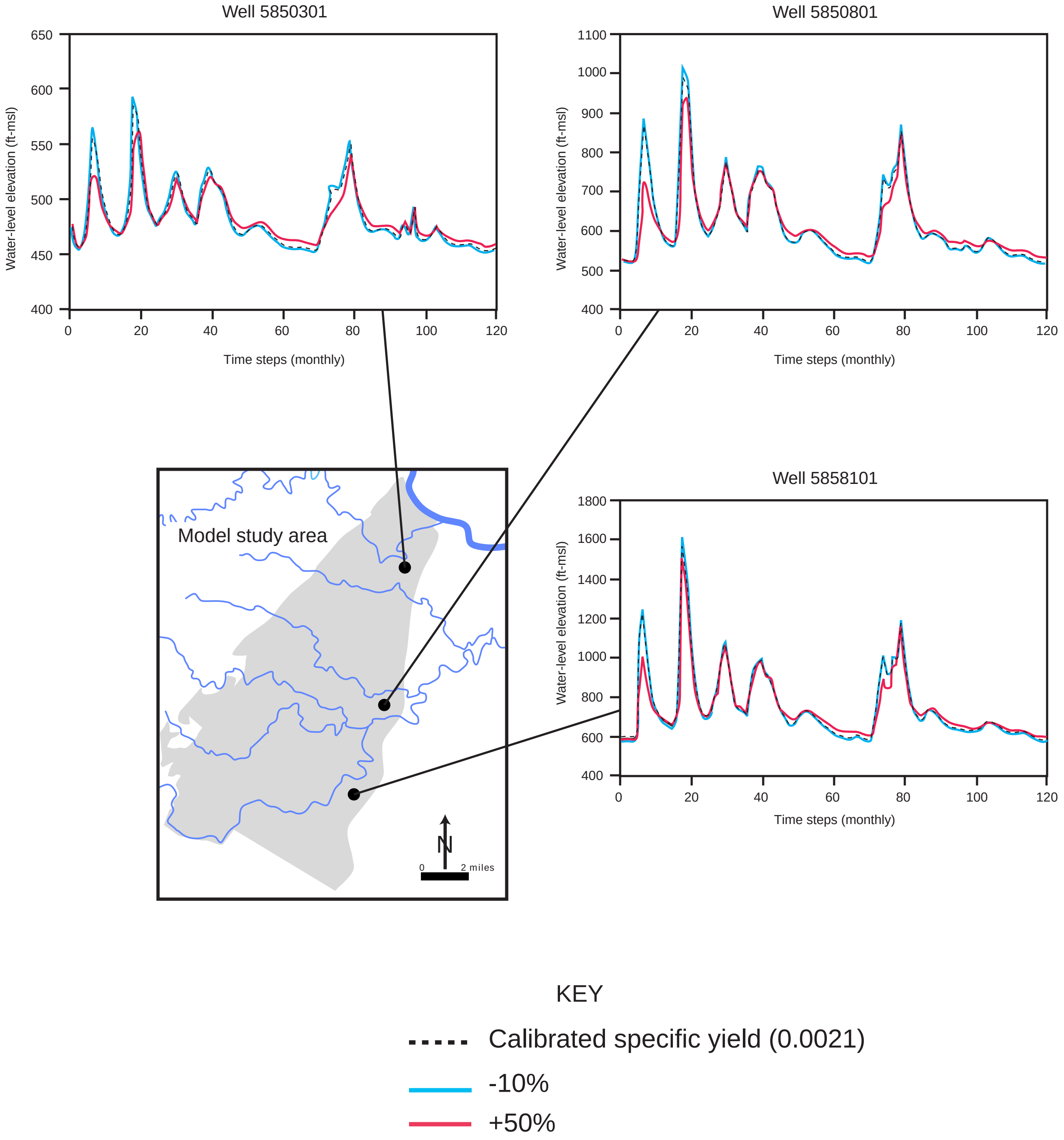

Figure 3-8. Sensitivity of transient calibration water levels to specific yield.

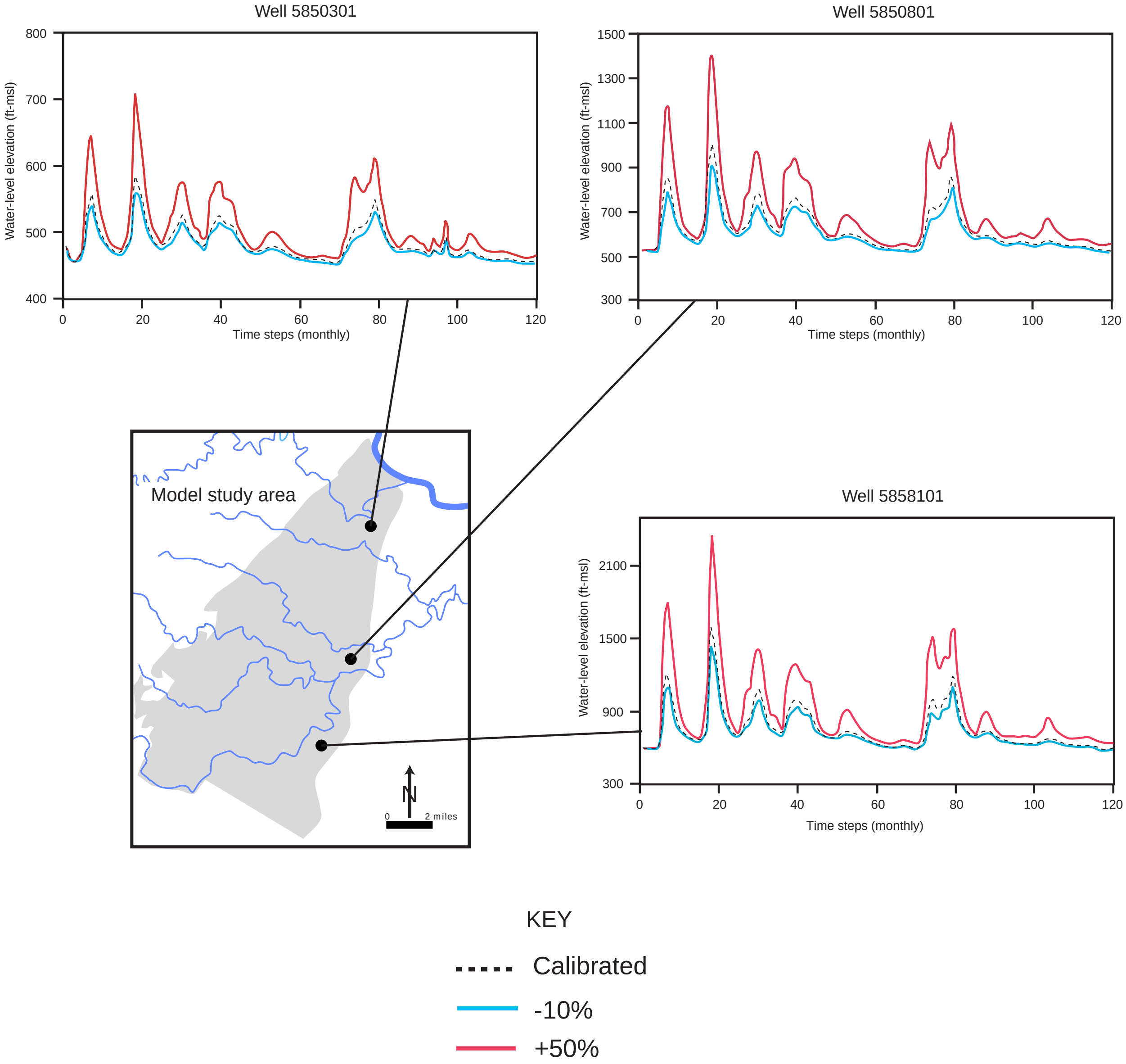

Figure 3-9. Sensitivity of transient calibration water levels to recharge.

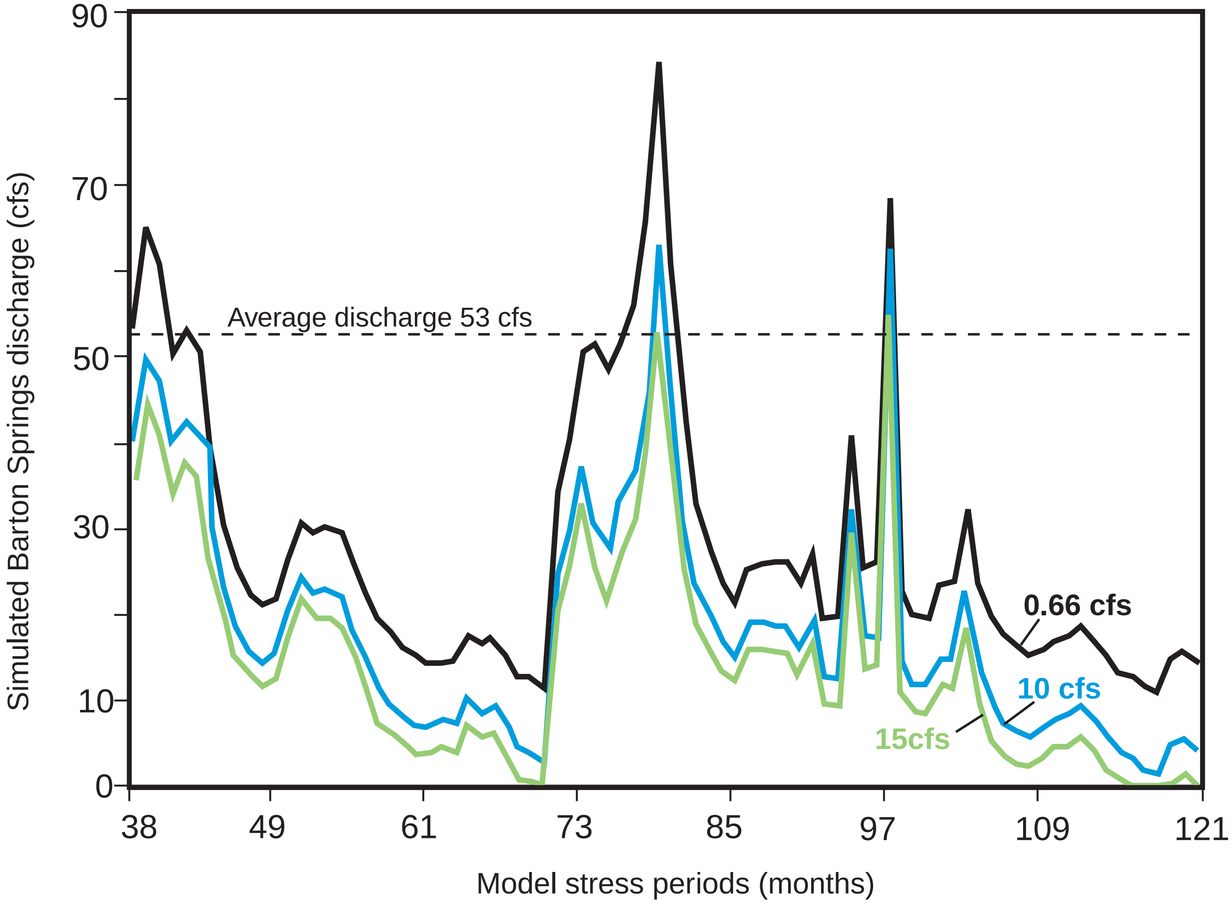

Figure 3-10. Hydrograph of simulated spring flow under 1950's drought conditions and 0.66, 10, and 15 cfs pumping rates.

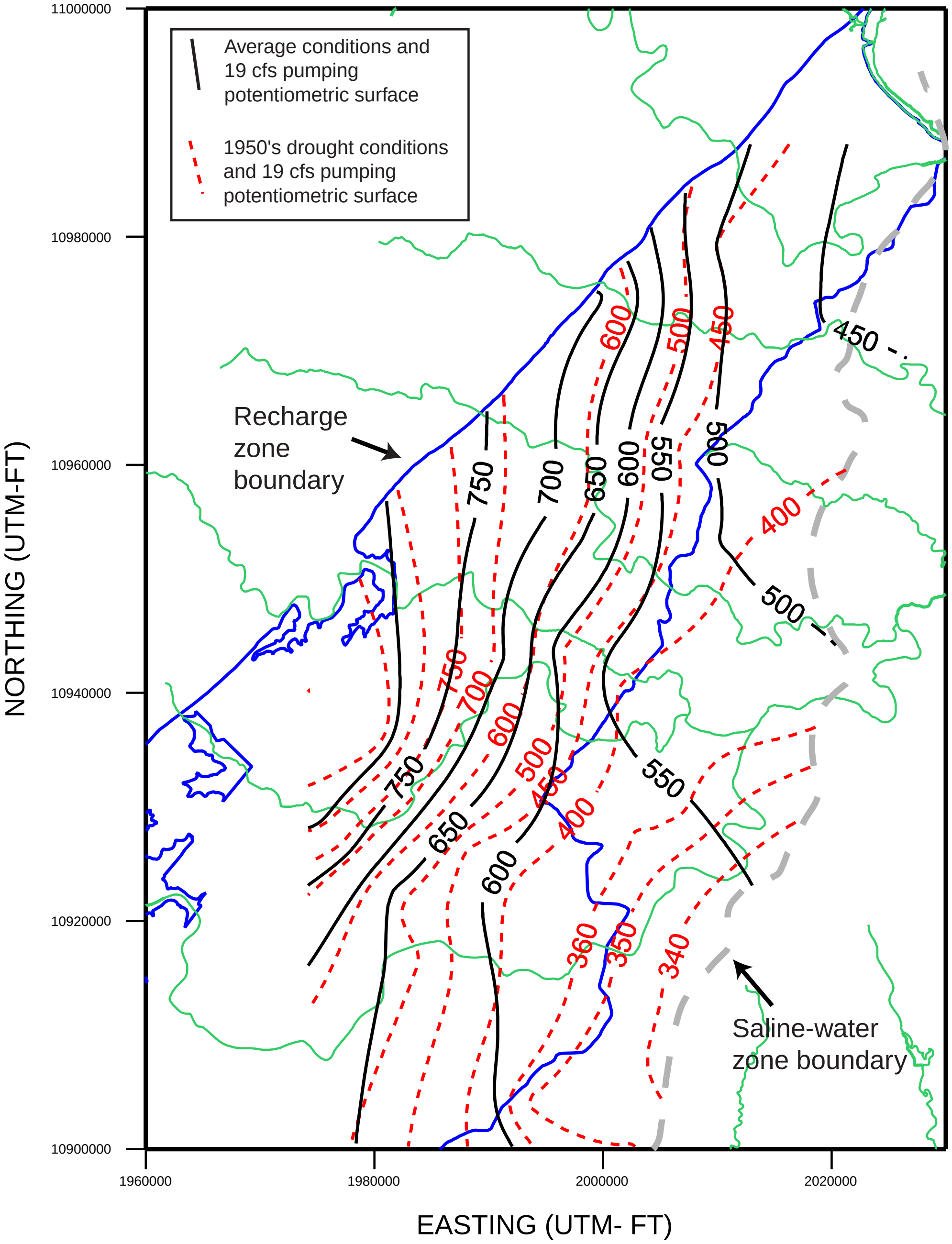

Figure. 3-11. Simulated potentiometric surface contour map under average conditions and 19 cfs of pumping (solid lines) and 1950's drought conditions with 19 cfs pumping (dashed lines). Springflow is 36 cfs and 0 cfs, respectively, at the end of simulations for each scenario .

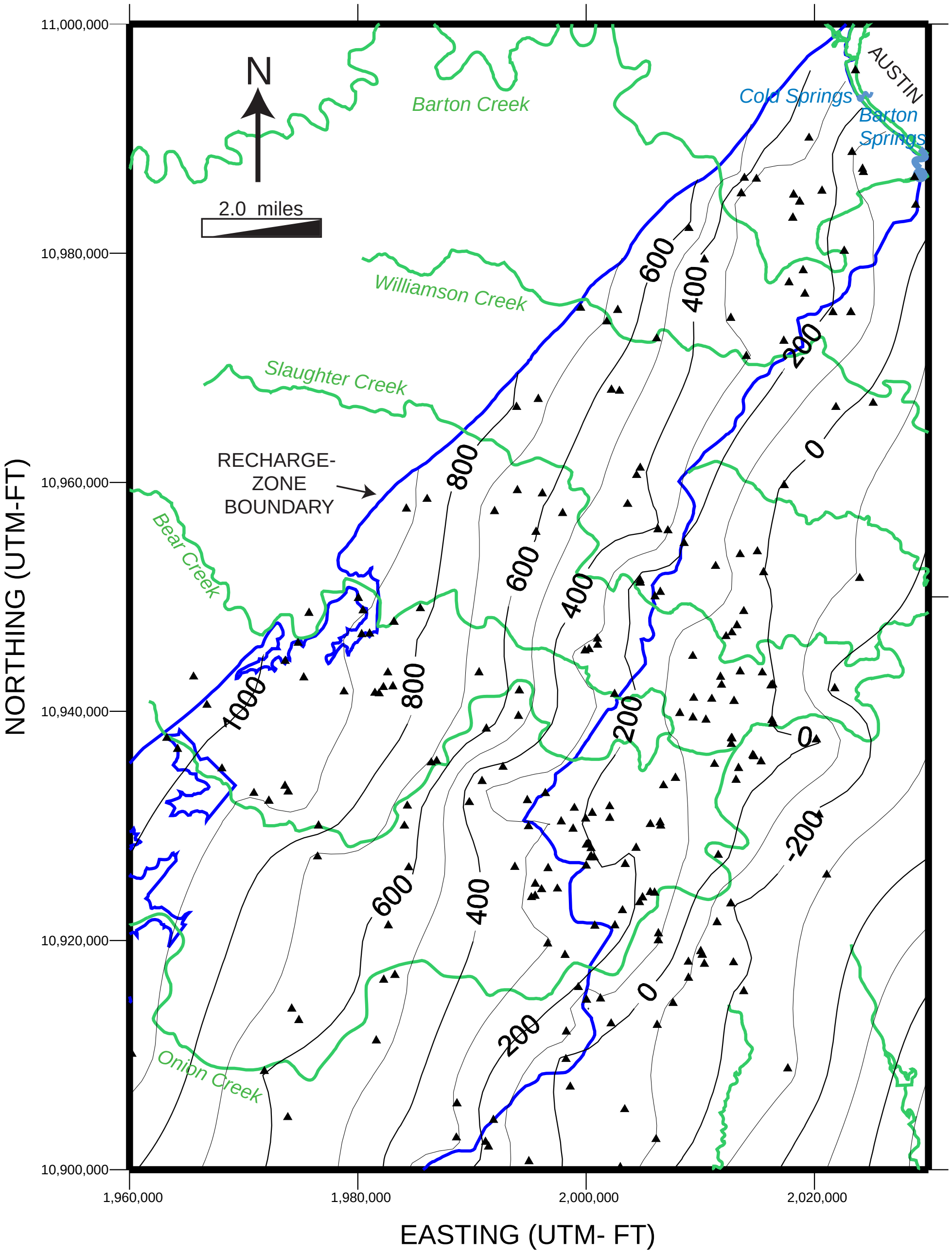

Figure 4-1. Structure contour of the elevation (ft-msl) of the bottom of the Edwards Aquifer. Note: control points shown as triangles.

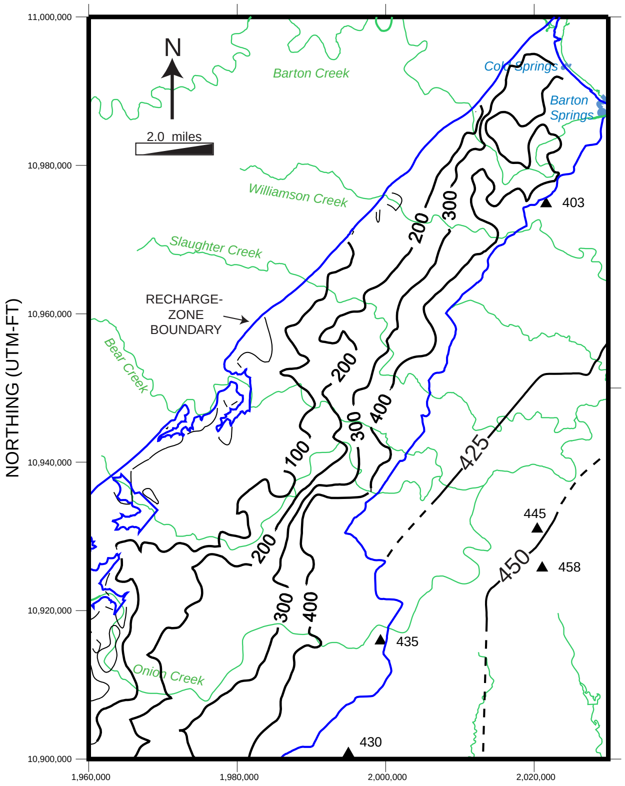

Figure 4-2. Isopach (thickness) map of the Edwards Aquifer. Note: triangles are fully-penetrating wells. Thickness contours are in ft.

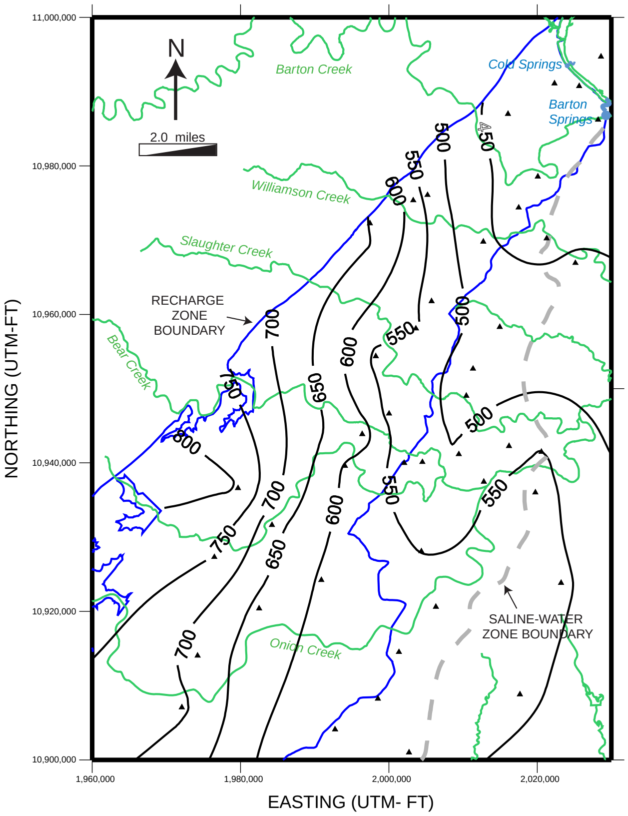

Figure 4-3. Potentiometric map of the Edwards Aquifer under 1950's drought conditions. Note: triangles indicate data locations. Contours are in ft above msl.

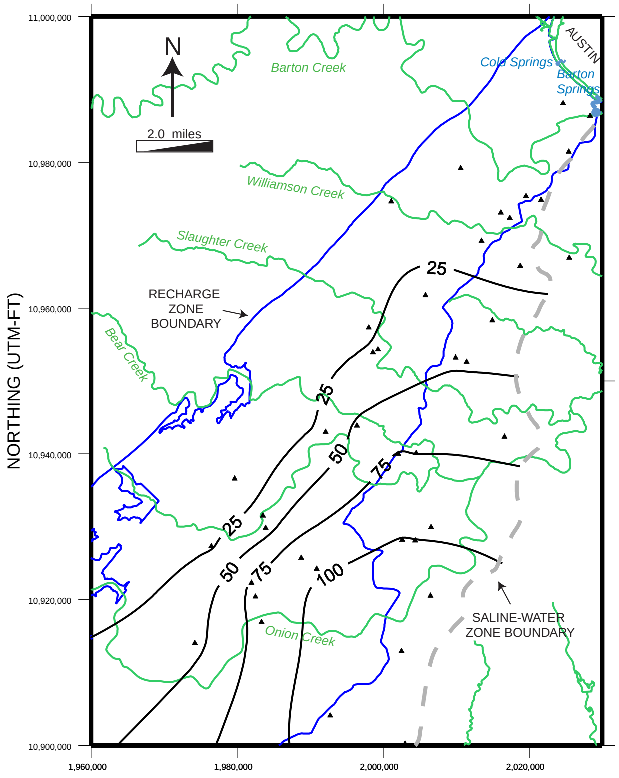

Figure 4-4. Simulated drawdown from pumping 10 cfs at the end of the 10-yr simulation. Note: contours are in ft of drawdown.

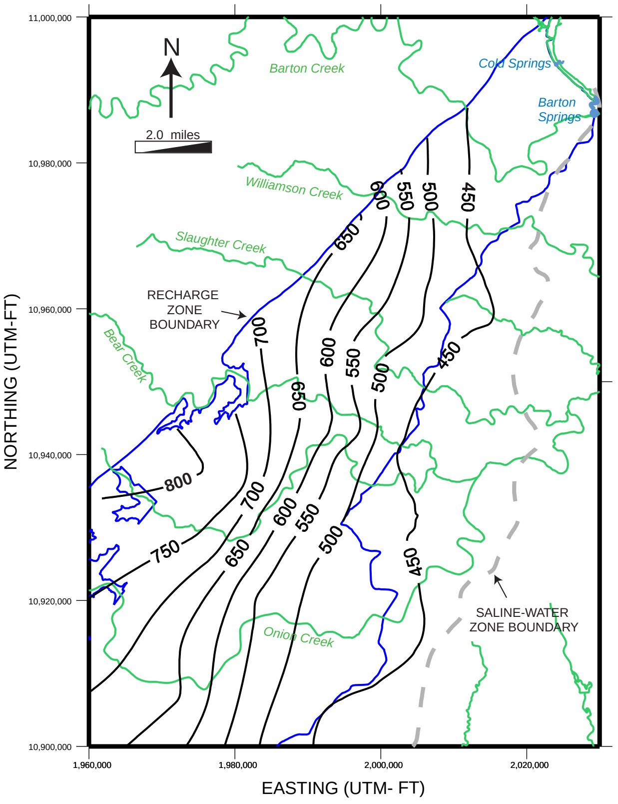

Figure 4-5. Potentiometric map of 1950's drought conditions and 10 cfs pumping. Note: contours are in ft above msl.

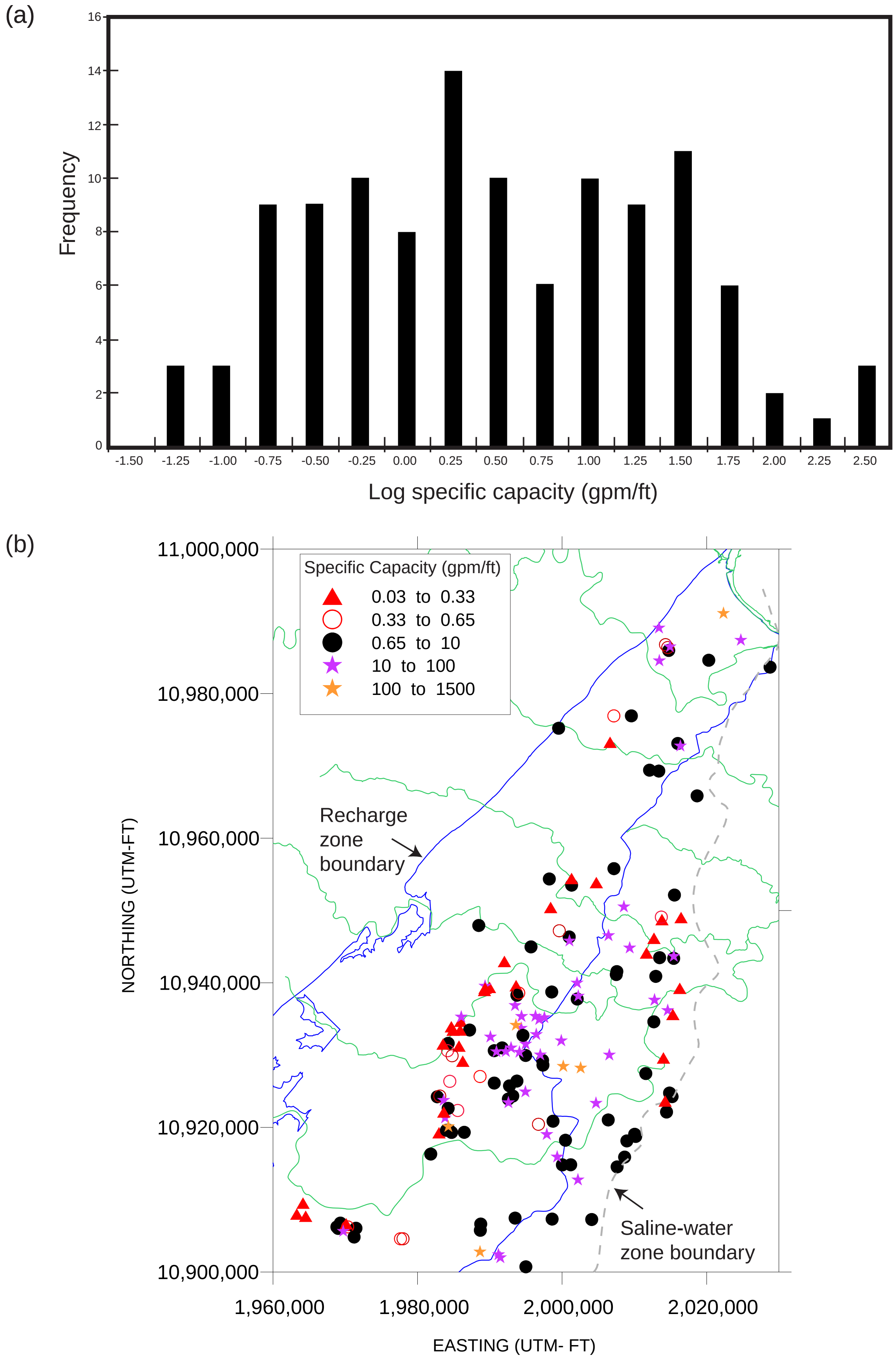

Figure 4-6. (a) Histogram of specific-capacity values from the unconfined portion of the Barton Springs aquifer (n=113). (b) Distribution and classed values of all specific capacity data (n=170).

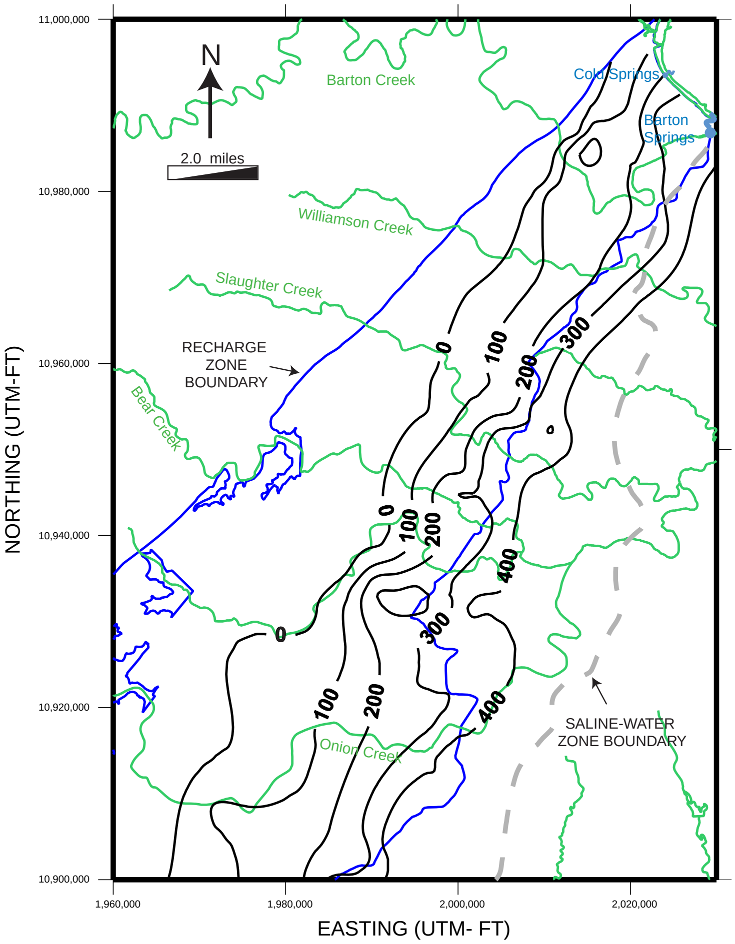

Figure 4-7. Saturated-thickness contour map of the Edwards Aquifer under 1950's drought conditions with minimal (0.66) pumping. Note: contours are in ft.

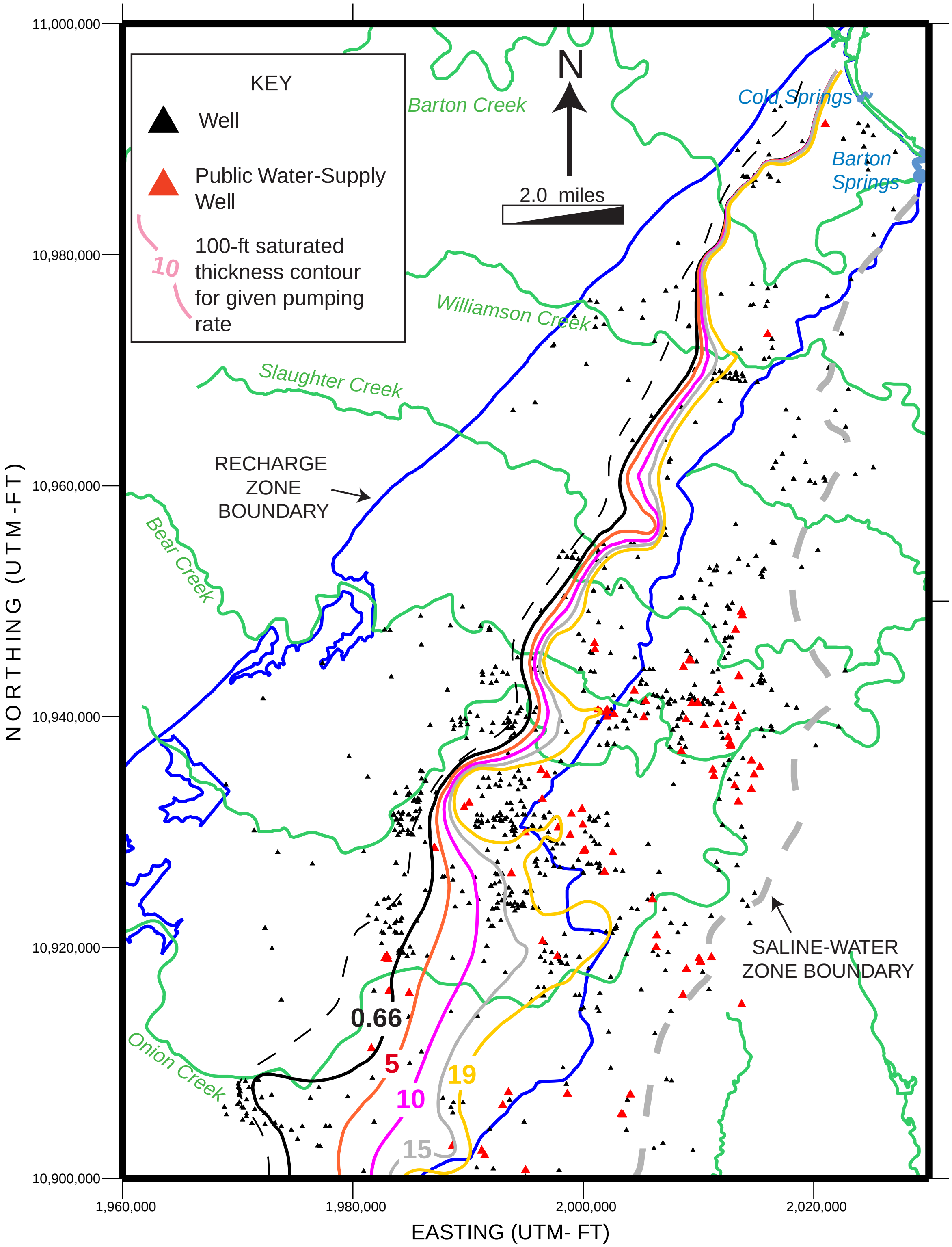

Figure 4-8. Composite of 100-ft saturated aquifer thickness contour lines under 1950's drought conditions with 0.66, 5, 10, 15, and 19 cfs of pumping. Dashed line is 100-ft saturated aquifer thickness contour under high-flow conditions.

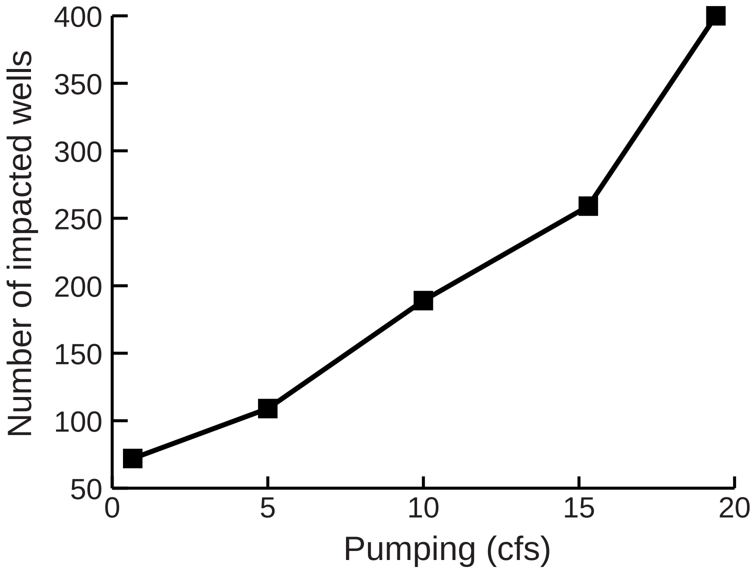

Figure 4-9. Chart summarizing number of wells impacted under 1950's drought conditions and various pumping rates.

APPENDIX A

Report:

Scanlon, B., Mace, R., Smith, B., Hovorka, S., Dutton, A., and Reedy, R., 2001, Groundwater Availability of the Barton Springs Segment of the Edwards Aquifer, Texas—Numerical Simulations through 2050: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for the Lower Colorado River Authority, under contract no. UTA99-0, 36 p. + figs., tables, attachment.

GROUNDWATER AVAILABILITY OF THE BARTON SPRINGS SEGMENT OF THE EDWARDS AQUIFER, TEXAS: NUMERICAL SIMULATIONS THROUGH 2050

by

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Scott W. Tinker, Director
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October 2001

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[1] This study was initiated while Dr. Mace was an employee at the Bureau of Economic Geology and his involvement primarily included initial model development and calibration.

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Figures

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ABSTRACT

A two-dimensional, numerical groundwater-flow model was developed for the Barton Springs segment of the Edwards aquifer to evaluate groundwater availability and predict water levels and spring flow in response to increased pumpage and droughts during the period 2001 through 2050. A steady-state model was developed on the basis of average recharge for a 20-yr period (1979 through 1998) and pumpage values for 1989. Transient simulations were conducted using monthly recharge and pumping data for a 10-yr period (1989 through 1998) that includes periods of low and high water levels. Values of hydraulic conductivity were estimated by calibrating the steady-state model using trial and error and automated inverse methods. Good agreement was found between measured and simulated flow at Barton Springs (root mean square error [RMS error, average of squared differences in measured and simulated discharges] 12 cfs), between measured and simulated water levels at different times and between measured and simulated water levels in many of the monitoring wells. To assess the impact of future pumpage and potential future droughts on groundwater availability, transient simulations were conducted using extrapolated pumpage for 10-yr periods (2001 through 2050) and average recharge for a 3-yr period and recharge from the 1950's drought for the remaining 7 yr. Results of these simulations were compared with those using average recharge and future pumpage. Predicted water-level declines in response to future pumpage under average recharge conditions are small (≤ 35 ft), whereas water-level declines under future drought conditions were much greater (≤270 ft). Simulated spring discharge in response to future pumpage under average recharge decreased proportionally to future pumpage (2 cfs per decade), whereas spring discharge decreased to 0 cfs in response to future pumpage under drought-of-record conditions. Management of water resources under potential future drought conditions should consider enhanced recharge and conservation measures.

INTRODUCTION

This modeling study focuses on a segment of the Edwards aquifer within and adjacent to Austin, Texas, that discharges into Barton Springs and Cold Springs and is hydrologically distinct from the rest of the Edwards aquifer. This region, referred to as the Barton Springs segment of the Edwards aquifer, constitutes the sole source of water to about 45,000 residents. Barton Springs pool was created when a dam was installed immediately downstream of the spring and it also serves as a municipal swimming pool in Zilker Park, downtown Austin. The pool was The Barton Springs salamander, listed as an endangered species, is restricted to the region immediately surrounding the spring. Increased population growth and recent droughts (1996) have focused attention on groundwater resources and sustainability of spring flow. A combination of increased pumpage and severe drought could severely impact future water resources.

A numerical groundwater flow model is a tool that can help in assessing the impacts of current and future pumpage on groundwater resources and spring discharge. A groundwater flow model numerically represents the aquifer using a computer. Information about the aquifer, such as water levels, recharge, and spring discharge, provides input to the model and helps us evaluate the reliability of the model. A calibrated groundwater model can provide a valuable tool for evaluating the impact of pumping and drought on an aquifer.

The objective of this study was to evaluate long-term groundwater availability in response to future pumpage and potential future droughts. To meet this objective, it was necessary to develop a two-dimensional numerical, finite-difference groundwater model of the Barton Springs segment of the Edwards aquifer. This model will provide (1) a management tool to the Barton Springs Edwards Aquifer Conservation District (BSEACD) and to the Regional Water Planning Group and (2) a tool for evaluating groundwater availability under drought-of-record conditions. This report describes the construction and calibration of the numerical model and the results of predictive simulations of water levels and spring discharge for the next 50 yr based on projected demands from the Regional Water Planning Group and the BSEACD.

The various components of the modeling study included (1) developing a conceptual model that included our current understanding of the geology, (2) quantifying groundwater recharge from stream-gage records, (3) calibrating a steady-state model using average recharge for a 20-yr period (1979–1998) and trial and error and automated inverse methods, (4) running a transient model for a 10-yr period (1989–1998), (5) conducting sensitivity analyses to determine the primary controls on the simulations, and (6) running predictive simulations through 2050. This report describes (1) the study area, previous work, and hydrogeologic setting used to develop the conceptual model; (2) the code, grid, and recharge assigned during model construction; (3) calibration of the steady-state model to estimate the hydraulic conductivity distribution; (4) the transient model for the 10-yr period; (5) sensitivity analysis for the steady-state and transient model; and (6) predictions of water-level changes and spring discharge under future pumpage and drought-of-record conditions; (7) the limitations of the current model; and (8) suggestions for improvements.

The model developed in this study differs from the previous two-dimensional, finite-difference model developed by Slade and others (1985) in the grid resolution (minimum 500 ft versus a minimum of 1,500 ft) in explicitly representing the aquifer thickness in the simulation, in simulating transient flow for a long time (10 yr versus 5 mo), and in predicting groundwater availability under increased pumpage and potential future droughts for the period through 2050. The spatially distributed model developed in this study allows the effect of pumpage in different regions of the model area to be assessed, which is not possible with the lumped parameter model developed by Barrett and Charbeneau (1996). More details on these other models are provided in the Previous Work section.

STUDY AREA

The Barton Springs segment of the Edwards aquifer constitutes the study area and includes parts of Travis and Hays Counties (fig. 1). The study region is within the Lower Colorado Region (Region K) water-planning group and includes the Barton Springs/Edwards Aquifer Conservation District (fig. 2). The model boundaries are all hydrologic boundaries and include the Mount Bonnell fault to the west, which acts as a no-flow boundary (Senger and Kreitler, 1984); a groundwater divide to the south along Onion Creek (Guyton and Associates, 1958); the “bad-water” line to the east; and the Colorado River (Town Lake) to the north. Groundwater circulation in the Edwards aquifer decreases to the east and total dissolved solids (TDS) increase. The bad-water line marks the zone where TDS exceeds 1,000 mg/L, which generally coincides with Interstate 35. The groundwater divide in the south separates the Barton Springs segment from the San Antonio segment of the Edwards aquifer, which discharges into Comal and San Marcos Springs.

Physiography and Climate

Physiographically the aquifer lies on the transition between the Edwards Plateau to the west and the Blackland Prairie to the east. The topography of the area is that of the Rolling

Prairie province. Surface elevations range from about 1,050 ft in the southwest to about 250 ft along the east margin (fig. 3).

The study area is in the subtropical humid climate zone (Larkin and Bomar, 1983). Annual precipitation ranges from 11 to 65 inches (1860 through 2000), a figure which is based on records from a NOAA station located north of the study area at Camp Mabry and Mueller Airport in Austin (fig. 4a). Long-term mean annual precipitation is 33.5 inches (fig. 4a). Precipitation occurs primarily in the spring and fall, mainly as a result of mixing of cool fronts and warm, moist air from the Gulf of Mexico. Convectional thunderstorms result in small amounts of rain in the summer. Mean annual gross lake evaporation is 66 inches (Larkin and Bomar, 1983).

The Edwards aquifer is unconfined in the outcrop area where recharge occurs and in part of the section to the east, where it is overlain by the Del Rio Clay (fig. 1). Farther to the east, the aquifer is confined by the Del Rio Clay. Approximately 80 percent of the aquifer is unconfined, and the remainder is confined (Slade and others, 1985).

Geology

The Barton Springs segment of the Edwards aquifer is a hydrologically significant element within an aquifer system developed in thick and regionally extensive Lower Cretaceous carbonates that underlie large areas of Texas. The components make up the northern segment of the Edwards aquifer, the Barton Springs segment, the San Antonio segment, and the Edwards-Trinity Plateau and Trinity aquifers (fig. 5).

The sediments hosting these aquifers were deposited when a Lower Cretaceous sea-level rise flooded the North American craton. Two transgressive–regressive cyclic genetic sequences are represented by conglomerate, sandstone, shale, and limestone in the lower and middle Trinity Group (Moore, 1996). Continued transgression recorded by cyclic sedimentation resulted in deposition of two thick carbonate-dominated sequences of the Glen Rose Formation in the upper Trinity Group overlain by four sequences that comprise the Edwards aquifer and facies-equivalent limestones (fig. 6). Edwards Group and temporally equivalent limestones and marls are recognized as far north as the Texas Panhandle, where they subcrop beneath the Ogallala Formation. Water depth continued to increase cyclically through part of the Late Cretaceous, but sedimentary patterns were modified by deposition of a number of shales separated by limestone and chalk. The first of these shale units is the Del Rio Formation, which forms the aquitard at the top of the Edwards Group over a wide area, and which is overlain by the Buda Formation (dominantly limestone) and the Eagle Ford Formation (dominantly shale). Maximum water depth is represented by deposition of the Austin Chalk over a wide area. Maximum water depth was followed by progradation, aggradation, and sea-level fall, during which clastics, including the Taylor and Navarro Formations, were the dominant deposits.

The major episode of structural deformation affecting aquifer development was uplift of the Edwards Plateau along the Balcones Fault Zone. This deformation occurred along a sinuous trend extending from Dallas through Austin and San Antonio and west toward Del Rio. Uplift of the Edwards Plateau began in the Miocene and during the creation of the regional hydraulic gradient. Normal faulting along en echelon faults and graben systems that yielded a total of 1,400 ft down-to the coast displacement across the Barton Springs segment accommodated uplift. Major faults trend north-northeast.

Uplift along the Balcones Fault Zone, followed by erosion, has resulted in stripping of younger units to expose the Glen Rose Formation to the west. This area is commonly described as the contributing zone to the Edwards aquifer. It is characterized by creeks that are maintained by spring flow. The recharge zone is the area where diverse stratigraphic units that form the Edwards aquifer crop out. The recharge zone is approximately coincident with the west edge of the Balcones Fault Zone, and structural and rock properties combine to create effective pathways for rapid recharge from streams. At the east edge of the study area, where less uplift has occurred, the aquifer is confined by younger, low-permeability units, including the Del Rio Clay, Eagle Ford Formation, Austin Chalk, Taylor, and Navarro Formations. Although faults are less easily mapped in weak and poorly exposed shales at the east edge of the study area, examination of subsurface structure shows that this area is within the Balcones Fault Zone.

PREVIOUS WORK

Numerical models of groundwater flow in the Barton Springs segment of the Edwards aquifer were previously developed by Slade and others (1985) and Barrett and Charbeneau (1996). Slade and others (1985) developed a two-dimensional numerical groundwater flow model for the part of the Edwards aquifer that discharges at Barton Springs by using a finite difference code written by Trescott and others (1976). The purpose of the modeling study was to determine the spatial distribution of hydraulic parameters and to assess different water-management scenarios that included increased pumpage and enhanced recharge. The model grid consisted of 318 active cells, with cell spacing ranging from about 1,500 to 8,000 ft. A steady-state model was developed for mean recharge conditions that corresponded to long-term average discharge at Barton Springs (53 cfs). Recharge was estimated from stream-loss records. The model did not explicitly represent aquifer thickness, although thickness was incorporated in the transmissivity data. Calibration of the steady-state model was used to determine the spatial distribution of transmissivity, which varied from 100 ft^2 d^{-1} in the west part of the aquifer to more than 1 million ft^2 d^{-1} near Barton Springs. A transient model was developed for a 5-mo period. Calibration of the transient model yielded values of specific yield and storage coefficient for the aquifer. Predictive simulations, conducted by using projected pumpage for the year 2000, indicated that the aquifer would be dewatered in the southwest part of the study area and major declines would occur in the southeast area. However, another simulation that included use of recharge enhancement predicted a rise in potentiometric surface of about 50 ft in the southwest part of the aquifer and moderate water-level declines in the southeast zone. The model developed by Slade and others (1985) is not appropriate for regional water planning because the model was developed with a code that is no longer in use (Trescott and others, 1976), the grid cell size is large (minimum 1,500 ft), the aquifer thickness is not explicitly represented in the model, and the transient simulation period was short (5 mo).

Barrett and Charbeneau (1996) developed a new type of lumped parameter model to predict the impacts of urban development on the quantity and quality of water in the Barton Springs segment of the Edwards aquifer. The aquifer was divided into five cells corresponding to the five watersheds in the region. A single well was used to represent conditions in each cell. The model successfully reproduced measured water levels and average nitrogen concentrations in the Edwards aquifer and at Barton Springs. Increased urbanization was simulated by estimating changes in creeks that recharge the system. The results indicate that increased development will reduce spring flow and increase nitrogen concentrations in the aquifer. The resolution of the model (cells equivalent to river basins) is too coarse to evaluate the impact of more local pumpage on spring discharge; therefore, the lumped parameter model is inadequate for regional water planning.

HYDROGEOLOGIC SETTING

The hydrogeologic setting describes the aquifer and hydrologic features and hydraulic properties that influence groundwater flow in the aquifer. For this study, we built on previous surface mapping to develop two new subsurface structure maps and an isopach map.

The hydrogeologic framework developed for this model was based on previous work. An unpublished geologic map in ARC/INFO Geographic Information System (GIS) provided the interpretation of bedrock geology at the surface (figs. 7, 8) (Hauwert and others, 1997). Maps of parts of the area were published by Small and others (1996) and Hanson and Small (1995). The other major data input was an unpublished notebook of subsurface well log data and a table of depth to top of formations compiled by Nico Hauwert for BSEACD (N. Hauwert, 1998, unpublished data). Following the convention developed in the San Antonio segment of the Edwards aquifer, we consider the interval between the regionally extensive markers at the top of the Glen Rose Formation and the base of the Del Rio Formation as part of the Edwards aquifer and is the interval modeled in this study.

Other research used for subsurface interpretation for conceptual model development includes stratigraphic descriptions (Rose, 1972; Hanson and Small, 1995; Moore, 1996; and Small and others, 1996) and structural interpretations of Garner and Young (1976) and Collins and Woodruff (2001). A number of differences in interpretation among previous researchers are noted. Moore (1996) emphasized the lateral facies variation in dominant lithology and nomenclature in response to genetic sequences and paleogeography. The nomenclature derived from Rose (1972) and developed for the San Antonio segment uses a stratigraphic approach, recognizing eight named and numbered, lithologically defined hydrostratigraphic units that were applied in the Barton Springs segment by Hauwert and others (1997) and Small and others (1996).

Similarly, variations in fault interpretation are noted. The mapping of Collins and Woodruff (2001) employs a relay-ramp conceptual model (Collins, 1996; Ferrill and Morris, 2001). In this model, the vertical displacement varies laterally along each fault strand. As displacement decreases on one strand, the strain is taken up on adjacent strands. The fault strands form an en echelon pattern, with each strand dying out along strike. Between the fault strands, the rocks are folded to accommodate deformation, forming structures described as a relay ramps. The mapping of Hauwert and others (1997), Small and others (1996), and Hanson and Small

(1995) follows a conceptual model in which faults generally continue until they intersect another fault. Rather than folds commonly interpreted in the relay-ramp model, changes in elevation of formation or member contacts are commonly interpreted as the result of cross-faulting between major fault strands.

Hydrostratigraphy

The Edwards aquifer is an interval containing carbonates that have numerous intervals of intercrystalline high porosity, as well as petrophysical properties that make the carbonates subject to development of karst conduits. Underlying and, to a lesser extent, overlying stratigraphic intervals also serve as aquifers and can develop karst conduits.

Conventionally the lower boundary of the Edwards aquifer is defined as the top of the Glen Rose Formation (fig. 6). The Glen Rose Formation is the uppermost unit in the Trinity aquifer (Mace and others, 2000). In the study area, supratidal and paleosol deposits at the top of the Glen Rose Formation are overlain by marly, nodular limestones and calcareous shales (Moore, 1996, Molineux, 2001). These onlapping transgressive systems tract deposits are classified as the Walnut Formation (Rose, 1972; Moore, 1996) or the basal nodular member of the Kainer Formation, Edwards Group (Rose, 1972; Small and others 1996; Hauwert and others 1997). Irrespective of stratigraphic complexity, in many areas these units limit vertical permeability. Evidence of limited vertical permeability includes (1) numerous springs and seeps that discharge at this contact in outcrop and (2) an increase in salinity in the subsurface below the Glen Rose contact evident on resistivity logs. Regionally, however, there is cross-formational interconnection across the Edwards-Glen Rose contact. Both units are karstic limestones, and large caves that cross the contact are interpreted as evidence that cross-formational flow occurs through karst systems in at least parts of the San Antonio segment of the Edwards aquifer. Likewise, modeling of flow in the Trinity aquifer (Mace and others, 2000) concludes that cross-formational flow of significant volumes of water occurs from the Trinity into the Edwards in the San Antonio segment, illustrating connection between the aquifers.

The carbonates in the Edwards aquifer are laterally and vertically heterogeneous. This heterogeneity reflects the complex interactions among (1) paleogeography, (2) sea-level variation, (3) carbonate accumulation (productivity and transport), (4) siliciclastic transport, (5), early diagenesis, and (6) subsidence. The study area was on the north flank of a broad, low-relief positive area known as the Texas Platform and San Marcos Arch (Rose, 1972). Stratigraphic units deposited on the platform include the Walnut Formation/basal nodular member of the Kainer Formation, and the Kainer and Person Formations. These units collectively are described as the Edwards Group (Rose, 1972). A regionally traceable transgressive unit, known as the Regional Dense Member of the Person Formation, separates the Kainer and Person. Slightly deeper water in the North Texas Basin toward the north is interpreted from facies changes. Time-equivalent units recognized in North Central Texas include the Walnut, Comanche Peak, Kiamichi, and Duck Creek Formations (Rose, 1972; Moore, 1996). Sea-level variation is reflected in regionally correlated sequences (Immenhauser and Scott, 1999) and patterns of stacked high-frequency cycles. High-frequency cycles have been described in the Walnut Formation (Moore, 1996). Inspection of outcrop and log data suggests that the same type of high-frequency upward-shoaling cyclicity recognized in the San Antonio segment (Hovorka, 1996) is a dominant pattern in the Barton Springs segment; however, no detailed stratigraphic studies have been done in units younger than the Walnut. In the San Antonio segment of the Edwards aquifer, interaction between lithologies and structure was observed to influence distribution of karst conduits (Hovorka and others, 1998). Karst conduits developed preferentially where fractures intersect subtidal dolomites. Beds of calcitized and dissolved evaporites may also focus karst dissolution. The relationship between lithofacies and structure within the Edwards aquifer of the Barton Springs segment will most likely impact flow within the aquifer similarly; however, the relationships have not been documented.

The Edwards Group is overlain by transgressive carbonates of the Georgetown Formation. The contact is at least locally unconformable, with development of pre-Georgetown karst (Rose, 1972). The Georgetown Formation is generally of a lower porosity than the Edwards Group. It is commonly included within the Edwards aquifer because (1) there is no barrier to hydrologic connection between the Edwards and Georgetown, (2) karst features are at least locally developed in the Georgetown, and (3) it is difficult to separate the carbonates of the Edwards Group consistently from the carbonates of the Georgetown using the gamma-ray logs or driller’s reports commonly available from the subsurface.

The thick and regionally extensive shale of the Del Rio Formation forms a significant aquitard at the top of the Edwards aquifer. This contact can be recognized reliably on almost any type of log. Locally fracture systems may allow interconnection between the Edwards aquifer and overlying fractured or karsted carbonates; however the high clay content and plasticity of the Del Rio suggest that in most places it will function as an effective barrier to vertical flow.

Structure

For this study, we developed three maps covering the area of the Barton Springs segment: faults and structure contour on top of the Edwards aquifer (base Del Rio) in the confined aquifer (fig. 9), faults and structure contour on the base of the Edwards aquifer (top Glen Rose) throughout the aquifer (fig. 10), and an isopach map of the Edwards aquifer (fig. 11).

The procedure for creating digital maps was designed to reduce the frequency of errors and artifacts in this structurally complex area. A table of subsurface depths to stratigraphic formation tops prepared by Nico Hauwert (unpublished digital data, 1998) was reviewed and compared with the source log data from which it was derived. Many tops were reported from driller's logs and other data sources and could not be checked. Four hydrostratigraphic units were initially isopached and the isopach maps digitized: the Georgetown, Person, and Kainer (without basal nodular member) Formations and the Walnut Formation/Basal Nodular Member. Isopachs reflect stratigraphic thickness, not a reduction in thickness as a result of normal faulting. A combination of low density of subsurface information for the lower units and apparent inconsistencies in unit identification resulted in low confidence in interpretation of isopach maps. Therefore, the digital isopachs were summed, giving a net aquifer thickness (fig. 11).

The elevation of picks (in feet, sea-level datum) was posted on a paper plot for two contacts at each subsurface data point (fig. 12). In the unconfined section, the top Glen Rose/base Edwards aquifer (Walnut/basal nodular) was mapped. In the confined section, the top Edwards aquifer (top Georgetown)/base Del Rio contact was mapped. A match line generalized from the downdip edge of the Edwards outcrop was selected to control merging of the two maps. Data density on the surface geologic map is much higher than in the subsurface. In order to increase control and assure a good match between the subsurface and surface mapping, the surface geologic mapping was used to estimate the geometry of the aquifer in the subsurface. Faults mapped at the surface were extrapolated vertically into the subsurface (fig. 7). Although we know that most Balcones faults are high angle but nonvertical, this simplification is necessary because we have little control on fault-plane dip. In addition, some refraction and possibly change in fault abundance are likely because faults intersect units with different mechanical properties (Collins and Woodruff, 2001). Generalized isopach maps of map units were prepared. Then, within each fault block, the depth to the selected subsurface mapping horizon was calculated at several points from the elevation of the mapped contacts and the unit thickness. Because of the structural complexity, we elected to hand contour the resulting data using an irregular contour interval. This allows geologic intuition to be used to guide interpolation through areas with few data. In most fault blocks, regional dip was required to accommodate the mapped outcrop pattern and subsurface data, supporting a relay-ramp geometry, so this concept was used throughout the mapping. Integration of data and comparison of one structure map with another suggested some revision and downdip extension of the fault and outcrop patterns, which were modified to match the revised interpretation in ARC/EDIT.

The hand-contoured structure maps were digitized, attributed, and imported into ARC/INFO. The resulting contours for the top of the Edwards aquifer in the confined zone and the bottom of the Edwards aquifer in the unconfined zone were imported into GeoQuest CPS3 gridding software. This software was selected for its fault-handling capabilities. Several iterations of the grid were created until all fault blocks were completely populated with elevation data and artifacts removed.

We subtracted the gridded aquifer thickness map from the gridded top of the Edwards aquifer in the confined zone to create a grid for the base of the Edwards aquifer structure in the confined aquifer. This procedure is preferred over creation of two structure maps in structurally complex areas because it eliminates artifacts that impact the isopach used in the model. Thinning of the aquifer because of fault offset was not incorporated into the isopach. The impact of faults with greater than 250 ft of throw were represented as flow barriers in the model as discussed later in this paper. Grids for the base of the aquifer in the confined and unconfined zones were then merged along the merge line to create a base aquifer grid. The gridded top of the Edwards aquifer in the confined zone was merged with the grid for land surface in the unconfined zone to create a grid for the aquifer top.

Structure in the aquifer can be described in terms of a regional eastward dip created by faulting on north-northeast-trending normal faults and graben systems. Faulting impacts the flow in the aquifer by limiting cross-fault flow because of reduced aquifer thickness or enhancing fault-parallel flow through fracture zones associated with faults (Hovorka and others, 1998).

Water Levels and Regional Groundwater Flow

A generalized water-level map was developed for the Barton Springs segment of the Edwards aquifer by using water levels measured in July/August 1999 (fig. 13). This time period was chosen because it includes the largest compilation of synoptic water-level measurements. Water levels generally follow the topography and the groundwater flow direction is generally to the east in the west part of the aquifer and to the northeast in the east part of the aquifer, toward Barton Springs.

Water-level fluctuations vary throughout the aquifer. Unlike many of the aquifers in the state, such as the Ogallala aquifer, where there is a continual decline in groundwater levels in response to pumping, water levels in the Barton Springs aquifer do not show a long-term decline as a result of pumping. The Barton Springs aquifer is dynamic, and water levels generally respond to temporal variations in recharge and local areas of pumping. Although water levels decline during long periods of drought, they recover rapidly in response to recharge. Slade and others (1985) noted that maximum water-level fluctuations range from 1 to 10 ft in the west area, 10 to 50 ft in the central area, and 40 to 119 ft in the east area. Water-level fluctuations are greatest in the confined section of the aquifer.

Water levels are continuously monitored in eight wells in the study area (figs. 14, 15). A variety of factors impact the range of water levels recorded by various wells, including penetration of fractures and/or conduits and location near major pumping centers. It is difficult to compare the range in water-level fluctuations among the monitoring wells because the record lengths are quite variable. In wells with the longest monitoring record, the range in water levels was from 96 ft (58-58-123; fig. 15c) to 164 ft (58-50-216; fig. 14b). Minimal water-level fluctuations in well 58-50-411 (range 28 ft; fig. 15a) are attributed to penetration of conduits during well construction. Most of the monitoring wells demonstrate large seasonal fluctuations in water levels. Senger and Kreitler (1984) indicated that water-level fluctuations in many of the wells in the confined section of the aquifer correlated with variations in spring discharge. For example, well 58-58-301, which is just east of the bad-water line, correlated with spring discharge, indicating a hydraulic connection between the “bad-water” zone and the fresh-water aquifer. Short-term fluctuations in water levels were also recorded in several wells. Hauwert and Vickers (1994) noted that well 58-50-801 showed rises of 10 to 20 ft in response to 1- to 2-inch rainfall events in early 1992. Similarly well 58-58-123 showed an 8-ft rise in water level in response to rain in May 1994. These large water-level fluctuations represent the movement of pressure pulses through the aquifer and indicate that the wells are hydraulically connected to the recharge area.

Rivers, Streams, Lakes, and Springs

Five major drainage basins traverse the study area (fig. 1). The drainage basins include a catchment area where the groundwater discharges to the streams and the streams are gaining. When the streams reach the outcrop area of the Edwards, they become losing streams and recharge the aquifer. The catchment area of the streams is 264 mi^2, whereas the recharge zone is about 90 mi^2. Stream flow is recorded in nine gaging stations in the study area (figs. 16 through 24). Stream-gaging stations are located upstream and downstream of the outcrop zone on Onion Creek (fig. 25). The other creeks have gaging stations on the upstream edge of the outcrop zone. Most of the streams are ephemeral and oftentimes record no flow during the summer (July, August, September) or during winter months (December, January, February) (figs. 16 through 24).

Most flow in the aquifer discharges in Barton Springs (figs. 1, 26). The mean spring discharge is 53 cfs (1917 through 1998). Discharge ranged from 13 cfs at the end of the drought in the 1950’s (1956) to 106 cfs (1992). Barton Springs consists of five major springs (Senger and Kreitler, 1985). The Main Springs consists of three springs in the pool area and constitutes about 80 percent of the discharge; Concession Springs, just north of the pool, and Old Mills Springs discharge from a small pool downstream from Main Springs on the south bank of Barton Creek. Cold Springs, located northwest of Barton Springs, discharges into the Colorado River and is flooded by Town Lake.

Recharge

The primary source of recharge is provided by seepage from streams crossing the outcrop area. Flow losses from the creeks are sufficient to account for groundwater discharge in springs and through wells. Five major creeks (Barton, Williamson, Slaughter, Bear, and Onion) provide most of the recharge to this area (fig. 1, table 1). The creek watersheds can be subdivided into contributing and recharge zones. The contributing zone (264 mi^2) is west of the recharge zone, and the streams are gaining streams as they flow over low-permeability Glen Rose limestone. The recharge zone (90 mi^2) coincides with the outcrop area of the Edwards aquifer, where the streams become losing streams. About 15 percent of the total recharge also occurs in interstream regions, where rainfall infiltrates the soil (Slade and others, 1985).

Calculation of stream recharge was described in detail by Barrett and Charbeneau (1996) and Slade and others (1985). Procedures developed in these earlier studies were followed in this study. Hourly flow records from gaging stations located upstream and downstream of the recharge zone were downloaded from the U.S. Geological Survey Web site (http:\\tx.usgs.gov). Recharge was calculated by subtracting daily average flow downstream of the recharge zone from that upstream of the recharge zone for Onion Creek. With the exception of Barton Creek, recharge increases linearly with flow in the upstream gaging station until a threshold flow is exceeded. These threshold values were determined by Slade and others (1985) and were used in this study (table 1). All flow in the upstream gaging station less than the threshold value was therefore assigned to recharge. Once the threshold value was reached, recharge was assumed constant at that value. Barrett and Charbeneau (1996) calculated recharge values by using data from 1979 through 1995. These recharge calculations were extended to December 31, 1998, in this study. Surface runoff from interstream areas to streams in the recharge zone was ignored in the recharge calculations because such runoff generally only occurs during very large storms, when recharge is already maximized. In the case of Barton Creek, the downstream gaging station is located within the recharge zone; therefore, recharge from this creek may be underestimated. A new gaging station was installed 110 ft upstream of Barton Springs on October 1, 1998, and a low-flow rating curve was developed for this station (Mike Dorsey, U.S. Geological Survey, personal communication, 2000). Additional data are required to develop rating curves for higher flows. Various relationships were used to assign recharge to Barton Creek. For low flows (≤ 30 cfs in Lost Creek), recharge is equal to stream loss. Between 30 and 250 cfs, a quadratic relationship developed by Barrett and Charbeneau (1996) was used. Flows greater than 250 cfs were assigned this value for recharge because this was the highest measured recharge. Average annual recharge was calculated for the 20-yr period (1979 through 1998). The percentage of total recharge represented by each creek is similar to values found by Barrett and Charbeneau (1996) (table 2). Diffuse interstream recharge was assumed to equal 15 percent of total recharge on the basis of studies conducted by Barrett and Charbeneau (1996) and is similar to the estimate provided by Slade and others (1985).

Hydraulic Properties

Although hydraulic property data from aquifer tests are not very useful in estimating zonal properties for equivalent porous media models, information on hydraulic properties from the literature was compiled to estimate the range in measured hydraulic parameters. On the basis of aquifer tests in the Edwards and associated limestones in Travis County (north of the Colorado River), Brune and Duffin (1983) reported a range of transmissivities from 400 to 300,000 gal/d/ft (53.6 to 40,200 ft^2/d). Senger and Kreitler (1984) calculated transmissivity using recession-curve analyses from wells near Barton Springs. Values range from 0.1 m^2/s (93,000 ft^2/d) to 0.4 m^2/s (372,003 ft^2/d).

To determine a range of values of hydraulic properties in the BSEACD, aquifer-test reports and analyses were compiled. Aquifer tests are required as part of the application process for commercial and public water-supply wells in the Barton Springs Edwards Aquifer Conservation District. Data from 24 aquifer tests conducted within the study area from 1982 through 2001 were compiled. Several hydraulic conductivity values, or a range of values, were averaged for each aquifer test. Hydraulic conductivity values range from 0.40 to 75.3 ft/d. Hydraulic conductivity values appear to be log-normally distributed, although the limited number of data may not adequately define the distribution (fig.27). The geometric mean hydraulic conductivity is 0.6 ft/d (table 3).

Brune and Duffin (1983) estimated the range of specific yield to be 0.04 to 0.06 and specific storage to be 0.00025 to 0.00045 ft^{-1}. Senger and Kreitler (1984) estimated storativities using recession-curve analyses from wells near Barton Springs. Values range from 0.001 to 0.023. Slade and others (1985) calculated a mean specific yield of 0.017 and estimated the storativity (0.00003 to 0.00006 ft^{-1}) taken from aquifer compressibility analyses by Maclay and Small (1984). Specific yield and storativity values were estimated for 10 of the 24 aquifer tests compiled from the study area. Specific yield ranged from 0.005 to 0.06 (n=5), and storativity ranged from 1×10^{-6} to 2.9×10^{-2} ft^{-1} (n=5).

Discharge

Groundwater discharge occurs primarily at Barton Springs, which consists of a series of springs in the Barton Springs Pool area in Barton Creek close to where it enters the Colorado River. Barton Springs discharge is calculated from a rating curve that relates water levels in well

YD-58-42-903 to spring discharge. Discharge at Barton Springs was highly erratic during the winter and spring of 1992, as a result of a large flood in December 1991. Barton Springs Pool was drained for repairs as a result of the flood (Barrett and Charbeneau, 1996). The lower water level in the pool resulted in underestimation of spring discharge because of its effect on the water level in the well used to estimate spring discharge. During the spring of 1992, several large storms caused the pool to fill, resulting in large increases in estimated spring discharge.Although a separate rating curve has been developed for periods when the pool is empty (Slade, personal communication, 2001), the reported decrease in spring discharge is questionable.Accurate discharge estimates are available from when the pool was refilled in the summer of 1992. Long-term discharge at Barton Springs is 53 cfs (1918 through 1999). Cold Springs, northwest of Barton Springs, discharges into the Colorado River but is not gaged because it is flooded by Town Lake. A limited number of flow data are available from Cold Springs.Discharge from Cold Springs of 3.7 cfs was measured on 8/10/1918 when discharge at Barton Springs was 14 to 15 cfs (N. Hauwert, BSEACD, personal communication, 2000), suggesting that discharge at Cold Springs is about 25 percent of that at Barton Springs. This value is considered the most accurate total measurement of flow at Cold Springs. Other measurements, considered partial measurements for Cold Springs, indicate that flow at Cold Springs ranges from 3 to 4 cfs when the corresponding flow at Barton Springs ranges from 14 to 84 cfs. These data suggest that discharge at Cold Springs may be as low as 4 percent of the discharge at Barton Springs.

Groundwater is also discharged through pumping wells. Monthly pumpage data are collected by the BSEACD and are available from 1989 through present. Pumpage data are also available from the Texas Water Development Board (TWDB); however, the data from the BSEACD are considered more reliable for later years because the district requires discharge reporting and meters have been installed in a number of wells, whereas the TWDB reporting is voluntary. The number of reported users ranged from 100 in 1989 to 142 in 1998 (table 4). The location of the major pumping areas is shown in fig. 28. Values for unreported pumpage were calculated from countywide estimates obtained from the TWDB and percentage of the county in the study area (~ 5%). This pumpage was uniformly distributed among all the active cells in the model. Annual pumpage ranged from 3.9 cfs (1990, 1991) to 6.3 cfs (1998). The years with lowest pumpage (1991 and 1992) correspond to years with highest precipitation. Annual pumpage ranges from 3 percent (1991, 1992) to 138 percent (1996) of recharge (table 4).

Other potential discharge areas include subsurface flow from the Edwards to other underlying aquifers (that is, the Glenrose Limestone); however, Slade and others (1985) concluded that such flow is negligible.

CONCEPTUAL MODEL OF GROUNDWATER FLOW

Development of a conceptual model of groundwater flow is a prerequisite for numerical modeling of any aquifer. This conceptual model describes our understanding of how the aquifer works. Precipitation falling on the contributing zone generally moves into streams, which recharge the aquifer as they traverse the outcrop. There are five major stream drainages in the study area. Recharge increases linearly with stream flow to a threshold stream flow and remains uniform after further increases in stream flow. Approximately 15 percent of the recharge in the study area results from infiltration of precipitation on the outcrop. Groundwater generally flows from areas of higher to lower topography (west to east) in the west part of the aquifer and then flows north in the east part of the aquifer toward Barton Springs and Cold Springs. Most of the aquifer discharges to the springs. Discharge to wells represents about 10 percent of long-term average discharge at Barton Springs. The aquifer is unconfined in the outcrop zone and in the adjacent area, where the Edwards limestone is overlain by the Del Rio Clay. Farther to the east the aquifer is confined (fig. 1). The east boundary of the region is marked by the bad-water line, where the TDS of the water exceeds 1,000 mg/L. The aquifer is dynamic and responds rapidly to recharge events. This rapid response is attributed to the high degree of karstification, as evidenced by caves. Additional evidence of karstification is provided by the results of dye tracer tests, which indicate that water travels long distances within hours.Groundwater levels fluctuate to as much as 90 ft in some areas. Because of the dynamic nature of the aquifer, it will also respond quickly to drought conditions, and flow at Barton Springs could decrease rapidly in response to severe droughts. The aquifer should recover fairly rapidly after drought, however, and cumulative effects of drought should be negligible.

MODEL DESIGN

Model design includes information on the code and processor, aquifer discretization, and model parameter assignment.

Code and Processor

MODFLOW-96 (Harbaugh and McDonald, 1996), a modular finite-difference groundwater flow code developed by the U.S. Geological Survey, was used for the simulations. This code was chosen because (1) it is the most widely used and tested code for groundwater resource evaluation, (2) it is well documented (McDonald and Harbaugh, 1988), and (3) it is in the public domain. A variety of pre- and postprocessors have been developed to facilitate data entry and allow analysis of model output. In this study we used the Processing MODFLOW for Windows (PMWIN) version 5.0.54 (Chiang and Kinzelbach, 1998). The model was run on Dell Latitude with a Pentium II Processor and 64 MB RAM running Windows NT.

Grid

The model consists of 1 layer that has 120 rows and 120 columns and a total of 14,400 cells. The cell size was chosen to be small enough to reflect the availability of input data, to provide appropriate details in the output, and to be manageable. Model rows were aligned parallel to the strike of the Edwards; the grid was therefore rotated 45° from horizontal. Rectangular cells were 1,000 ft long parallel to the strike of the faults and 500 ft wide (fig. 29). This discretization is much finer than that previously used by Slade and others (1985; minimum cell spacing was 1,500 ft). The zone of active cells was defined on the basis of the hydrologic boundaries as described previously. The north boundary is the Colorado River. The east boundary is the bad-water line that was obtained from the BSEACD. The south boundary is a hydrologic divide located along Onion Creek in the Edwards aquifer recharge zone and between the cities of Buda and Kyle in the confined part of the aquifer, as determined by Stein (1995). The west boundary is the Mount Bonnell fault, which acts as a hydrologic (no-flow) barrier (Senger and Kreitler, 1984). Cells with layer thickness of less than 20 ft were assigned as inactive. Cells outside the model area were made inactive, resulting in 7,043 active cells.

Model Parameters

Model parameters include (1) elevations of the top and bottom of the layer, (2) horizontal hydraulic conductivity, (3) specific yield, and (4) specific storage. Specific yield and specific storage are required only for the transient simulations.

The structure of the top of the aquifer was based on ground-surface elevation in the unconfined recharge zone. A digital elevation map of the ground surface was downloaded from the U.S. Geological Survey Web site. East of the outcrop zone, the top of the aquifer corresponds to the base of the Del Rio Clay. The base of the aquifer corresponds to the base of the Walnut Formation, determined from recent studies by Small and others (1996). The location of faults was also based on interpretations by Small and others (1996). The contoured structure surfaces and faults were digitized and gridded using CPS3 for input to the model. Structure surfaces were interpolated to model cell centers using GIS software (ARC/INFO).

The model layer was assigned as confined/unconfined. The model was set up to calculate transmissivity and storativity on the basis of saturated thickness. The length unit was feet, and the time unit was days for all model input. Initial head for the steady-state simulations was the top of the aquifer.

MODEL BOUNDARIES

We assigned model boundaries for (1) recharge, (2) pumping, (3) springs, and (4) initial conditions. Recharge values were assigned to stream cells on the basis of analysis of flow losses in the streams. Recharge was uniformly distributed in each stream where the stream intersects the outcrop. Interstream recharge was 15 percent of the total stream recharge and was assigned to all active cells.

Pumping was assigned to cells on the basis of the location of pumping wells reported to the BSEACD. Unreported domestic (rural) pumpage was calculated from countywide estimates and was assigned to all active cells.

We used the Drain Package of MODFLOW to represent Barton Springs and Cold Springs. The drain elevation is the spring elevation (432 ft for Barton Springs and 430 ft for Cold Springs), and a high drain conductance value was used (1,000,000 ft^2/d) to allow unrestricted discharge of water.

Modeling Approach

Three basic steps were followed in modeling the aquifer: (1) a steady-state model was developed to determine the spatial distribution of hydraulic conductivity, (2) a transient model was run for a 10-yr period (1989 through 1998) by using monthly recharge and pumpage, and (3) a predictive model was developed to evaluate effects of increased pumpage and potential future droughts on groundwater availability. The steady-state model was developed because it is much more readily calibrated (because specific yield or storage coefficient data are not required) and the simulations run much faster. The calibration process involved matching simulated and measured water levels. Water levels measured during July/August 1999 were used for the steady-state calibration because spring discharge (66 cfs) was close to average conditions (53 cfs) during this time and water levels measured during this time represent the most extensive survey conducted in the aquifer. Trial and error and automated procedures were used to estimate the zonal distribution of hydraulic conductivity during model calibration. Sensitivity analyses were conducted to assess the impact of varying recharge and hydraulic properties on the model results. We quantified the calibration, or goodness of fit between the simulated and measured water-level values, using the root mean square (RMS) error, where n is the number of calibration points, h_m is the measured hydraulic head at point i, and h_s is the simulated hydraulic head at point i.

$$RMS = \left[\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i^2\right]^{0.5} \tag{1}$$

The framework of the steady-state model was used to develop a transient model for the years 1989 through 1998, using monthly time steps. The zonal distribution of hydraulic conductivity developed from the calibrated steady-state model was used in the transient model. Hydraulic heads simulated in the steady-state model were used as input to the transient model. The 10-yr time period was chosen because pumpage records were only available for this time period, detailed synoptic water levels were measured during this time, transient water-level monitoring records correspond to this time period, and this record includes a range of hydrologic conditions from dry (1996 drought) to wet (1991, 1992). Very little calibration was required for the transient model.

The transient model was then used to predict how water levels and spring discharge might change during the next 50 yr in response to increases in pumping and potential future droughts.

STEADY-STATE MODEL

Calibration

Measured water levels in July and August (1999) were used to evaluate the steady-state model calibration because the number of measured water levels (99) was greatest for this time and spring discharge was close to average conditions (~ 66 cfs). The spatial distribution of recharge among the streams and in the interstream settings was based on the average recharge for a 20-yr record (1979 through 1998; table 2). The total amount of recharge was reduced to equal the average spring discharge for Barton and Cold Springs of 55 cfs and pumpage for 1989 of 5 cfs. Recharge was assumed to be known and was not changed during calibration. The distribution of hydraulic conductivity was estimated using a combination of trial and error and automated inverse approaches. The trial-and-error calibration involved the following steps:

- Horizontal hydraulic conductivity was adjusted during successive steady-state runs. Initial simulations used a uniform distribution of hydraulic conductivity that ranged from 5 to 50 ft d^{-1}.
- The next set of simulations used a zonal distribution of hydraulic conductivity, with conductivities ranging from 5 to 40 ft d^{-1} in the recharge zone and 200 ft d^{-1} outside the recharge zone. A zone of high conductivity (~ 1,000 ft d^{-1}) was then set adjacent to Barton Springs. Either the simulations did not converge or the simulated heads were much too high.
- We then imported the spatial distribution of hydraulic conductivities used by Slade and others (1985); however, almost the entire model region went dry when these conductivity values were used.
- We simulated faults with the greatest amount of offset as horizontal flow barriers (Hsieh and Freckleton, 1993). Input data required for this module include the hydraulic conductivity divided by the aquifer thickness; values of 0.01 d^{-1} (southwest fault) and 0.05 d^{-1} (other faults) were used in the simulations. Three faults were used in the simulations.
- The final approach that was used to achieve a calibrated model involved increasing the complexity of the hydraulic conductivity distribution from the

> simple three-zone model based on calibrated hydraulic conductivities determined by Slade and others (1985) and variations in the hydraulic gradient. Steep hydraulic gradients in the southwest part of the model suggested low hydraulic conductivities, and shallow hydraulic gradients near Barton Springs suggested high hydraulic conductivities. The structure of the base of the aquifer was adjusted in some of the steady-state simulations to achieve convergence.

The results of the trial-and-error calibration indicated that there are 10 zones of hydraulic conductivity that range from 1 to 1,000 ft/d. Monthly pumpage at 1989 rates was also included in the final steady-state model and represents approximately 6 percent of the discharge at Barton Springs. Including this amount of pumpage did not significantly alter water levels or spring discharge in the model.

The results of the trial-and-error calibration generally reproduced the spatial distribution of water levels. Comparison of measured and simulated water levels resulted in an RMS error of 35 ft. The RMS error indicates that, on average, the simulated water levels differ from the measured water levels by about 35 ft. We also evaluated the use of automated inverse modeling to estimate the zonal distribution of hydraulic conductivity. Initial attempts to use automated inverse modeling in the early stages of calibration suggested that this procedure could not be used to determine reasonable values of hydraulic conductivity. Once the trial-and-error calibration was completed, we wanted to determine whether automated procedures could further improve the calibration and reduce the RMS error. The automated inverse code UCODE (Poeter and Hill, 1998) was used for this process. The hydraulic conductivity estimates from the trial-and-error calibration were used as initial estimates of the zonal hydraulic conductivity for UCODE. Log transformation of the hydraulic conductivity was used. Initially all 10 zones were included in the automated fitting; however, best results were obtained when only 4 of the 10 zones were fitted. Use of automated inversion reduced the RMS error to 24 ft. This error represents 7 percent of the total head drop across the model. The primary difference between the trial-and-error and automated zonal hydraulic conductivity estimates was in the confined section to the southeast, where hydraulic conductivity was increased from 1 to 39 ft/d. The final distribution of hydraulic conductivity is shown in fig. 30. The steady-state model generally reproduced the potentiometric surface developed from water-level measurements in July/August 1999 (fig. 31). The scatter plot of simulated versus measured heads indicates that there is very little bias in the simulation results (fig. 32). The RMS error reflects both uncertainties in measured and simulated hydraulic heads. The heads were measured over a 2-mo period. Synoptic water-level measurements over a 2-mo period is generally considered very short for most porous media aquifers but is fairly long for this karst aquifer, which is dynamic, and spring discharge decreased from 80 to 60 cfs during this time.Therefore, the measured heads may not reflect the average discharge of Barton Springs (~53 cfs). Most of the head data were based on well locations and elevations obtained from 1:250,000 topographic maps, whereas some head data were based on global positioning system measurements. Errors were generally low throughout the model area with the exception of the southwest area, where heads are underpredicted by up to 60 ft (fig. 33). Simulated discharge was 52 cfs at Barton Springs, 2.8 cfs at Cold Springs, and 5 cfs from pumping wells.

Sensitivity Analysis

Once the steady-state model was calibrated, the sensitivity of water levels in the model to different aquifer parameters was evaluated. Sensitivity analysis quantifies the uncertainty of the calibrated model to uncertainty in the estimates of the aquifer parameters, stresses, and boundary conditions (Anderson and Woessner, 1992, p. 246). Sensitivity analysis is used to evaluate the nonuniqueness of the calibrated model. The hydrologic parameters that have the greatest impact on simulated water levels and spring discharge can be identified through sensitivity analyses.

Sensitivity analyses were conducted on hydraulic conductivity, recharge, spring conductance, and pumpage. Each parameter was varied systematically, and the change in simulated water levels from the base case was calculated (1) at the location of the calibration wells and (2) in each active cell in the model. Any bias in the sensitivity analysis and the calibration between the calibration points and the entire model layer could be identified by comparing the results at the well locations and the active cells. The change in water levels was quantified by calculating the mean difference:

$$MD = \frac{1}{n}\sum_{i-1}^{n}\left(h_{sen} - h_{cal}\right) \tag{2}$$

where n is the number of points, h_{sen} is the simulated water level for the sensitivity analysis, and h_{cal} is the calibrated water level. Positive values indicate that simulated water levels are higher than calibrated values, and negative values indicate that simulated water levels are lower than calibrated values.

Simulated water levels in the model were most sensitive to recharge and hydraulic conductivity and insensitive to pumpage and drain conductance (fig. 34). The mean differences calculated at the calibration locations and at each active cell in the model are similar, indicating that the calibration points probably do not bias the sensitivity analysis and represent the aquifer well. Higher values of recharge resulted in higher simulated water levels. The model failed to converge for reductions in recharge of 25 and 50 percent of the calibrated value. Higher values of hydraulic conductivity resulted in lower simulated water levels, whereas lower values of hydraulic conductivity resulted in higher water levels. The sensitivity to hydraulic conductivity was slightly asymmetric in that the simulated water levels were more sensitive to lower than to higher hydraulic conductivities.

TRANSIENT MODEL

Simulated heads and the calibrated distribution of horizontal hydraulic conductivity from the steady-state model were used as input for the 10-yr transient model, which was from 1989 through 1998. Annual precipitation during this time ranged from 26 inches in 1989 to 52 inches in 1991 (fig. 35; table 4). Monthly stress periods were used for the transient simulations, with 12 time steps in each stress period. This setup resulted in a total of 120 stress periods for the 10-yr simulation (1989 through 1998). A stress period is a time interval in MODFLOW during which all inflow, outflow, properties, and boundary conditions are constant. Recharge and pumpage were changed for each stress period (fig. 35a, b). Recharge rates were estimated from stream-loss studies, as discussed previously. Annual recharge was highest in 1992 (169 cfs) and lowest in 1996 (4 cfs) (table 4). Monthly recharge was much more variable and ranged from 0.3 to 500 cfs (fig. 35b). Pumpage was assigned on the basis of data from the BSEACD. Annual pumpage ranged from 3.9 cfs (1990, 1991) to 6.3 cfs (1998) (table 4). Because recharge varied greatly from year to year, the percentage of recharge represented by pumpage varies from 3 percent during 1991 and 1992 to 138 percent during 1996. Initial estimates of specific yield (0.005) and specific storage (5×10^{-5} ft^{-1}) were based on data from Slade and others (1985).

Initial transient simulations did not converge because of cells near the west-central portion, in which the simulated hydraulic head oscillated between iterations. These cells were located in a zone where the base of the Edwards aquifer was much higher than surrounding areas. By lowering the base of some of these cells to values similar to those in adjacent areas, we achieved convergence. This lowering assumes that the underlying Glen Rose Formation is locally permeable and connected to the Edwards aquifer.

The transient simulation was evaluated using three different criteria: (1) Simulated and measured spring discharge were compared (figs. 36, 37). (2) Simulated hydraulic heads were compared with hydrographs for eight monitoring wells (figs. 38 and 39). (3) Scatter plots were developed for simulated and measured heads during low (1994, 1996) and moderately high (1998) flow conditions (fig. 40).

Generally good agreement was obtained between measured and simulated discharge at Barton Springs (figs. 36, 37). Simulated discharge at Barton Springs was calculated by subtracting discharge at Cold Springs (6 percent of total discharge) from total discharge listed in the output file. The RMS error between measured and simulated discharge for the distributed model is 12 cfs, which represents 11 percent of the discharge fluctuations measured at Barton Springs during that time. Data from an 8-mo period, December 1991 through July 1993, were omitted from the error calculations because of uncertainties related to the measured discharge data as a result of flooding. One of the main objectives of the model is to accurately simulate low flows in Barton Springs. The scatter plot suggests that on average there is no bias in the results (fig. 37); however, this plot masks underpredictions and overpredictions at different times. Overprediction of low spring flows in 1989 and early 1990 is attributed to the initial conditions (hydraulic head from steady-state model) not being in equilibrium with the boundary conditions (recharge and discharge) for the transient simulation. Good correspondence between measured and simulated discharge was found for 1990 through1991. Simulated spring discharge generally underestimates measured discharge during the 1994 low flow period; however, both measured and simulated discharges have the same minimum value. In contrast, simulated discharge overestimates measured discharge during the 1996 low flow period. The slope of the simulated recession is more gradual than that of the measured recession, which is U shaped, and the timing of the minimum simulated discharge is later than that of the measured data. Peak discharges are underestimated in some cases (1990 through 1991), simulated accurately in other cases (1989, 1993, 1995), and overestimated in other cases (1991 - 1992, 1997, 1998). During high flows, some of the discharge may be diverted to an ungaged spring and other smaller springs along Barton Creek, which is unaccounted for in the model.

The transient model generally reproduces water levels monitored continuously in many of the continuously monitored water levels (figs. 38, 39). Water levels in the north part of the aquifer are reproduced more accurately than those to the south. The RMS error ranged from 3.8 ft (58-42-8TW) to 31 ft (58-50-221) in the four wells in the north, and these errors represent 16 to 63 percent of the range in water-level fluctuations. RMS errors increase in wells to the south and range from 37.5 ft (58-50-411) to 83.7 ft (58-58-123). Because well 58-50-411 is located adjacent to a cave (N. Hauwert, BSEACD, personal communication, 2000), its water levels remain fairly constant. These water levels are not reproduced in the simulation, which cannot represent flow in caves.

Scatter plots between measured and simulated water levels were developed for different times during the transient simulation (fig. 40). The scatter plot for March/April 1994 shows that the model generally simulated the water levels during low-flow conditions (fig. 40a). The RMS error of 29 ft represents 11 percent of the head drop in the model area. Comparison of measured and simulated water levels for July and August 1996 (fig. 40b) indicates that simulated water levels underestimate measured water levels by 37 ft (10 percent of the head drop across the model area) on average for this low-flow period. It is difficult to compare measured and simulated water levels during high flow periods because spring discharge is generally changing rapidly and synoptic water-level measurements over 2-mo time periods generally span large changes in spring discharge. The scatter plot for July and August 1998 generally represents the end of the transient simulation (fig. 40c). The RMS error of 64 ft (22 percent of the head drop in the model) is much higher than the other RMS errors and is attributed, in part, to the dynamic nature of the aquifer during high flow conditions. In general, the model provides reasonable simulations of water levels for different times.

Sensitivity analyses were conducted to assess the impact of varying groundwater recharge, pumpage, specific yield, and specific storage on simulated spring discharge and water levels in monitoring wells (figs. 41 through 45). In many cases, we could not evaluate the effect of reducing the various parameters by 50 percent because the simulations did not converge in most cases. Therefore, the evaluation is limited to the range of –10 to + 50 percent. Groundwater recharge had the greatest impact on spring discharge and water levels in monitoring wells. Increasing recharge by 50 percent resulted in increasing the mean spring discharge by about the same amount (table 5; fig. 41a). Increasing recharge had a greater impact on high spring flows than on low flows, and spring discharge was more variable, as shown by the range and coefficient of variation of spring discharge (table 5). Simulated water levels in monitoring wells displayed a similar response to variations in recharge as spring discharge (fig. 42). Decreasing recharge had the opposite effect of increasing recharge. Simulated spring discharge and water levels in wells were much less sensitive to variations in pumpage, specific yield, and specific storage (figs. 41b, c, d; 43, 44, 45; table 5). Increasing pumpage by 50 percent had a negligible effect on spring discharge and water levels in wells. Increasing specific yield and specific storage by 50 percent resulted in 1.6 and 0.7 percent increase in mean spring discharge, respectively, compared with 50 percent increase in response to recharge. Uncertainties in specific storage are greater than those of specific yield; therefore, an additional simulation was conducted to evaluate the impact of varying specific storage by a factor of 10. Increasing specific storage by 10 decreased the mean spring discharge slightly but greatly reduced the range in spring discharge (table 5). The increased specific storage does not simulate the low spring discharges which are critical for groundwater manaagement. Increasing specific storage by 10 had a similar effect on the simulated water levels in the monitoring wells, which better replicate the measured water-level fluctuations in the monitoring wells (fig. 45). However, the emphasis of the study on simulating low spring discharges over accurately simulating water levels in monitoring wells precludes using the higher specific storage in the final simulations.

PREDICTIONS

The calibrated model was used to evaluate the future availability of groundwater in the Barton Springs segment of the Edwards aquifer under average recharge and drought-of-record conditions. Senate Bill 1 requires water planning under drought-of-record conditions to ensure that future water needs are met during times of severe drought. The drought of record was evaluated for the study area.

Future Pumpage

The future simulations were initiated with pumpage data from BSEACD for 2000. Estimates of future groundwater demands were based on demand numbers from the Regional Water Planning Group (Region K). Future pumpage was estimated on the basis of projections made by the Region K Water Planning Group and the Capital Area Metropolitan Planning Organization (CAMPO). Estimates of future population and water usage have been made by these groups for cities and counties in and around the District; however, none of these projections could be applied directly to the District. On the basis of estimated total pumpage in the District (permitted and exempt wells), a multiplier of 2.1 was used to calculate pumpage in 2050 from current pumpage (2000). This multiplier is higher than estimates for rural areas, but lower than for towns. Starting with current (year 2001) total pumpage of 6,754 acre-ft/yr (equivalent to 9.3 cfs), pumpage in 2050 was estimated to be 14,183 acre-ft/yr (19.6 cfs). Monthly pumpage used in the future simulations was linearly interpolated between 2001 and 2050. The regional planning groups included the implementation of conservation measures as a part of projected water usage but did not consider substitution of surface water for groundwater. Because we do not have any information on the seasonal distribution of pumpage, we used the monthly data from the transient simulation from 1989 through 1998 and simply multiplied by the factors required to increase the annual pumpage to the values for 2001 through 2050.

Drought of Record

A drought of record is the most severe drought during the period of record in terms of duration and lack of rainfall. The drought of record for the study area occurred between 1950 and 1956 according to the 140-yr record of precipitation (1860 through 2000) (fig. 46). Precipitation ranged from 25.8 inches in 1950 to 11.4 inches in 1954. The mean annual precipitation during the 7-yr drought period (23.1 inches) was about two-thirds of the long-term annual precipitation (33.5 inches). The mean annual precipitation during the last 3 yr of the drought (16.5 inches) was about half the long-term average precipitation.

We tried to estimate the recharge that would correspond to the 1950's drought by relating precipitation to recharge for the period of record (1989 through 1998), but the relationship was very poor. We then tried to relate recharge to Barton Springs discharge for the same period, but the scatter plot indicated very poor relationships. Comparison of the time series nevertheless suggested a much stronger relationship, with some lag between recharge and discharge. Therefore, we finally decided to assume that recharge equals discharge, although doing so may slightly overestimate recharge during low recharge conditions because it might include discharge from storage in the aquifer. Annual discharge values for Barton Springs were obtained from Slade and others (1986) for the period 1950 through 1956 (fig. 26) and were increased by 5 percent to account for discharge from Cold Springs. Recharge for normal climatic conditions was based on long-term average discharge at Barton Springs and Cold Springs of about 55 cfs. The monthly distribution of recharge from the transient simulation (1989 through 1998) was used for the future simulations of drought conditions, and these values were reduced to average recharge of 55 cfs for the first 3 yr and reduced by the amount required to obtain the recharge for the 1950's drought for the remaining 7 yr. Future simulations of average recharge (55 cfs) with increased pumpage used evenly distributed recharge for each month of the year and not the seasonal distribution from the transient simulation from 1989 through 1998. The latter approach was used because the simulated potentiometric surfaces from future simulations with the seasonal distribution of recharge varied markedly, making it difficult to estimate drawdowns when comparing different potentiometric surfaces. The baseline potentiometric surface was developed by simulating average recharge (55 cfs) evenly distributed throughout the year and current pumpage conditions (2000) (fig. 47).

Predicted Groundwater Availability

Predictive simulations were conducted with the calibrated model: baseline run with average recharge (55 cfs) evenly distributed throughout the year and future pumpage for each 10-yr period (2001 through 2010; 2011 through 2020; 2021 through 2030; 2031 through 2040; 2041 through 2050); simulations with future pumpage and drought conditions for each 10-yr period (3 yr of average recharge followed by 7 yr of drought) (Table 6).

We calculated the water-level declines at the end of the first and last decades (2010 and 2050) by subtracting the predicted water levels at the end of these decades from the baseline water levels. The predictive simulations indicate that water-level declines in response to increased groundwater pumpage are small: ≤ 5 ft in 2010 and ≤ 35 ft in 2050 (figs. 48a, 49a). In contrast, water-level declines in response to increased pumpage and drought-of-record conditions were much greater: ≤ 200 ft in 2010 and ≤270 ft in 2050 (figs. 48b, 49b). These results are consistent with the sensitivity analyses for the transient simulation, which indicate that the model is much more sensitive to recharge than to pumpage.

Average discharge at Barton Springs in response to average recharge and current pumpage (9 cfs) is about 43 cfs (fig. 50a). The sum of discharge at Barton Springs (43 cfs), Cold Springs (3 cfs), and pumpage (9 cfs) equals the average recharge of 55 cfs. The model predicts that Barton Springs discharge will decrease to 41 cfs in 2010 and to 33 cfs in 2050, which is directly proportional to increased pumpage (~ 2 cfs per decade and 10 cfs over 50 yr). The model predicts that spring discharge should decline much more in response to potential drought-of-record conditions. Predicted spring discharge at the end of 2010 is 7.5 cfs and 0 cfs in 2050 under drought-of-record conditions (fig. 50b). The results for spring discharge are similar to those for water levels and emphasize the significance of recharge and potential droughts in controlling water availability in the future.

MODEL LIMITATIONS

All numerical groundwater models are simplifications of the real system and therefore have limitations. Limitations generally result from assumptions used to develop the model, limitations in the input data, and the scale at which the model can be applied.

Use of a distributed, porous media model to simulate flow in a karst system is a simplification, and the model will not be able to simulate some aspects of flow accurately in this system, particularly the effects of conduits on groundwater flow. This simplification is not critical for water-resources management, and the study showed that the model was able to predict variations in spring flow over time, as well as fluctuations in water levels in monitoring wells. However, this model was not able to simulate very low water-level fluctuations in one of the monitoring wells that was located adjacent to a cave. The model will not be able to simulate traveltimes for contaminants in the system and should not be used for this purpose. The bad-water line to the east was simulated as a no-flow line. This representation may not be entirely accurate, particularly during low flow periods when low gradients may induce flow from the east. Further studies should evaluate this process. The current model did not include the underlying Glen Rose Limestone, which in some areas may be sufficiently permeable and may contribute to flow in the Edwards aquifer.

There are also limitations associated with input data. Recharge data for this model are generally considered much more accurate than are available for many other regions. Stream recharge was distributed uniformly along the outcrop areas because of lack of information on spatial focusing of recharge in particular locations. This assumption may affect flow to Cold Springs because the line of recharge along Williamson Creek generally forms a divide, minimizing flow south of this creek to Cold Springs. Future studies should spatially distribute recharge along the streams. Because recharge data are not available for the 1950’s drought, we approximated recharge during this time by assuming that recharge equals discharge. More studies should be conducted to develop better estimates of recharge during this time. Water-level data for drawing potentiometric surfaces may affect our evaluation of the goodness of fit of the model because comparisons of simulated and measured water levels are restricted to areas where water levels have been measured.

The model also predicts drying in certain zones, such as in the south-central region.Such dry zones may be an artifact of the model as a result of steep gradients in the base of the Edwards and may or may not be realized in the future. Such drying may also depend on the conductivity of the underlying Glen Rose and the hydraulic connectivity of the units at the base of the Edwards units. The model also predicted unrealistically high water levels in the western fringe of the model, particularly in the southwest region. Overestimation of water levels in this zone may result from the aquifer being very thin in this region, and future modeling studies should evaluate whether this region should be included in the model. The high water levels may also be an artifact of the uniform distribution of recharge along streams in the model. This situation should also be evaluated in future studies.

This model was developed to evaluate variations in spring discharge and aquiferwide water-level declines over the next 50 yr. The model is not considered appropriate for local issues, such as water-level declines surrounding individual wells, because of the coarse grid size (500 × 1,000 ft) and limitations described earlier.

CONCLUSIONS

The Edwards aquifer is a critical source of water to about 45,000 residents in Travis and Hays Counties. We developed a numerical groundwater flow model for the Barton Springs segment of the Edwards aquifer to predict water levels and spring discharge under future pumping and potential future drought conditions. The model has 1 layer and 7,043 active cells and incorporates recent information on the geology and hydrology of the Edwards aquifer in this region. Recharge to the system was calculated by using stream-gage data. A steady-state model was calibrated to determine the distribution of hydraulic conductivity in the model, and a transient model simulated flow for a 10-yr period from 1989 through 1998. Future simulations included various projected pumpage scenarios and 3 yr of average recharge, followed by 7 yr of drought conditions similar to that of the 1950’s drought.

Good agreement was found between measured and simulated water levels for the steady-state model (RMS error is 24 ft, 7 percent of the hydraulic head drop across the study area). The steady-state model predicted that 6 percent of the discharge was through Cold Springs and the remainder through Barton Springs. The transient simulation generally reproduced measured spring discharge for 1989 through 1998. The RMS error was 12 cfs, which represents 11 percent of the discharge fluctuations measured at Barton Springs during that time**.**

To assess the future availability of groundwater in the Barton Springs segment of the Edwards aquifer, we used the calibrated model to predict future water levels under drought-of-record conditions using estimates of future groundwater demands that were based on demand numbers from the Regional Water Planning group. The model predicts that water-level declines in response to increased pumpage under average recharge conditions are small (≤35 ft), whereas water-level declines in response to increased pumpage and drought-of-record conditions are much greater (≤270 ft). Declines in spring discharge in response to increased pumpage are also small and proportional to the increased pumpage (~ 10 cfs in the next 50 yr), whereas the model predicts that spring discharge will decrease to 0 in response to drought-of-record conditions by as early as 2030. The extreme sensitivity of water levels and spring discharge to recharge and drought conditions indicates that aquifer management under drought conditions should consider enhanced recharge in addition to groundwater conservation.

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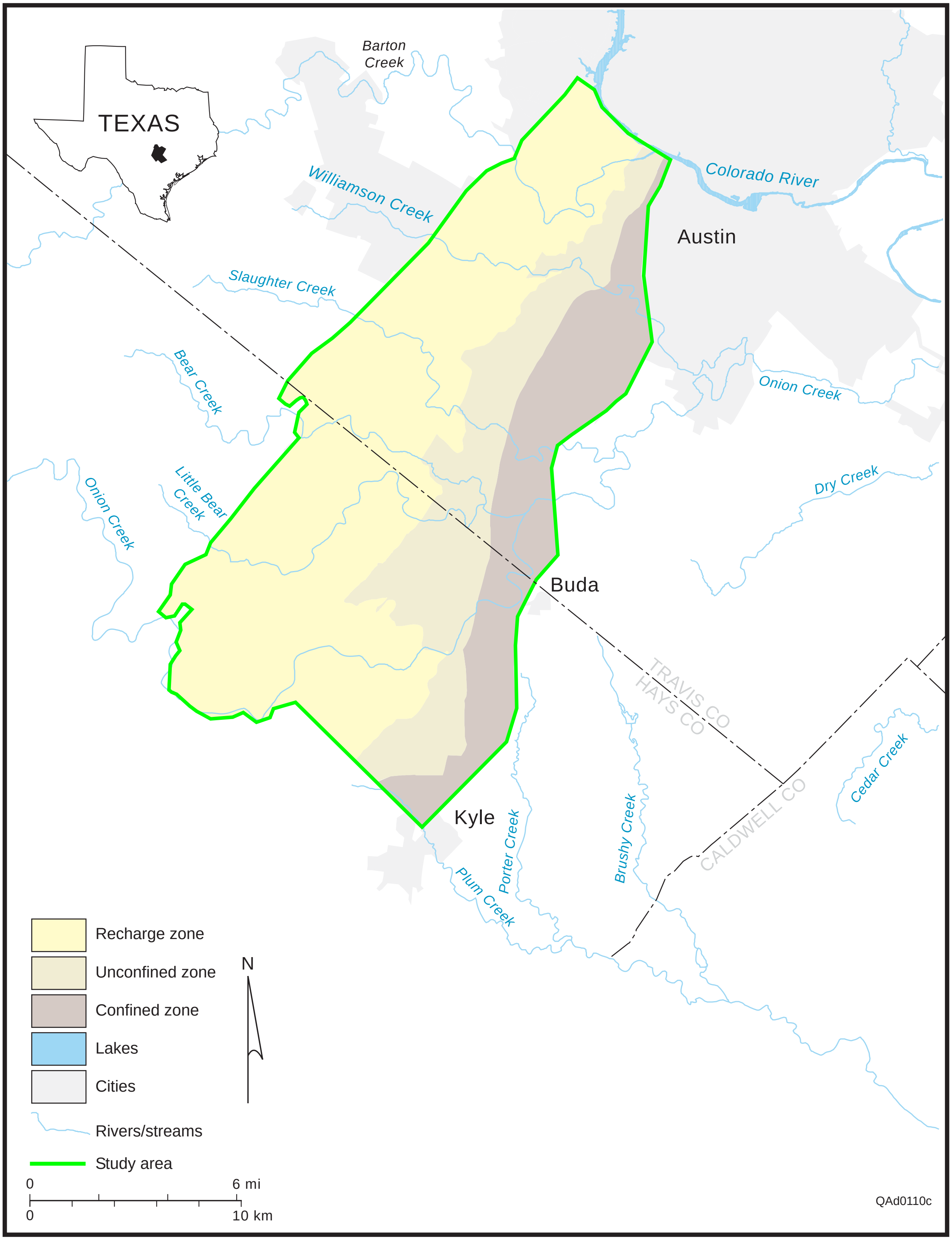


Figure 1. Location of the study area relative to cities, towns, roads, and rivers.

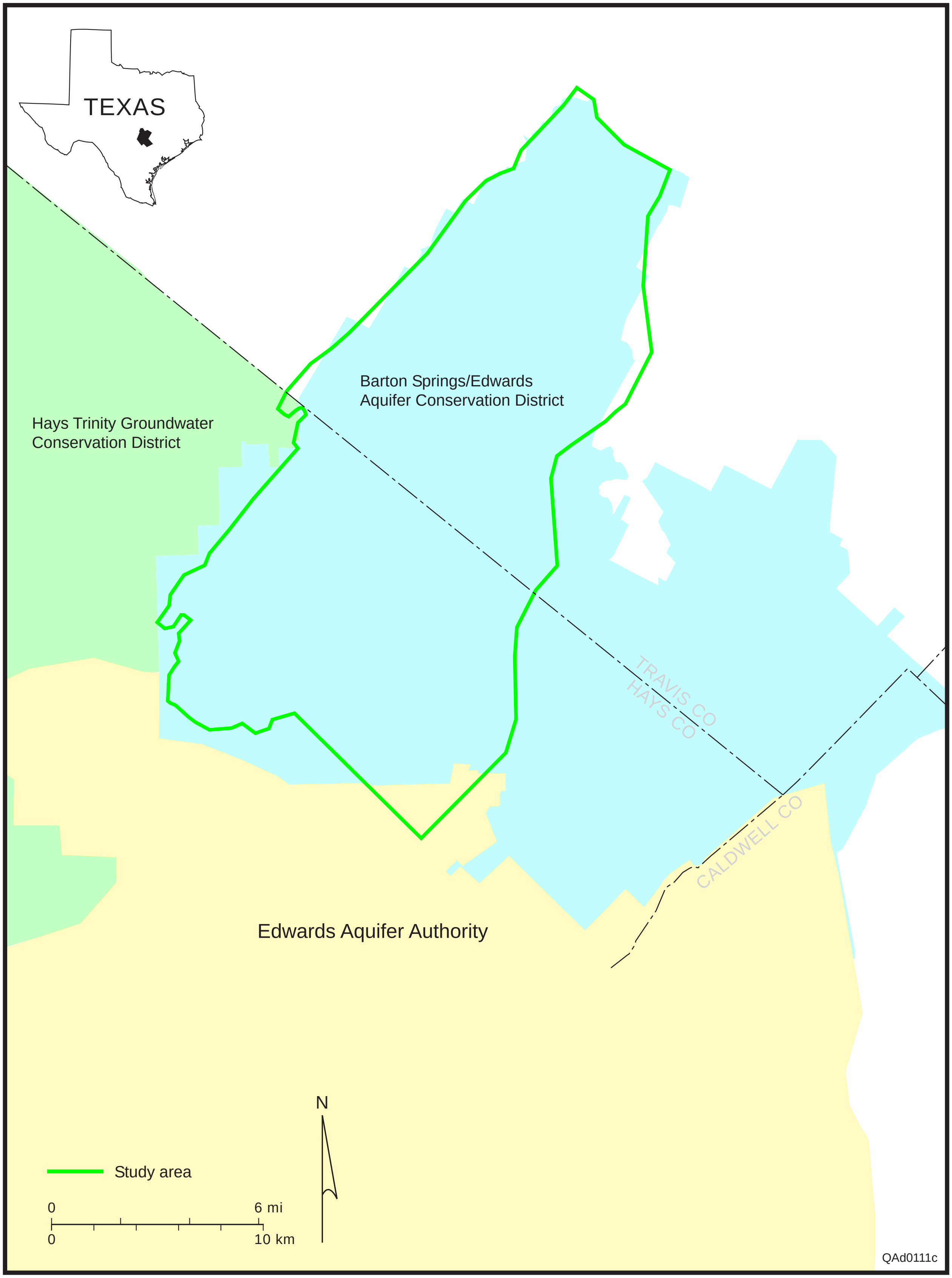


Figure 2. Location of Groundwater Conservation Districts in the study area.

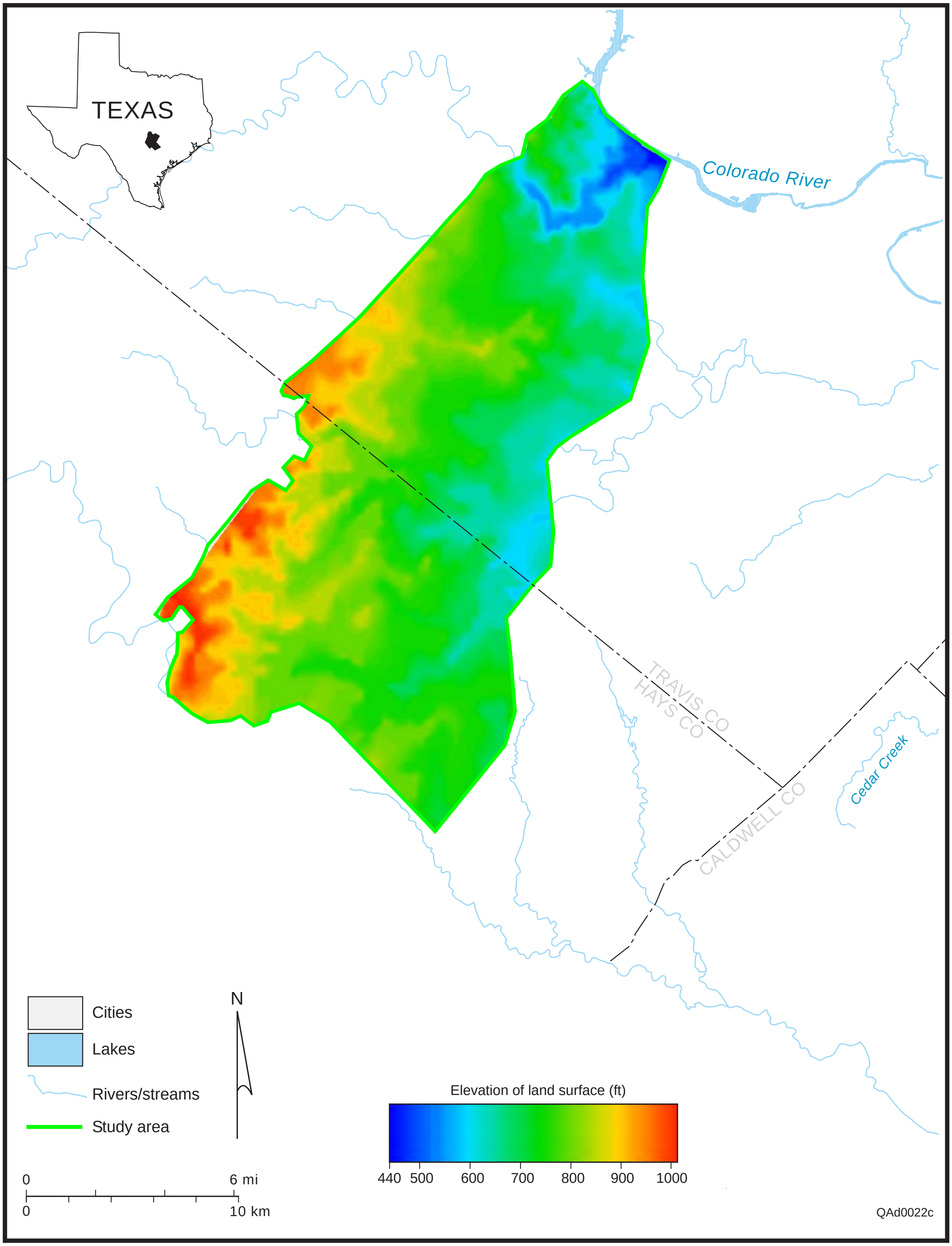


Figure 3. Land-surface elevation in the study area.

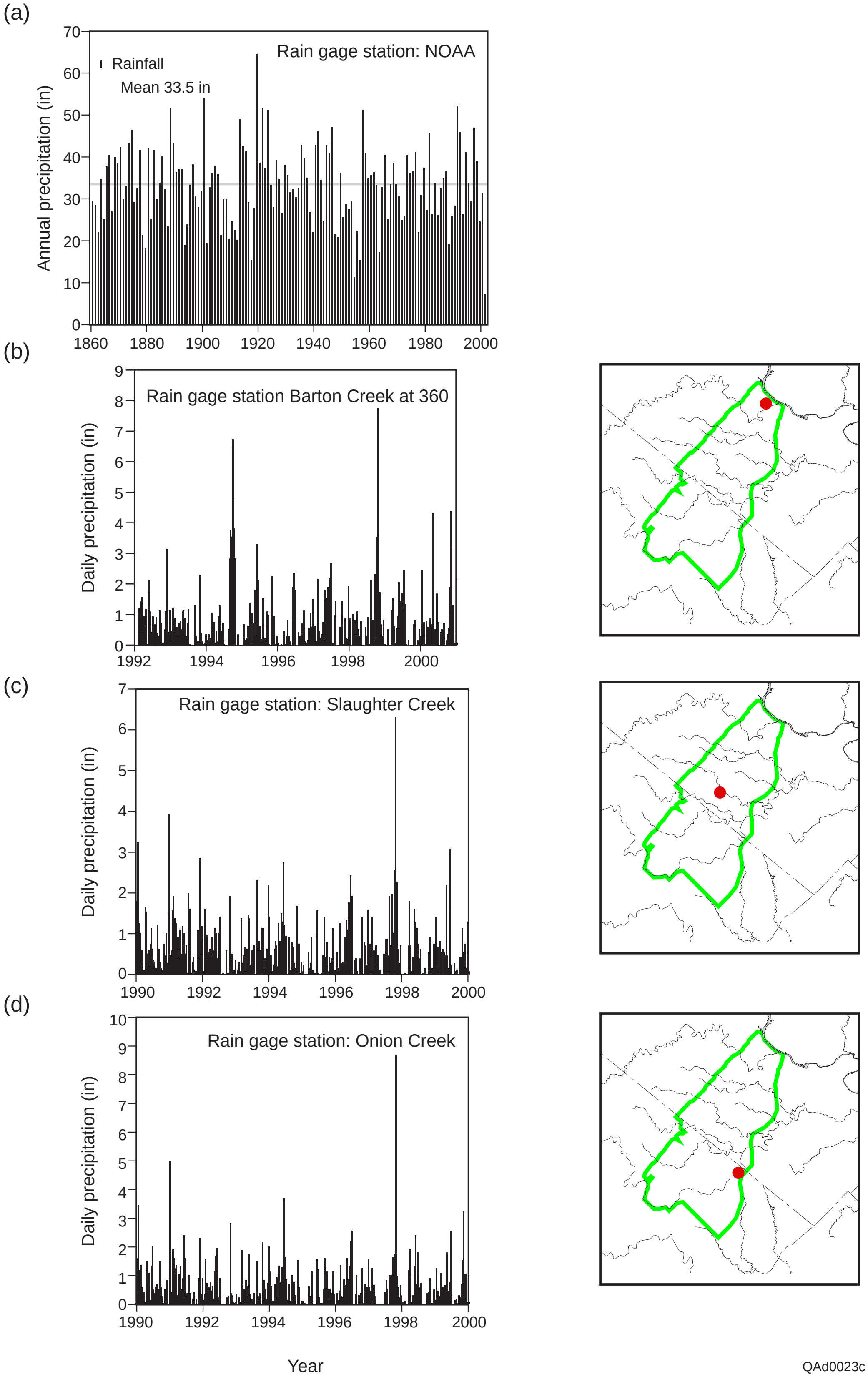


Figure 4. Historical annual precipitation for rain-gage stations at (a) Camp Mabry and Mueller Airport (NOAA station), (b) Barton Creek, (c) Slaughter Creek, and (d) Onion Creek.

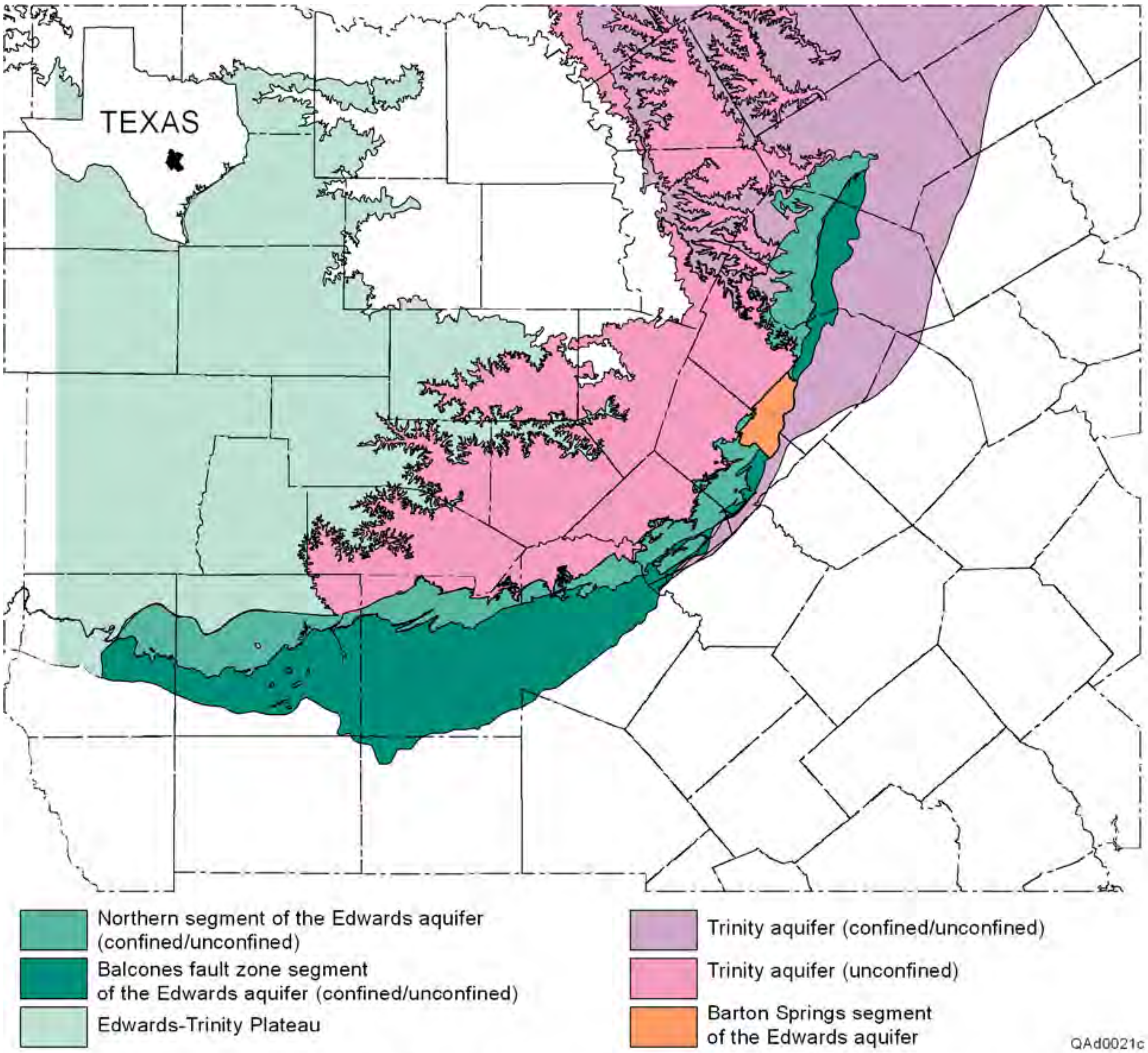


Fig. 5. Geologic setting of the Barton Springs segment of the Edwards aquifer.

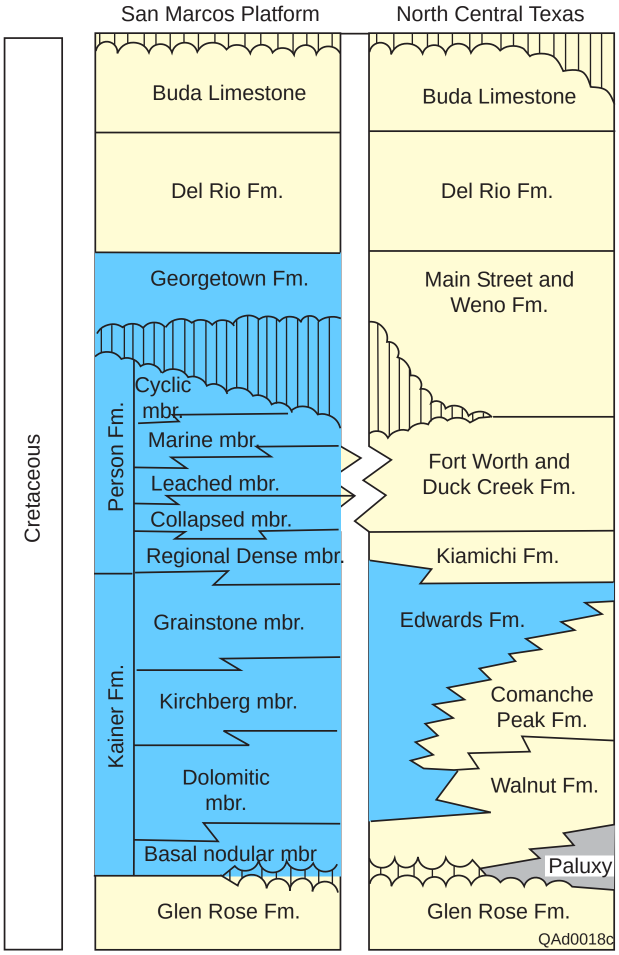


Fig. 6. Stratigraphic and hydrostratigraphic section of the study area.

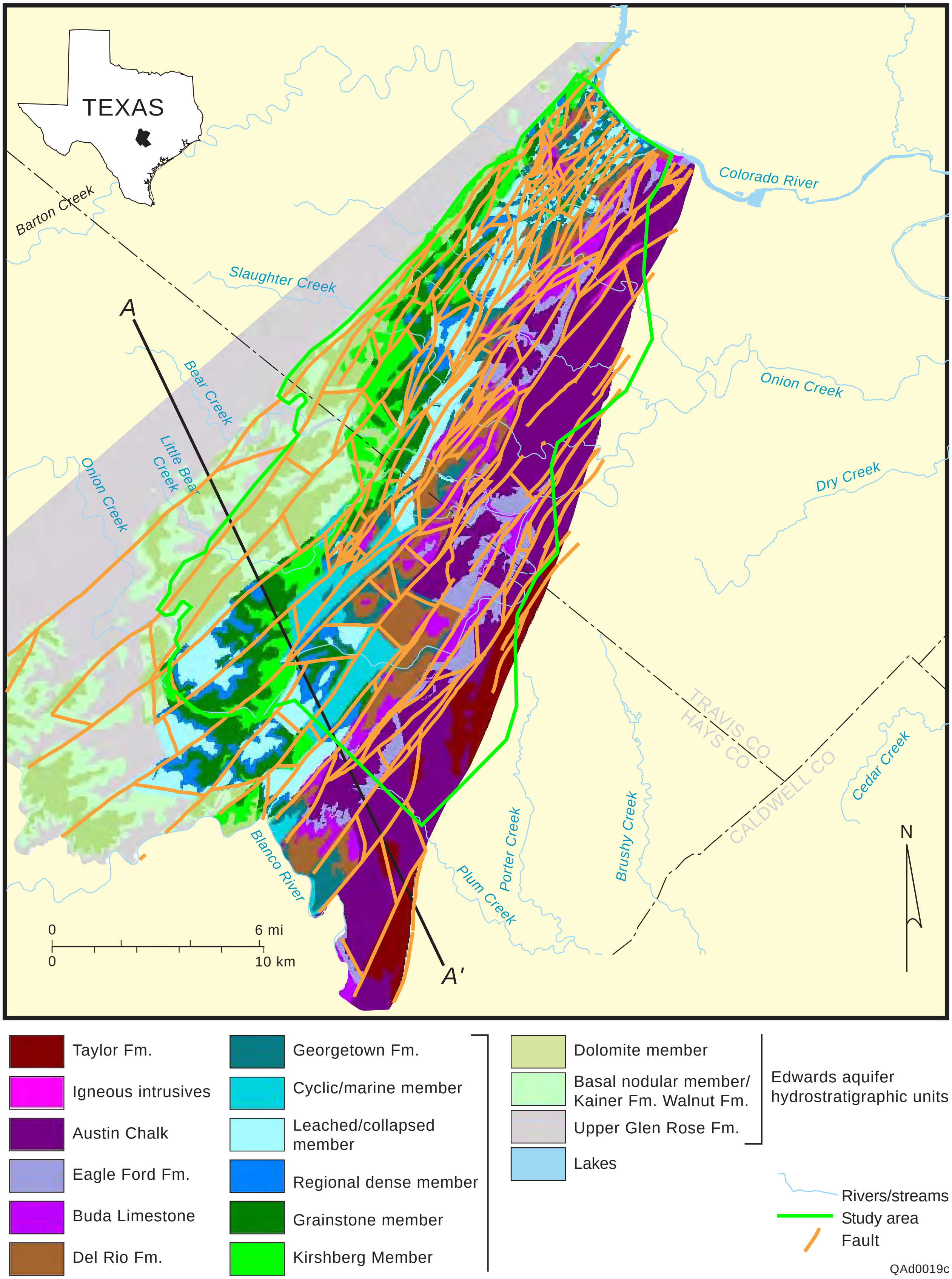


Fig. 7. Surface geology in the study area.

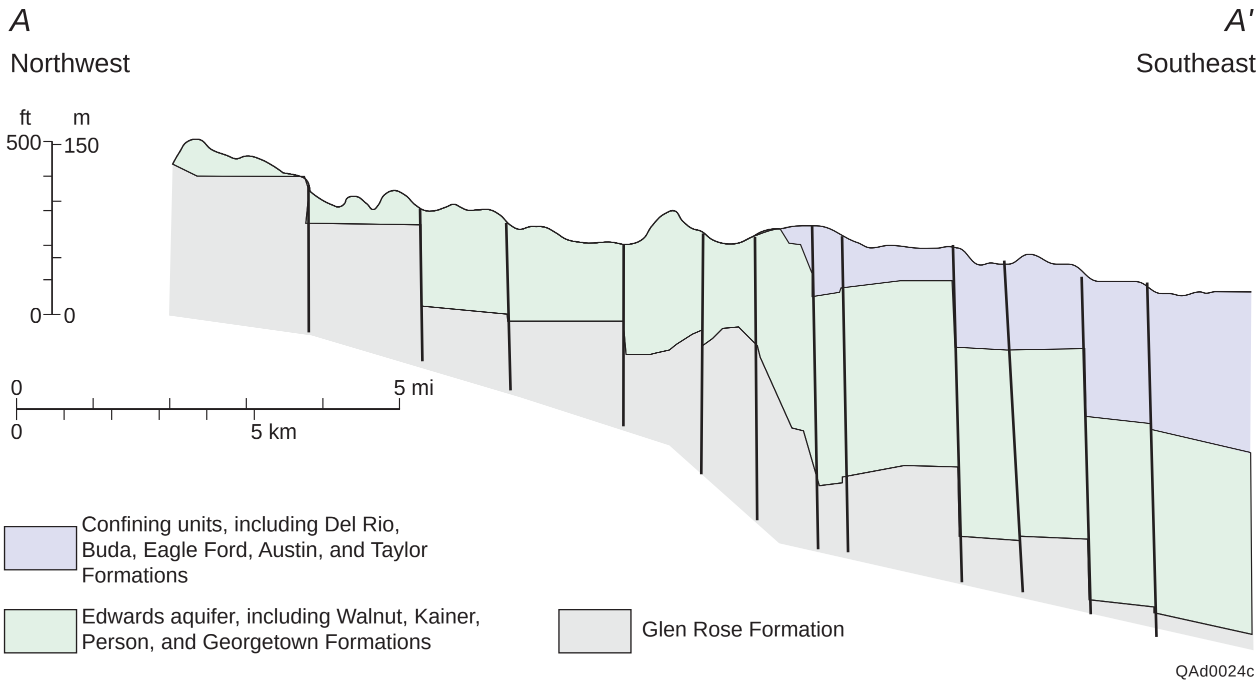


Fig. 8. Geologic cross section of the study area. Location of cross section shown in figure 7.

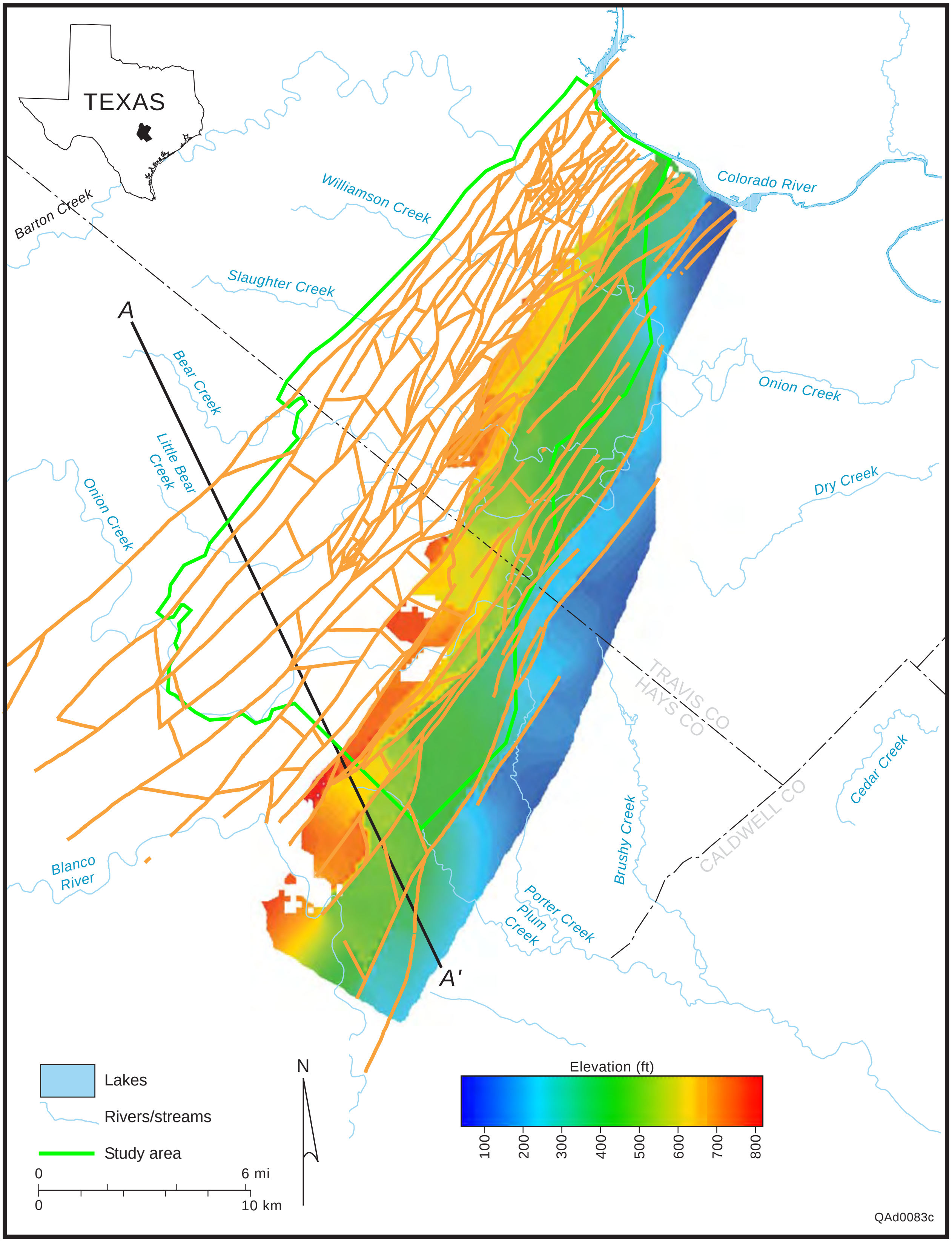


Fig. 9. Elevation of the top of the Edwards aquifer (which corresponds to the base of the Del Rio Formation). Figure 12 shows the location of the control points.

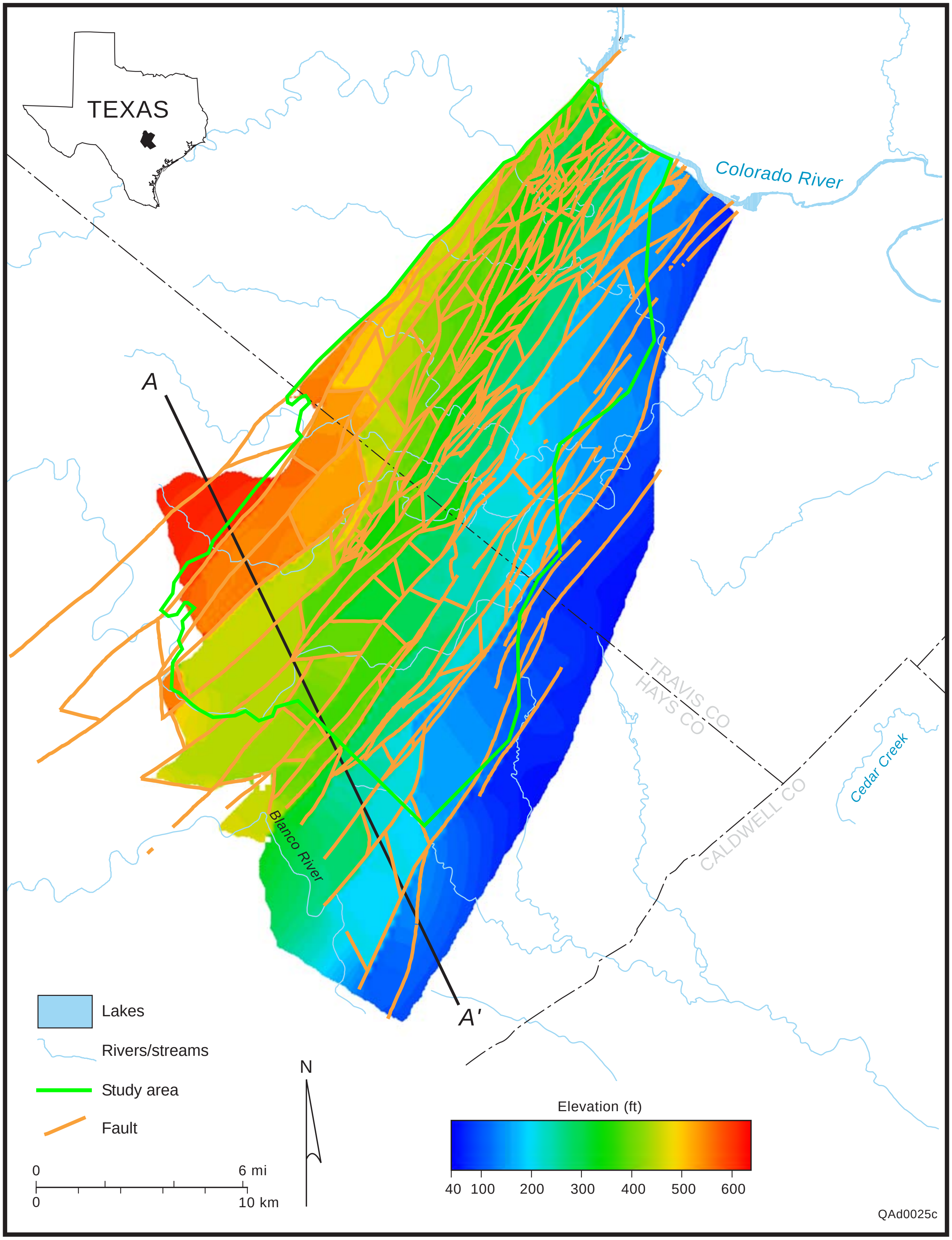


Fig. 10. Elevation of the base of the Edwards aquifer (which corresponds to the top Glen Rose Formation). Figure 12 shows the location of the control points.

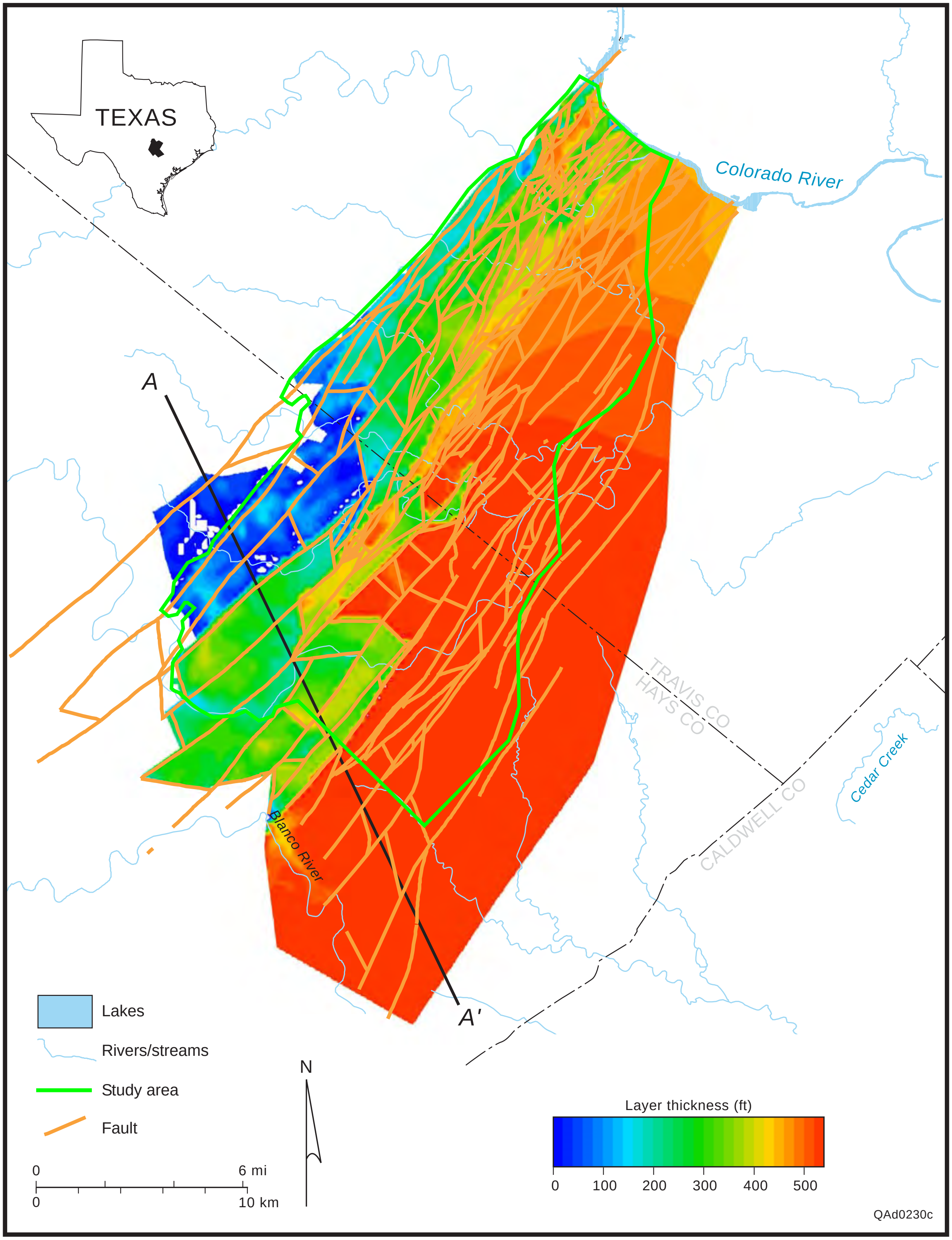


Fig. 11. Approximate thickness of the Edwards aquifer.

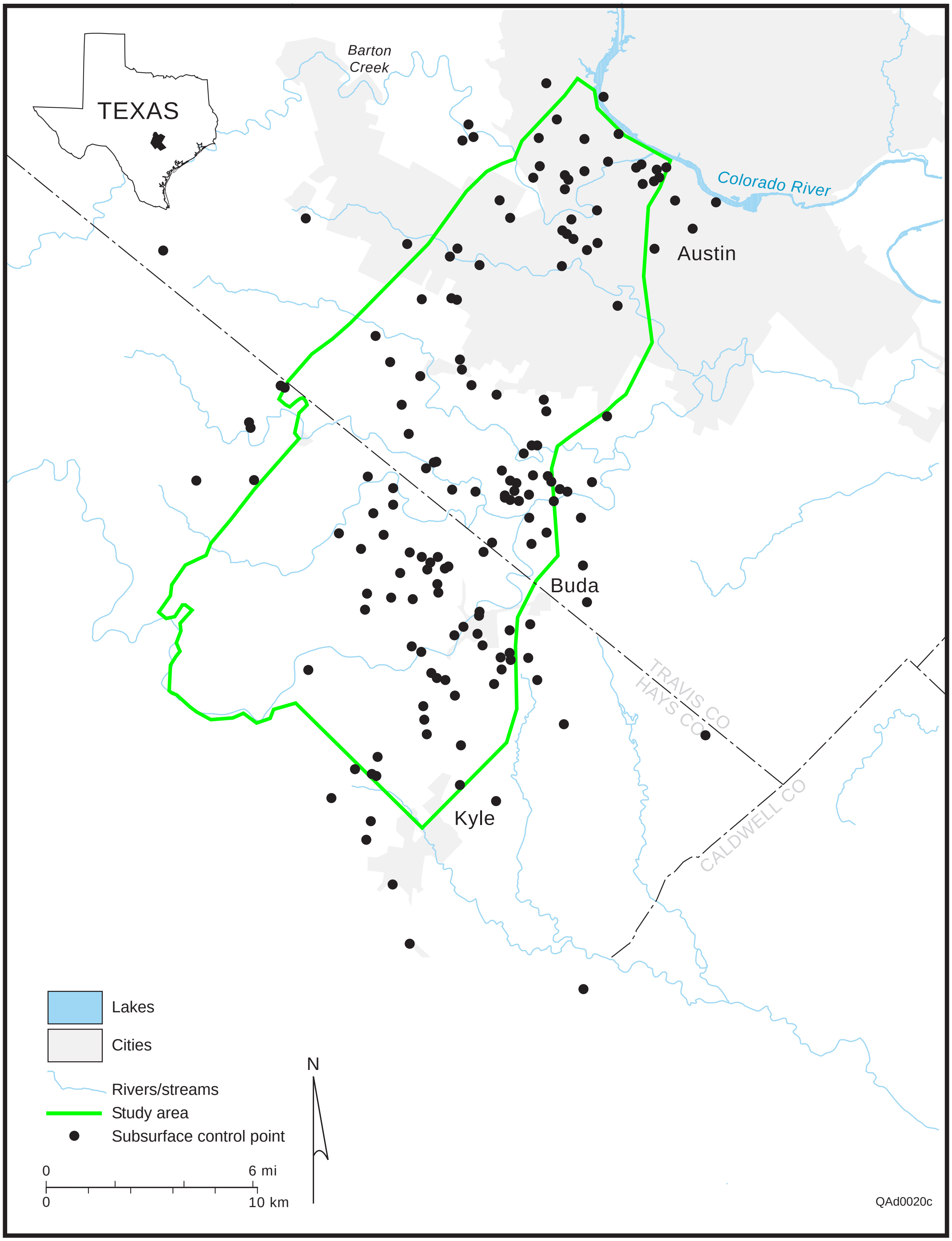


Fig. 12. Control points for the elevation of the top and the base of the Edwards aquifer.

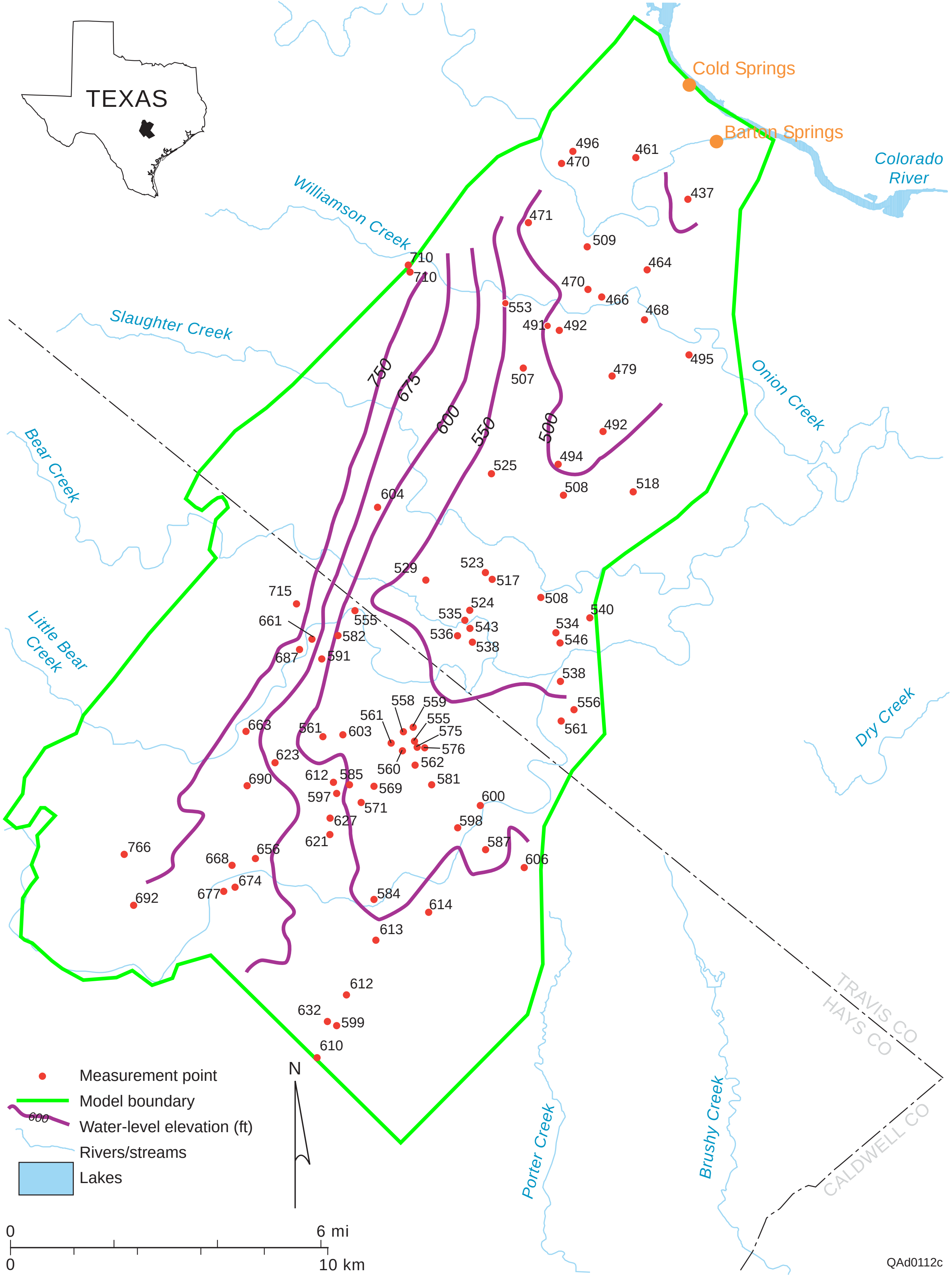


Figure 13. Water-level elevations in the aquifer (include water-level measurements in July and August 1999).

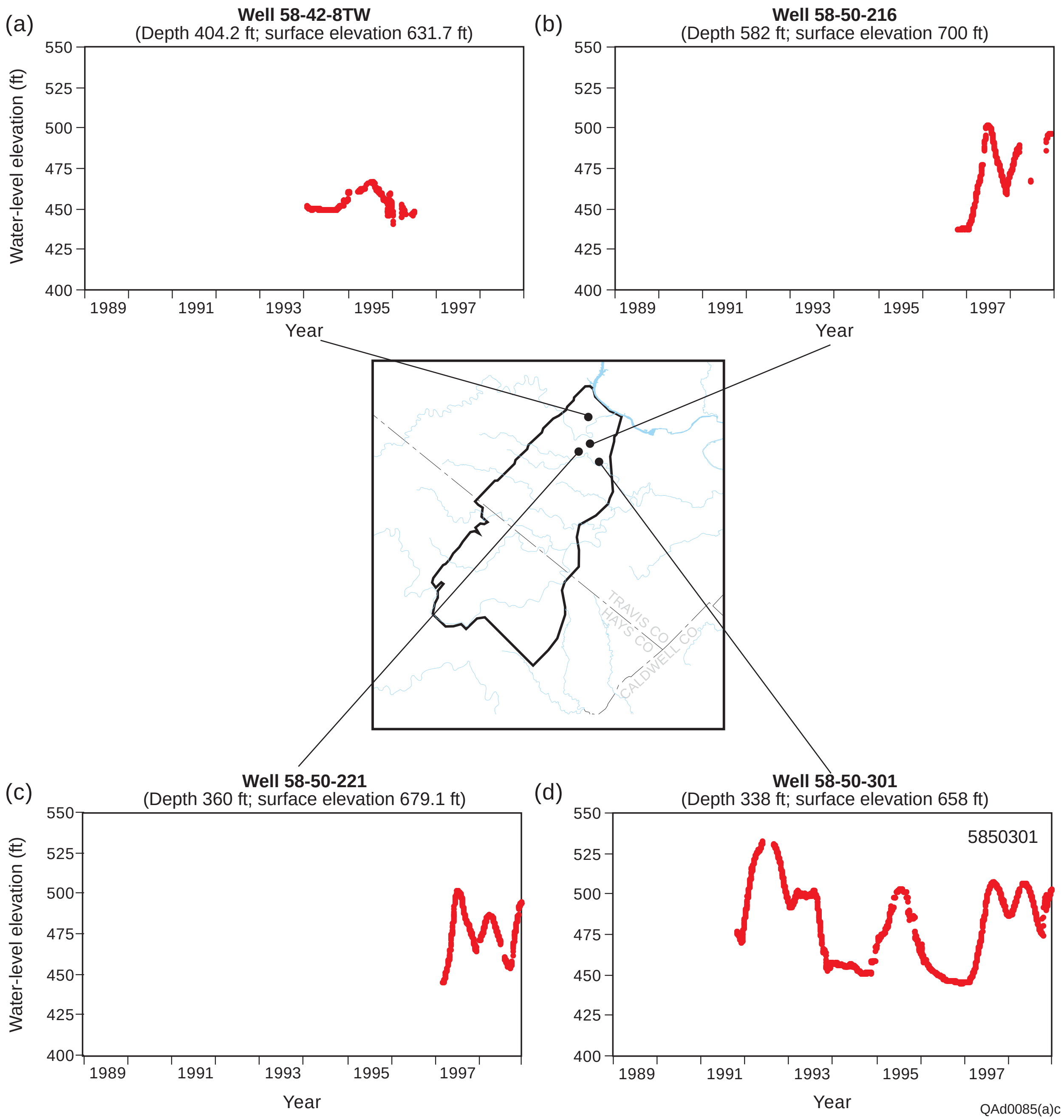


Figure 14. Hydrographs for wells (a) 58-42-8TW, (b) 58-50-216, (c) 58-50-221, and (d) 58-50-301.

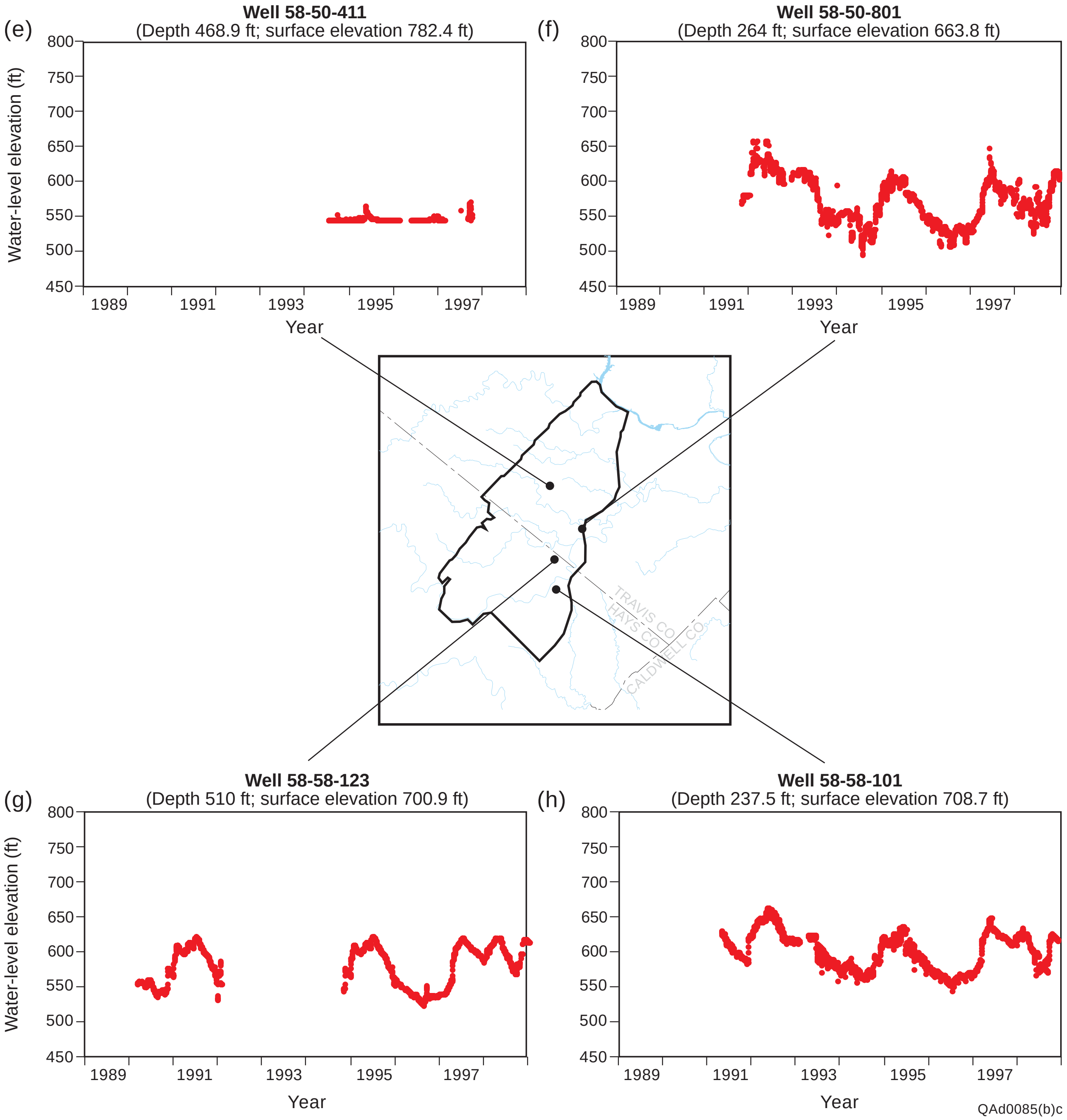


Figure 15. Hydrographs for wells (e) 58-50-411, (f) 58-50-801, (g) 58-58-123, and (h) 58-58-101.

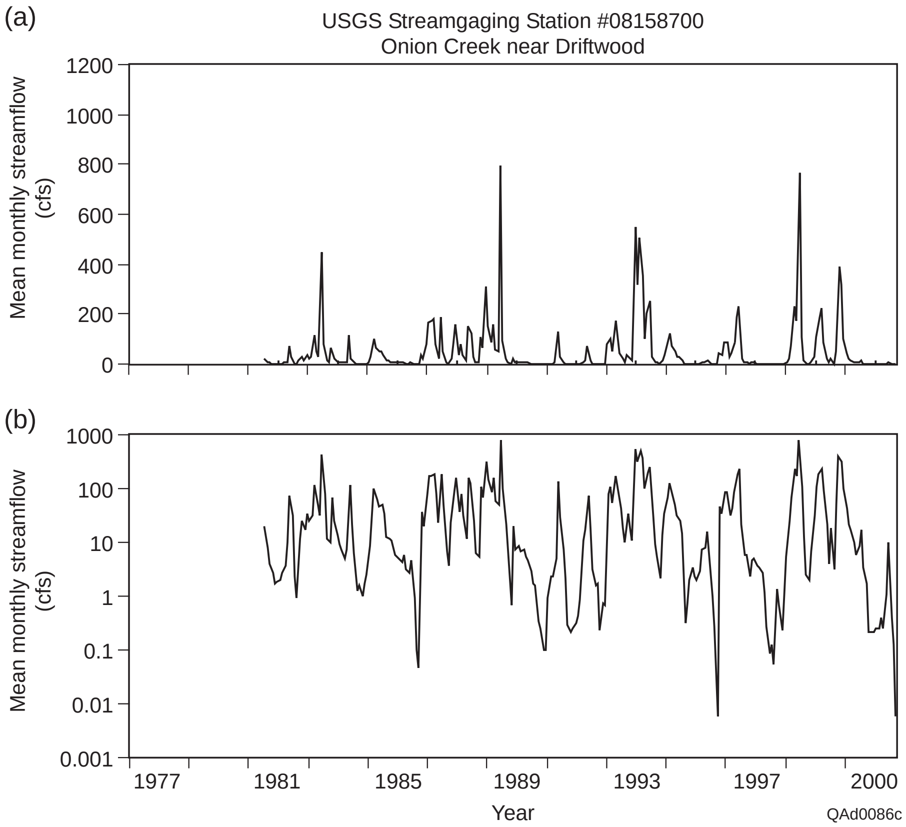


Figure 16. Mean monthly streamflow for USGS gaging station 08158700 on Onion Creek near Driftwood for (a) linear and (b) logarithmic scales. Figure 25 shows the location of the stream gage.

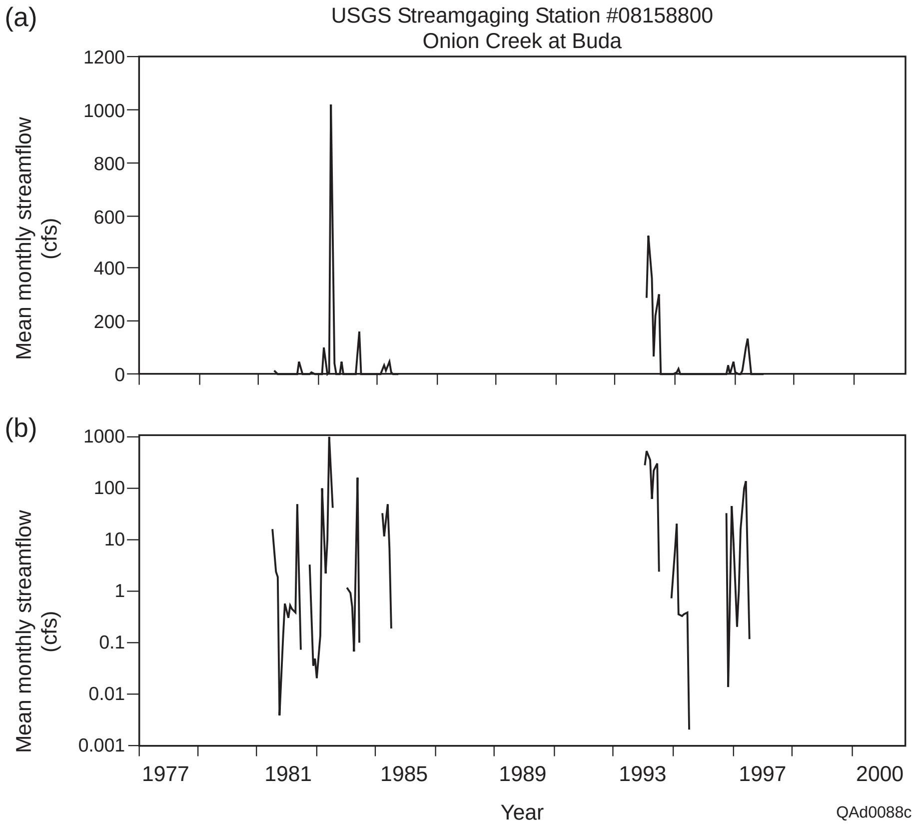


Figure 17. Mean monthly streamflow for USGS gaging station 08158800 on Onion Creek at Buda for (a) linear and (b) logarithmic scales. Figure 25 shows the location of the stream gage.

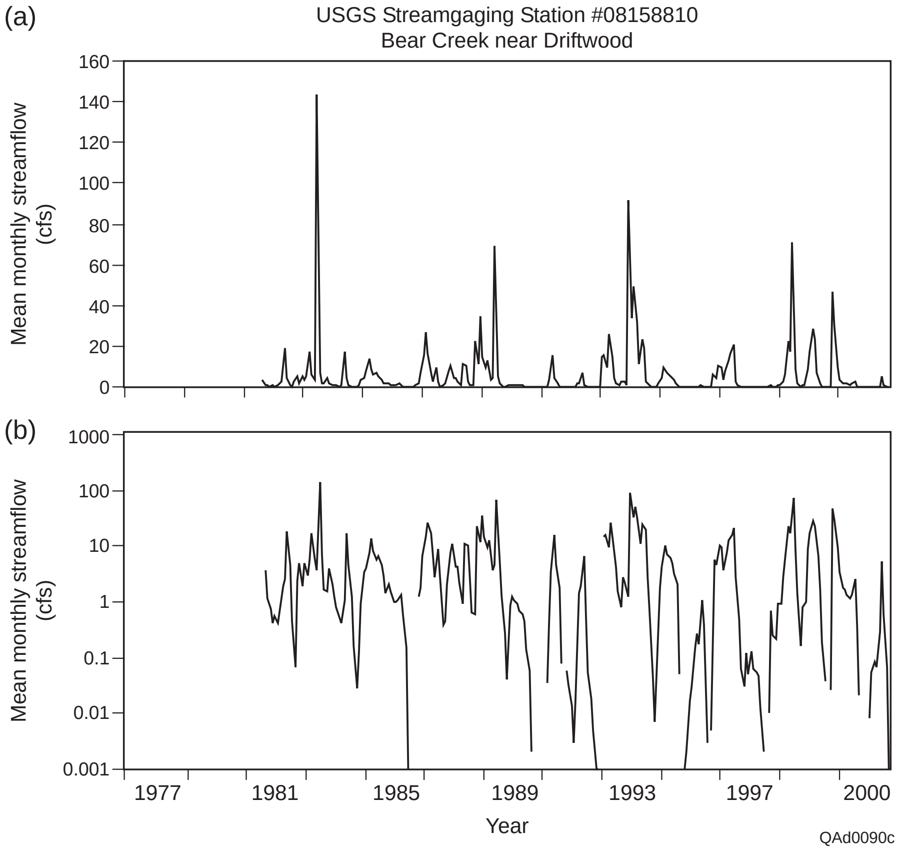


Figure 18. Mean monthly streamflow for USGS gaging station 08158810 on Bear Creek near Driftwood for (a) linear and (b) logarithmic scales. Figure 25 shows the location of the stream gage.

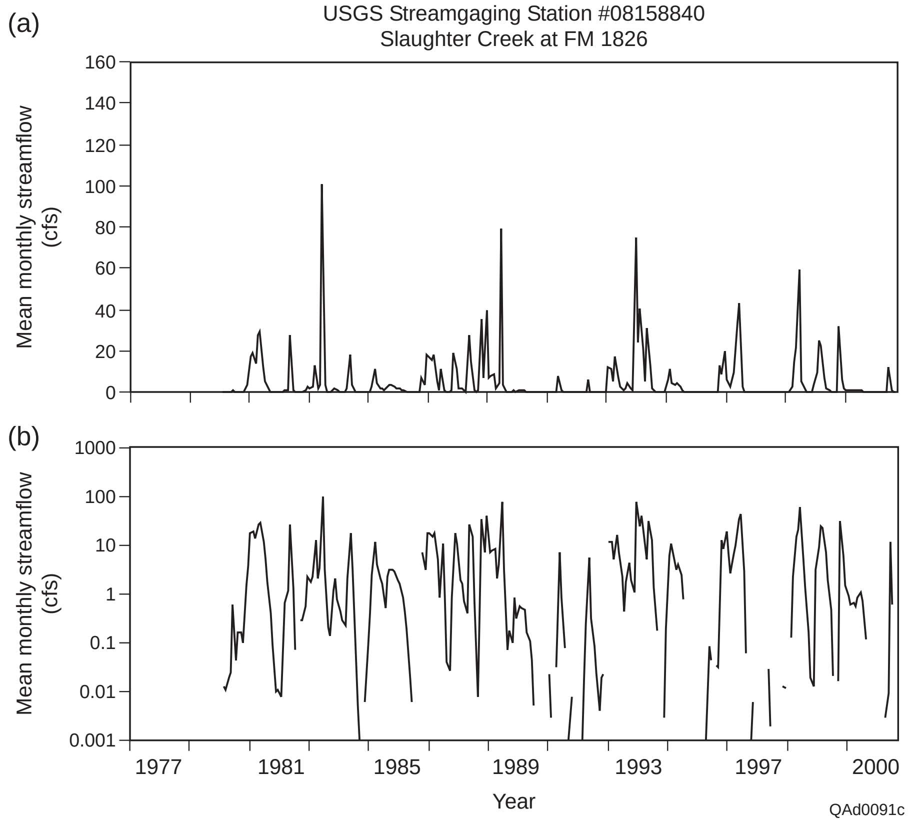


Figure 19. Mean monthly streamflow for USGS gaging station 08158840 on Slaughter Creek at FM 1826 for (a) linear and (b) logarithmic scales. Figure 25 shows the location of the stream gage.

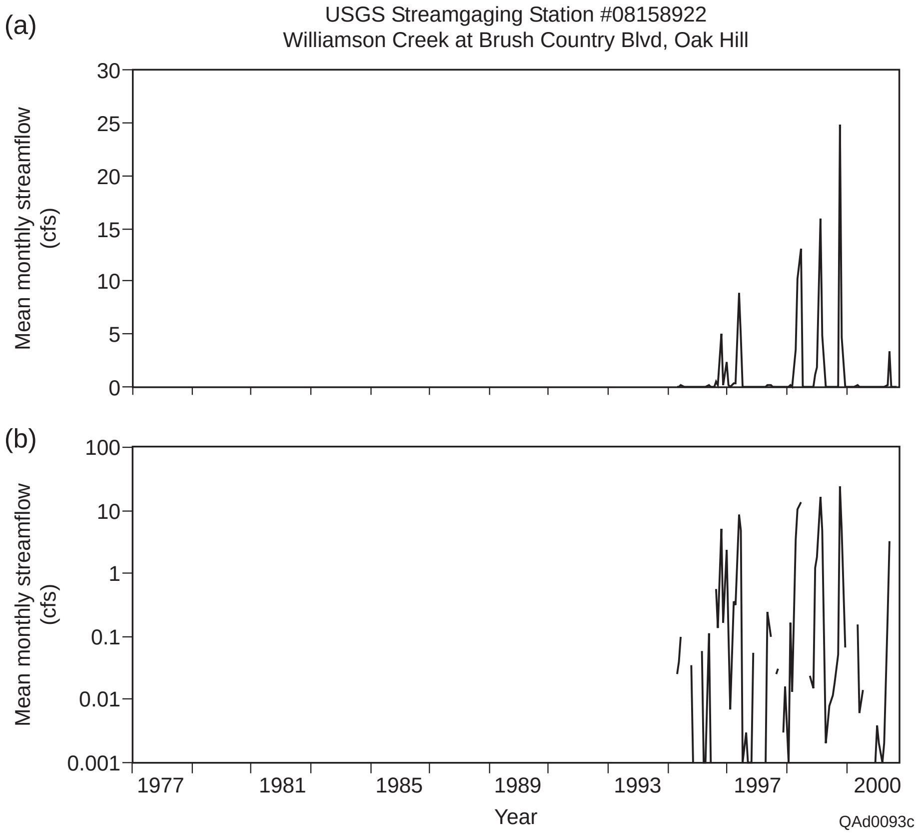


Figure 20. Mean monthly streamflow for USGS gaging station 08158922 on Williamson Creek at Brush Country Blvd., Oak Hill, for (a) linear and (b) logarithmic scales. Figure 25 shows the location of the stream gage.

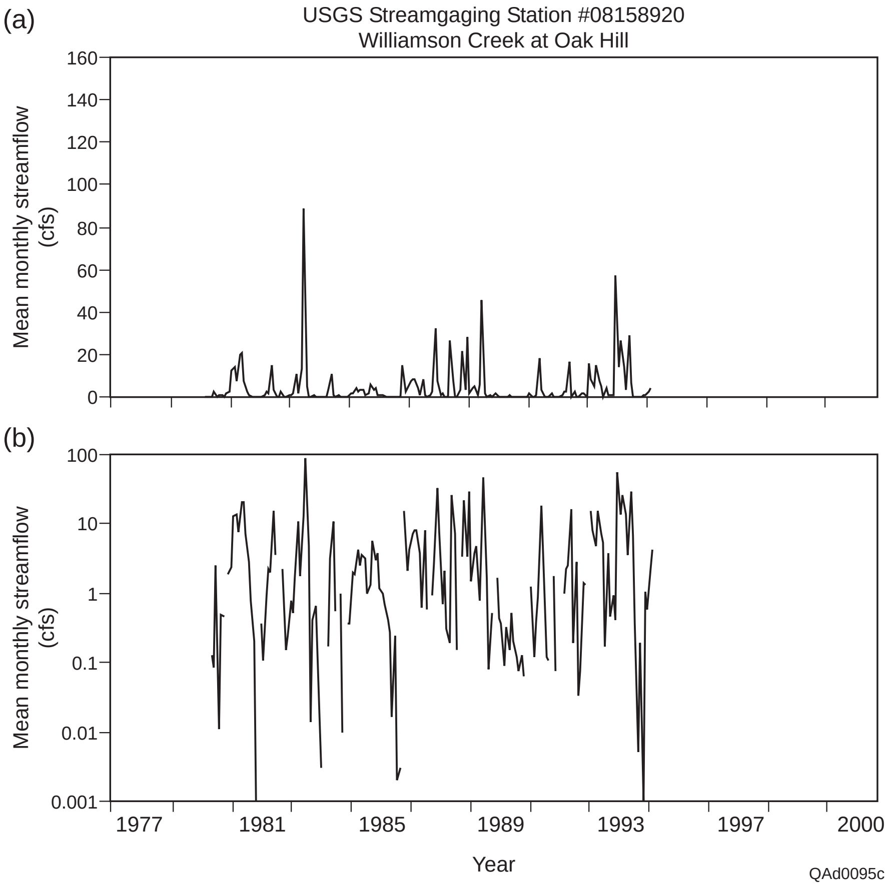


Figure 21. Mean monthly streamflow for USGS gaging station 08158920 on Williamson Creek at Oak Hill for (a) linear and (b) logarithmic scales. Figure 25 shows the location of the stream gage.

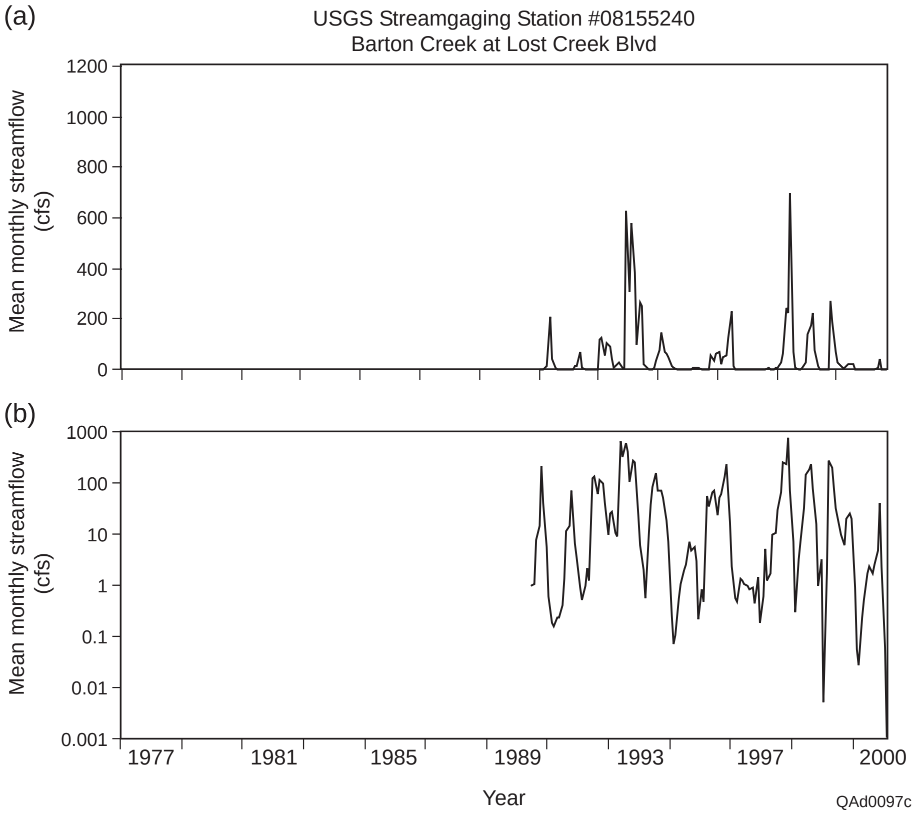


Figure 22. Mean monthly streamflow for USGS gaging station 08155240 on Barton Creek at Lost Creek Blvd. for (a) linear and (b) logarithmic scales. Figure 25 shows the location of the stream gage.

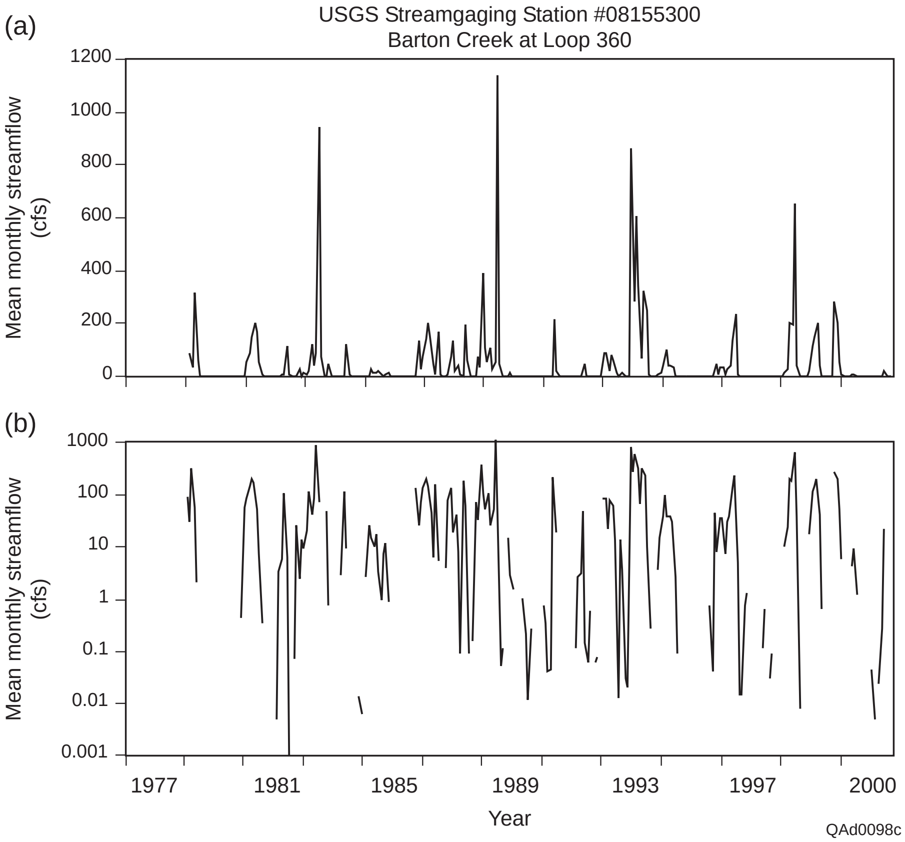


Figure 23. Mean monthly streamflow for USGS gaging station 08155300 on Barton Creek at Loop 360 for (a) linear and (b) logarithmic scales. Figure 25 shows the location of the stream gage.

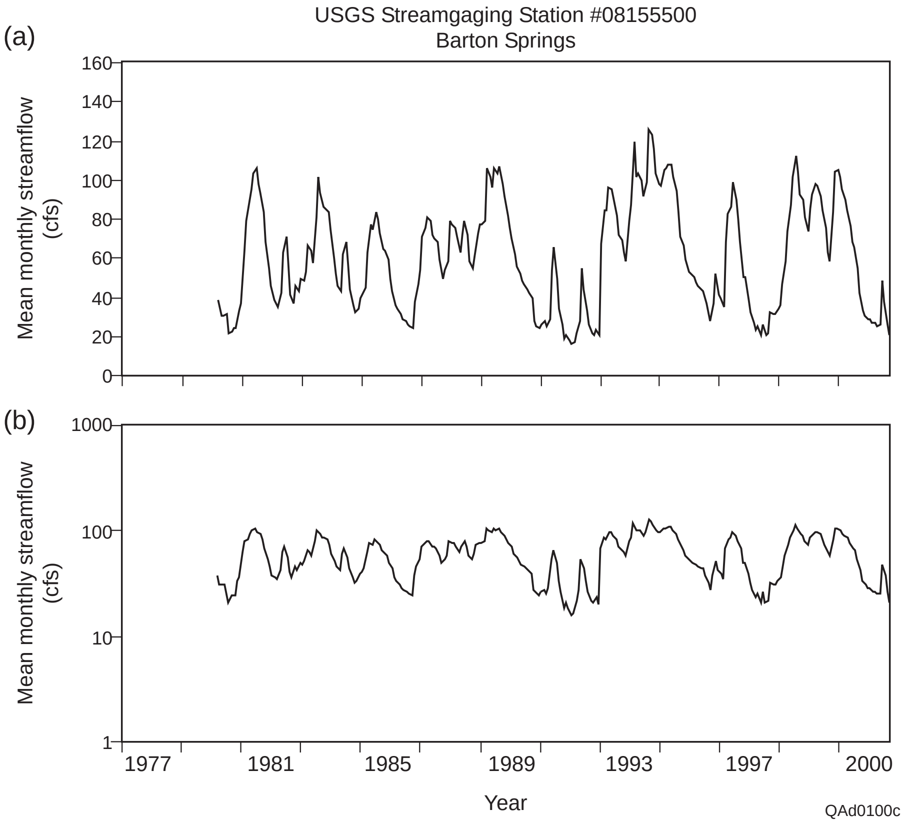


Figure 24. Mean monthly streamflow for USGS gaging station 08155500 at Barton Springs for (a) linear and (b) logarithmic scales. Figure 25 shows the location of the stream gage.

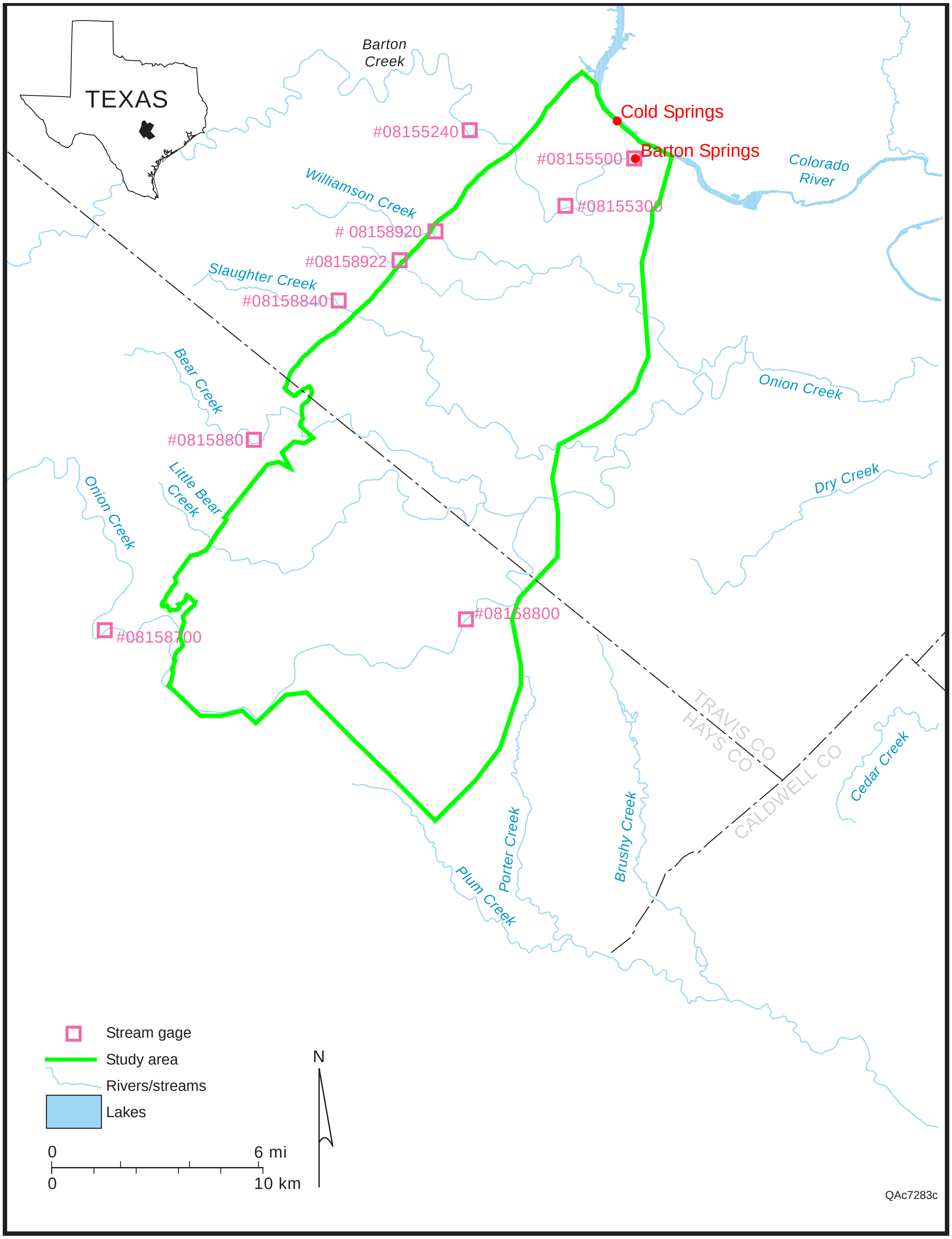


Figure 25. Location of the stream gages for the stream-flow hydrographs shown in figures 16 through 24.

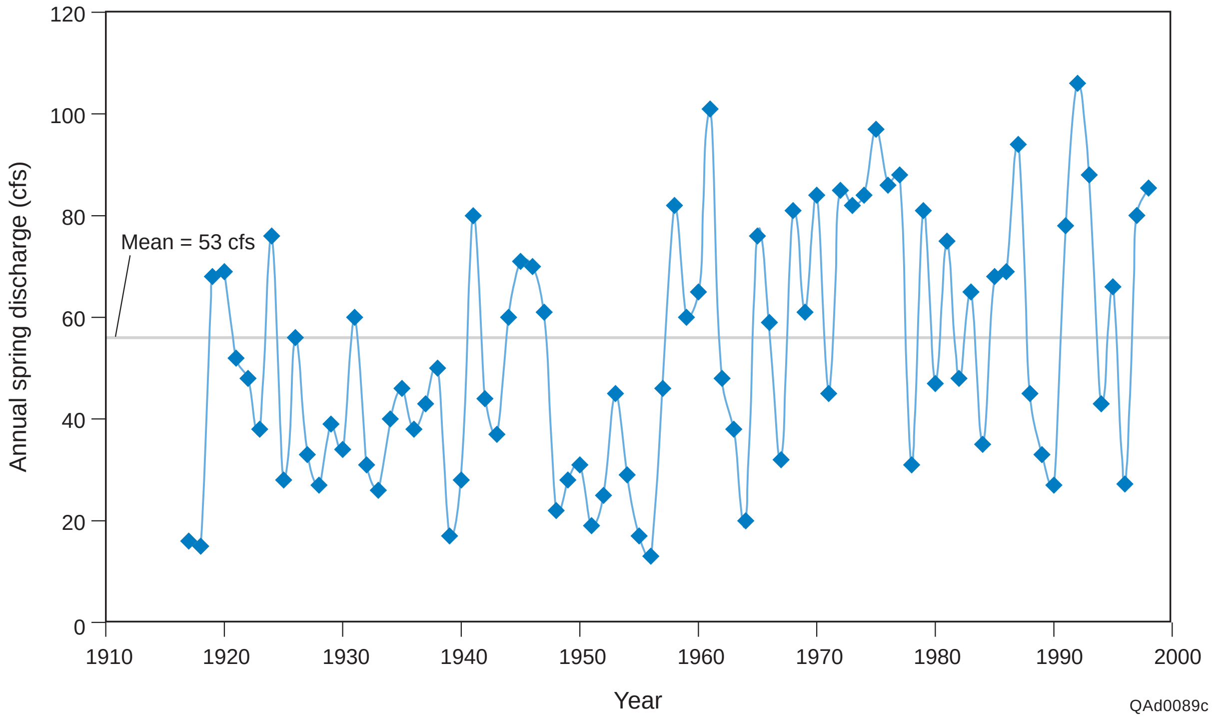


Figure 26. Discharge at Barton Springs.

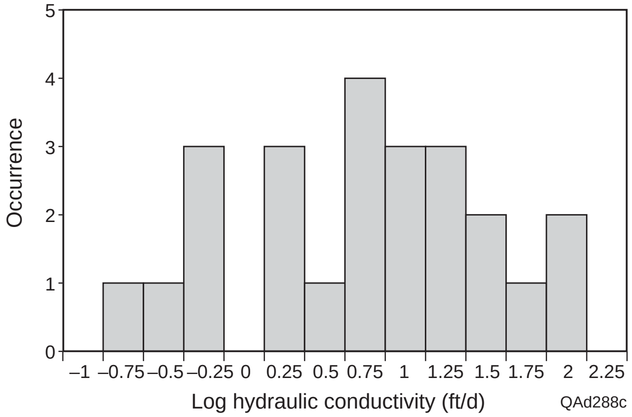


Figure 27. Histogram of hydraulic conductivity from aquifer tests.

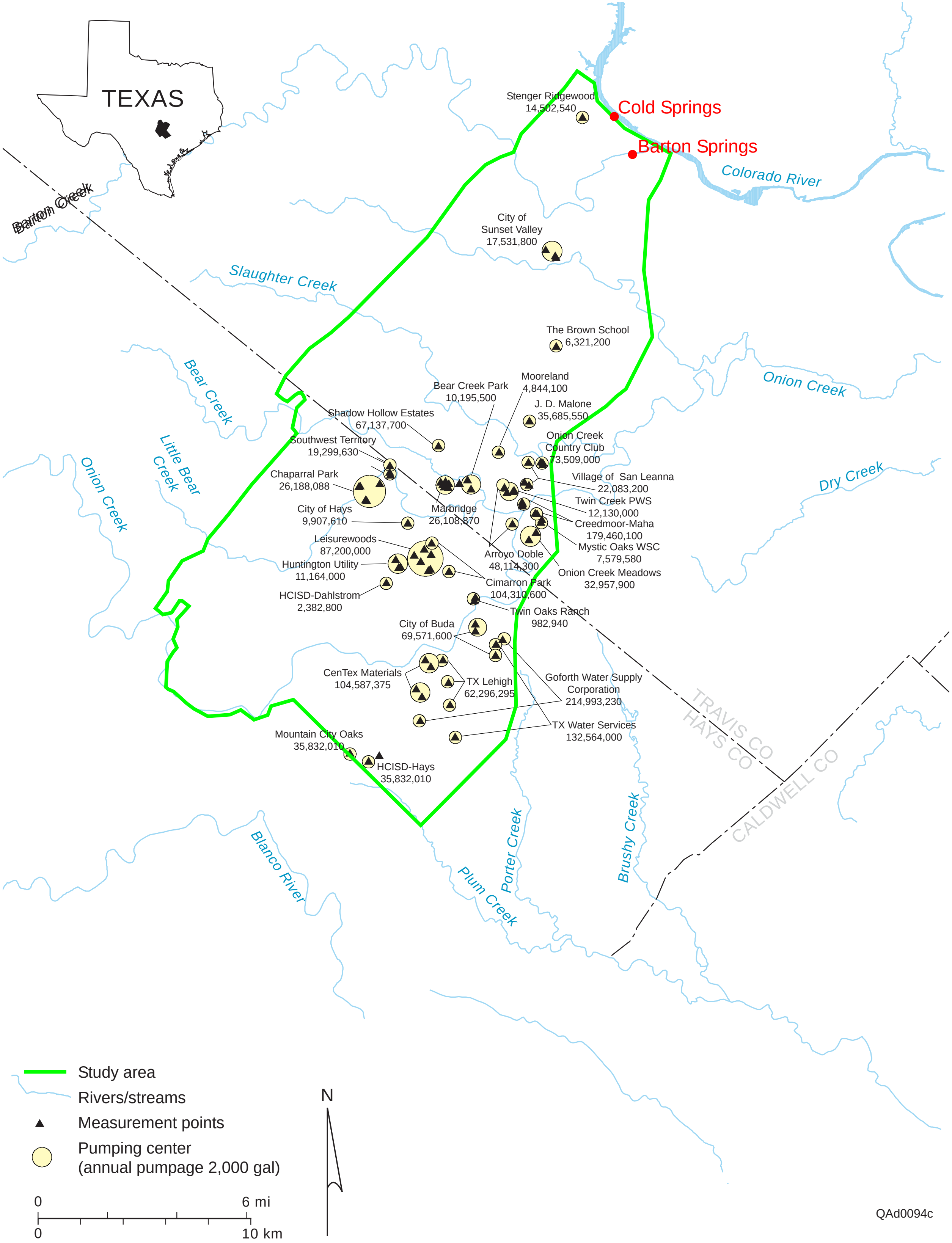


Figure 28. Spatial distribution of pumping in the aquifer.

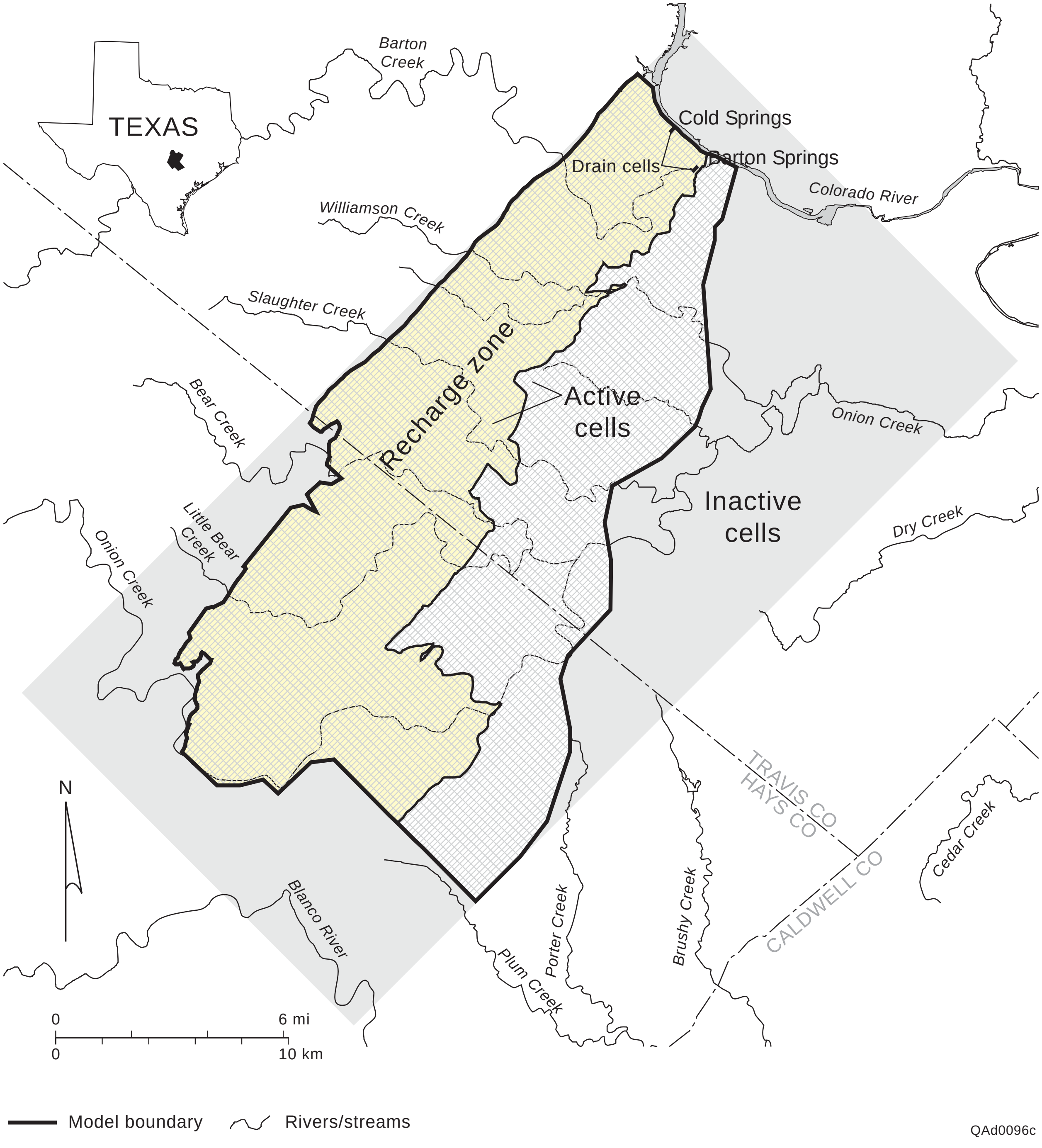
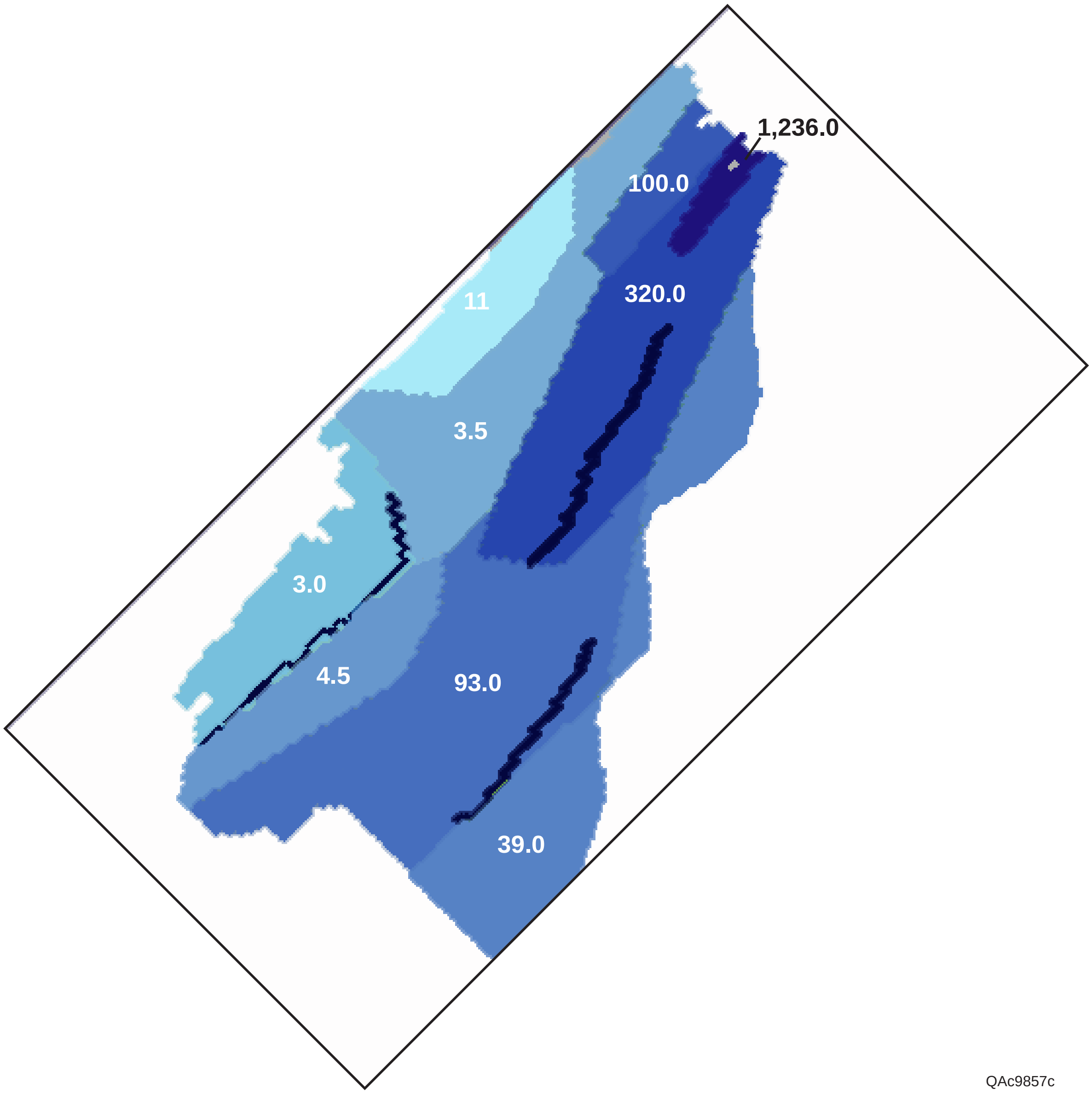


Fig. 29. Model grid, consisting of 120 cells 120 cells (14,400 cells) that ae 1,000 ft long 500 ft wide. The active zone of the model is shown by the solid line and consists of 7,043 cells.



QAc9857c

Figure 30. Zonal distribution of hydraulic conductivity resulting from calibration of the steady-state model.

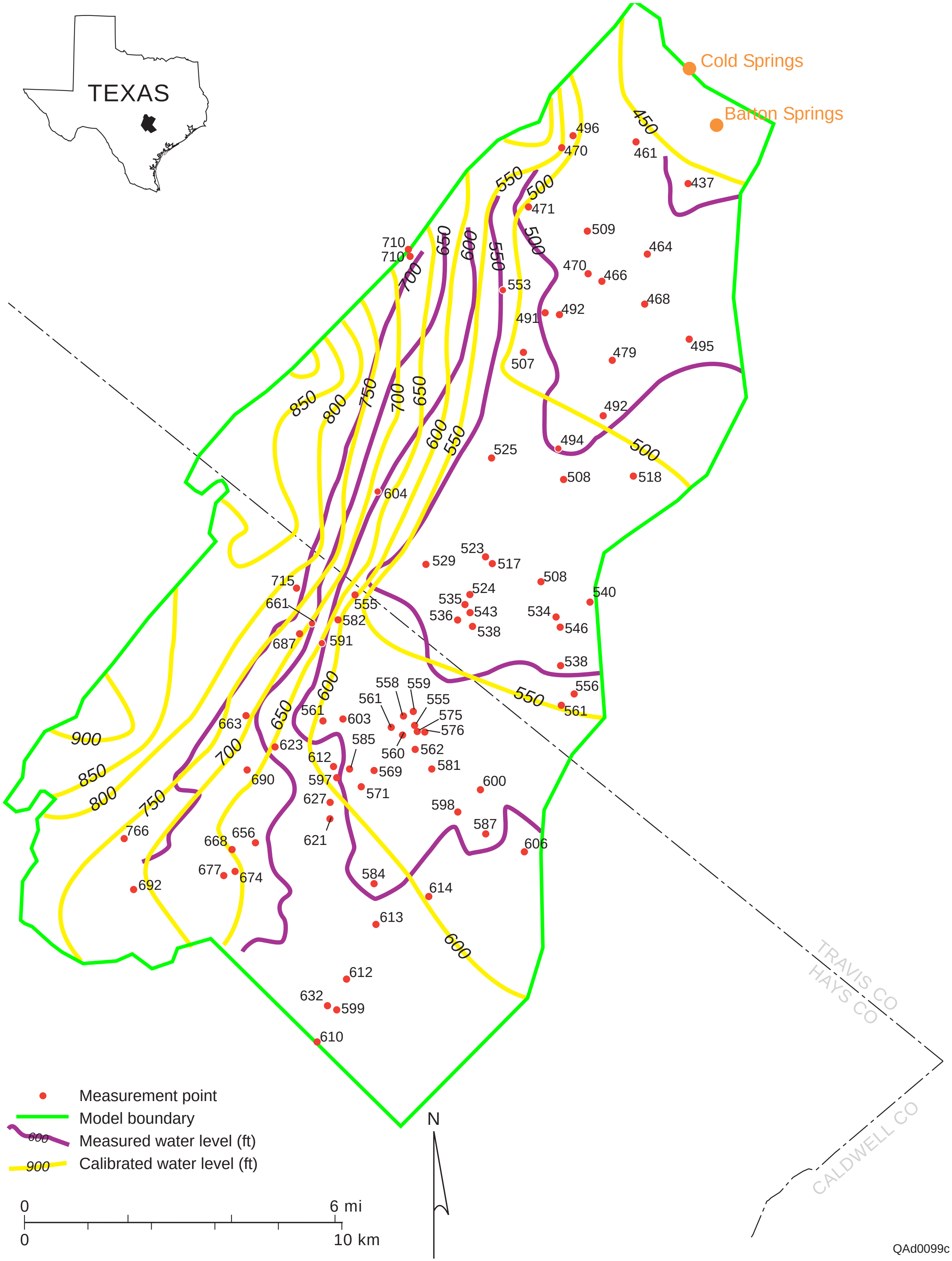


Figure 31. Comparison of simulated and measured (July/August 1999) water-level contours for the steady-state model.

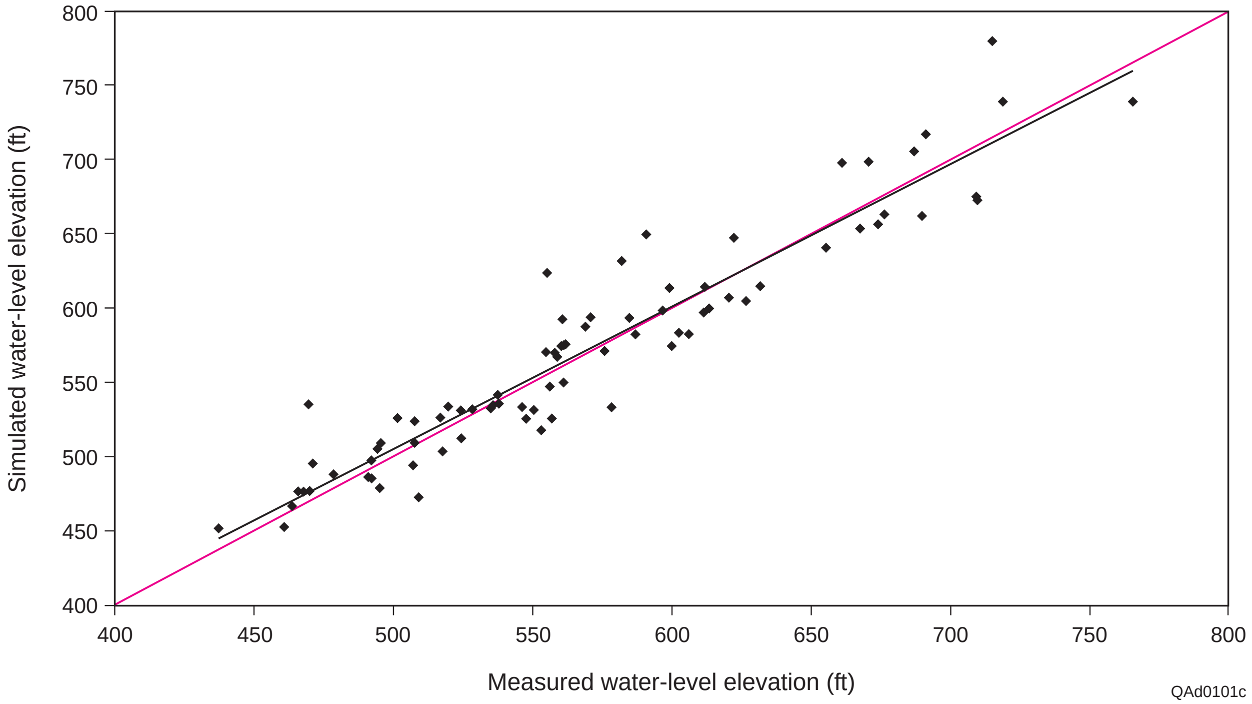


Figure 32. Scatter plot of simulated and measured (July/August 1999) water levels for the steady-state model.

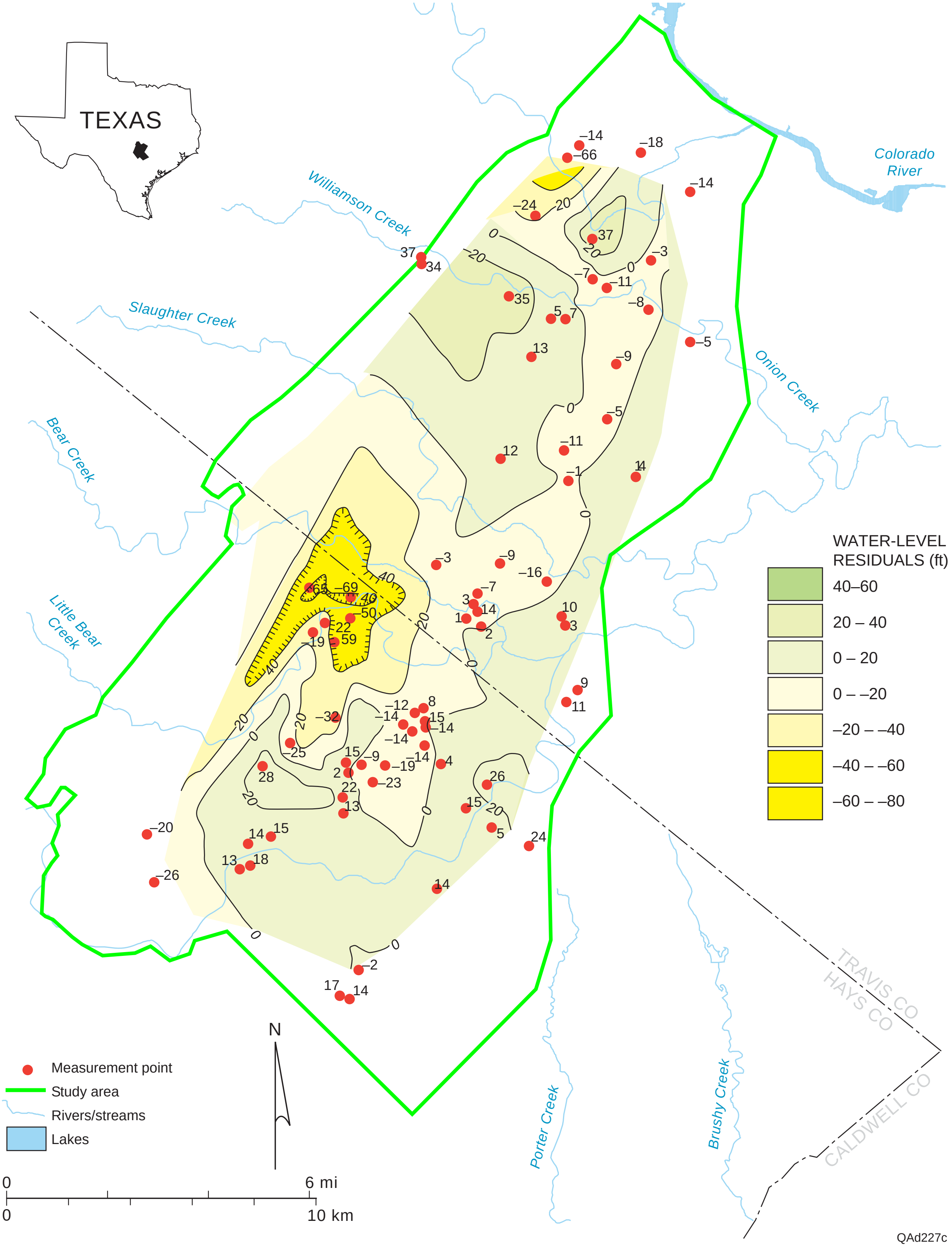


Figure 33. Water-level residuals (difference between measured and simulated water-level elevations) for the calibrated steady-state model.

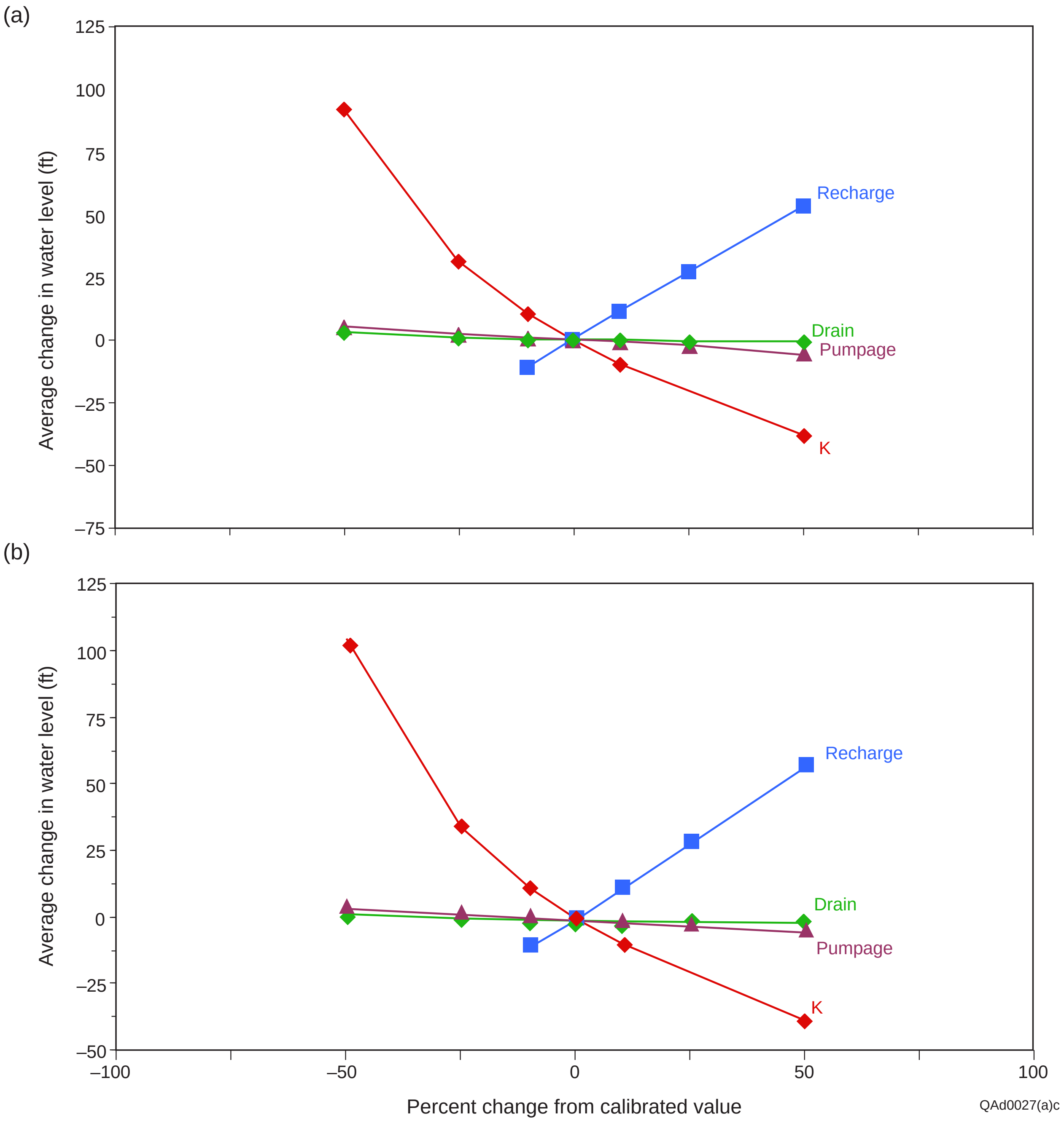


Figure 34. Sensitivity of the numerically predicted water levels of the steady-state model to changes in model parameters at (a) calibration wells and (b) each active cell in the model.

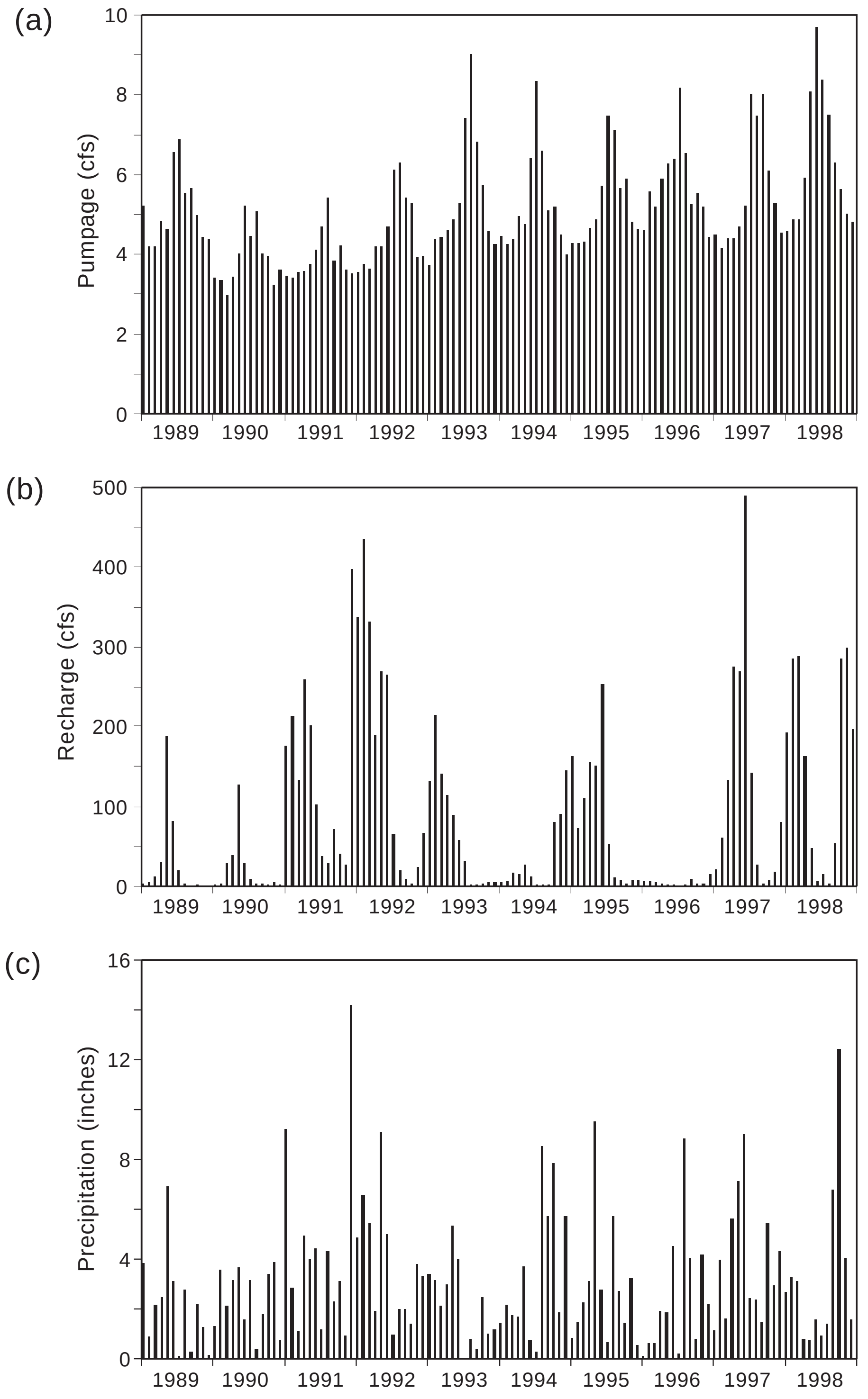


Figure 35. (a) Monthly pumpage, (b) recharge, and (c) precipitation for the transient model (1989 through 1998).

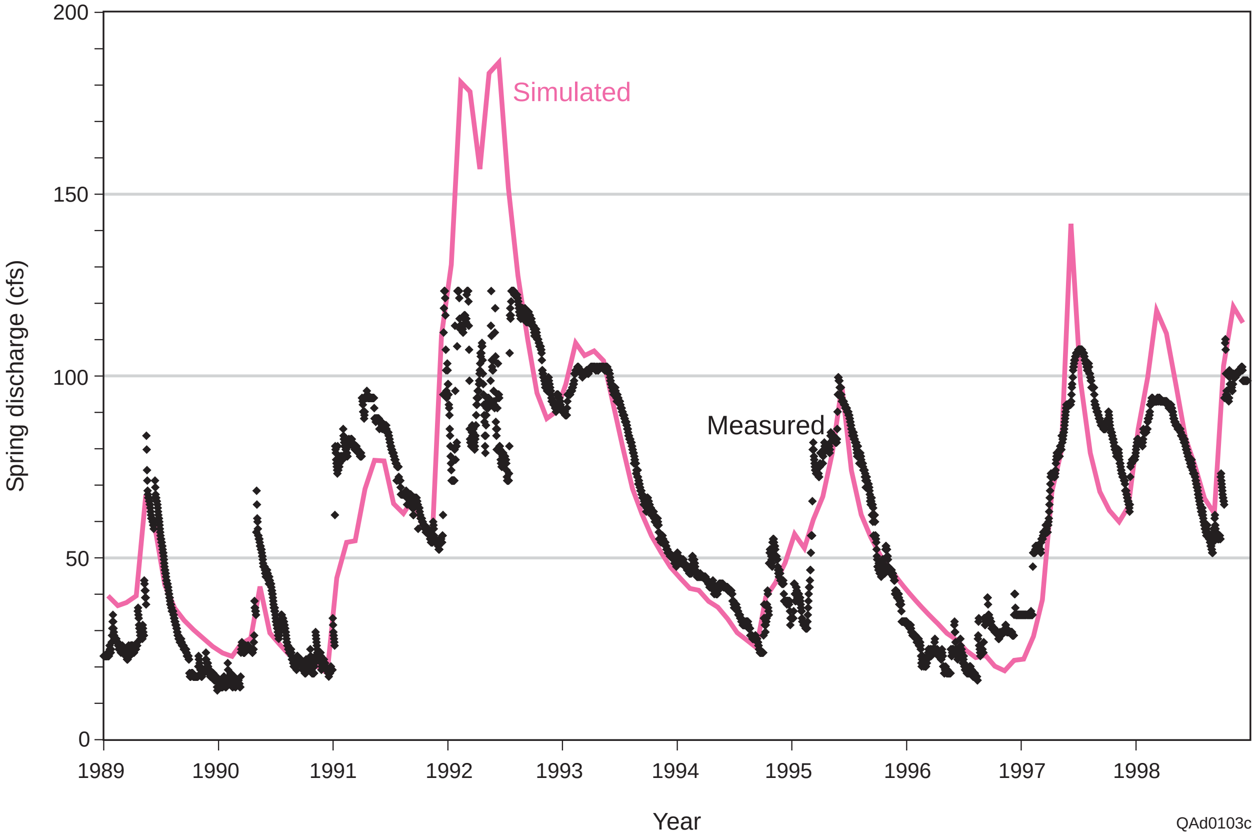


Figure 36. Comparison of simulated and measured discharge at Barton Springs for 1989 through 1998.

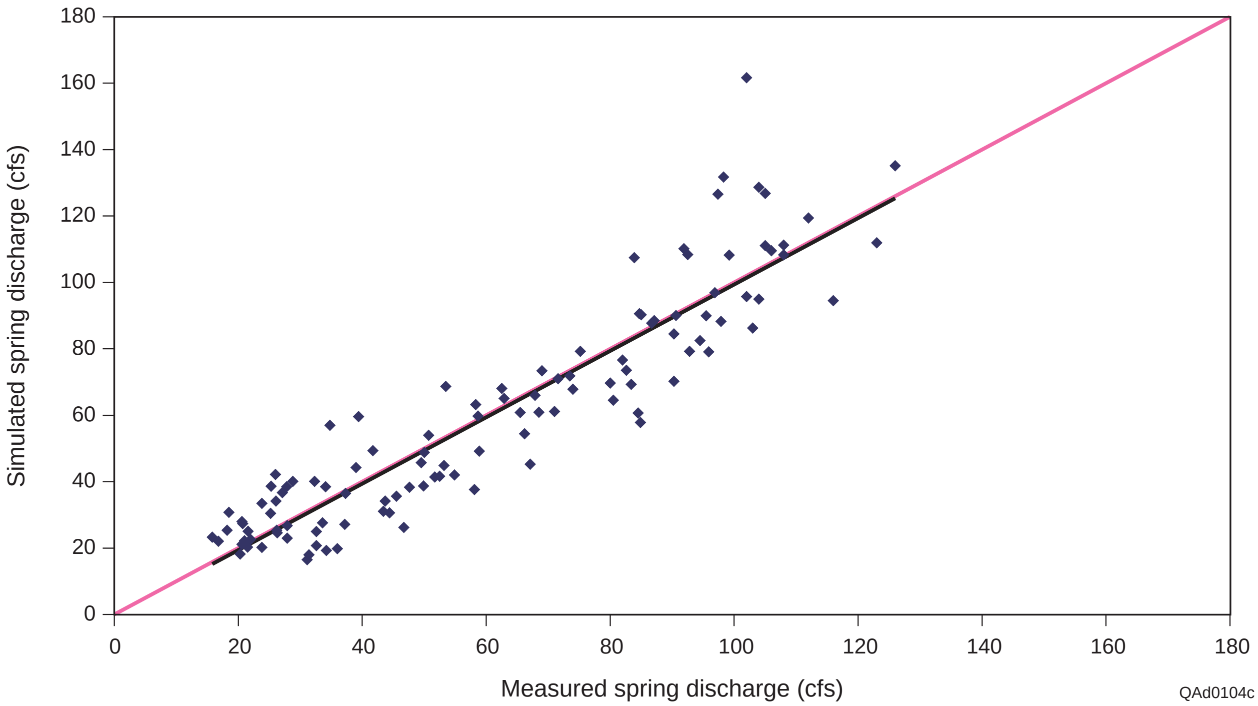


Figure 37. Scatter plot of simulated versus measured spring discharge for 1989 through 1998.

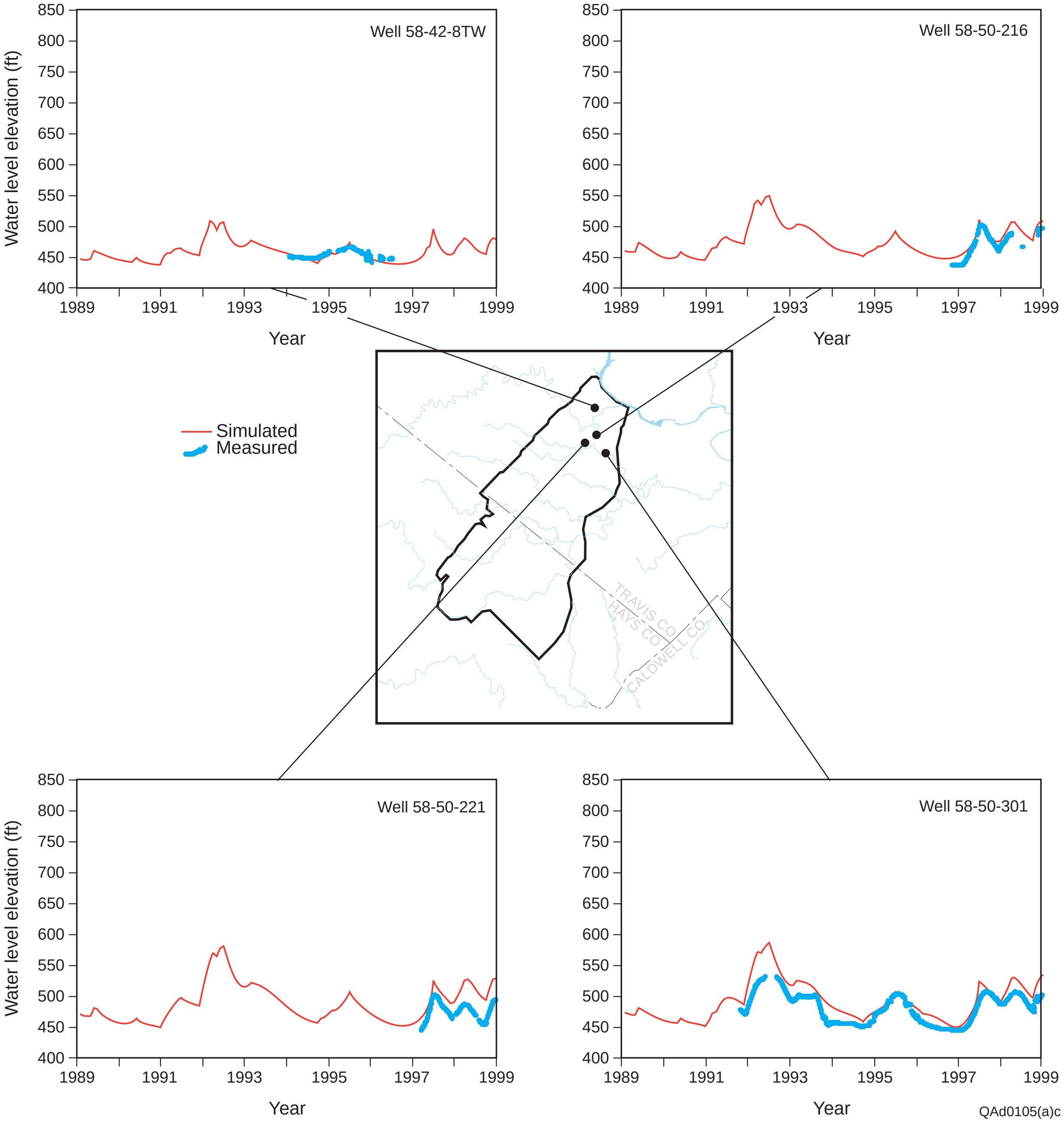


Figure 38. Comparison of simulated and measured water-level elevation hydrographs in four monitoring wells, northern study area.

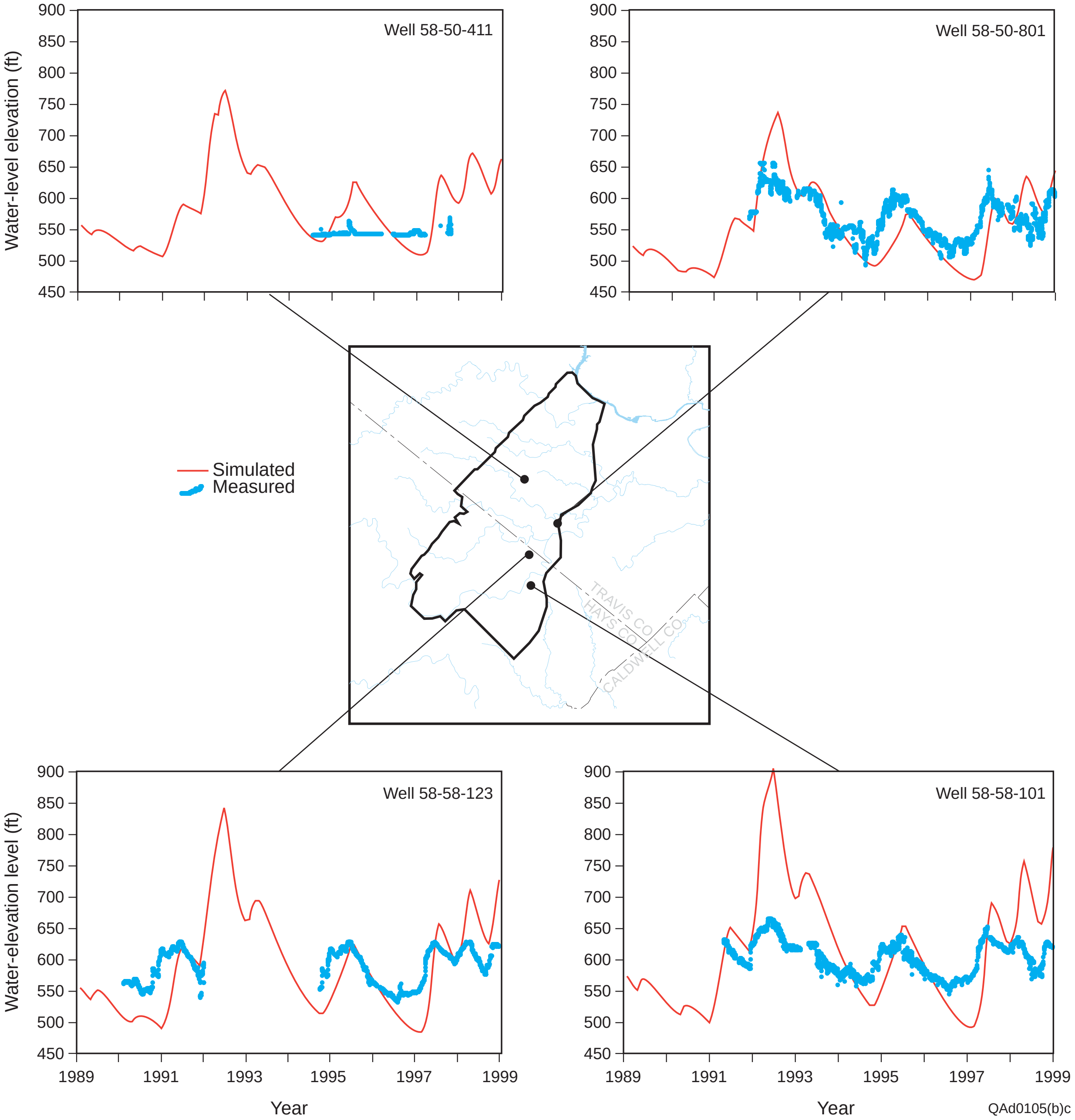


Figure 39. Comparison of simulated and measured water-level elevation hydrographs in four monitoring wells, central and southern study area.

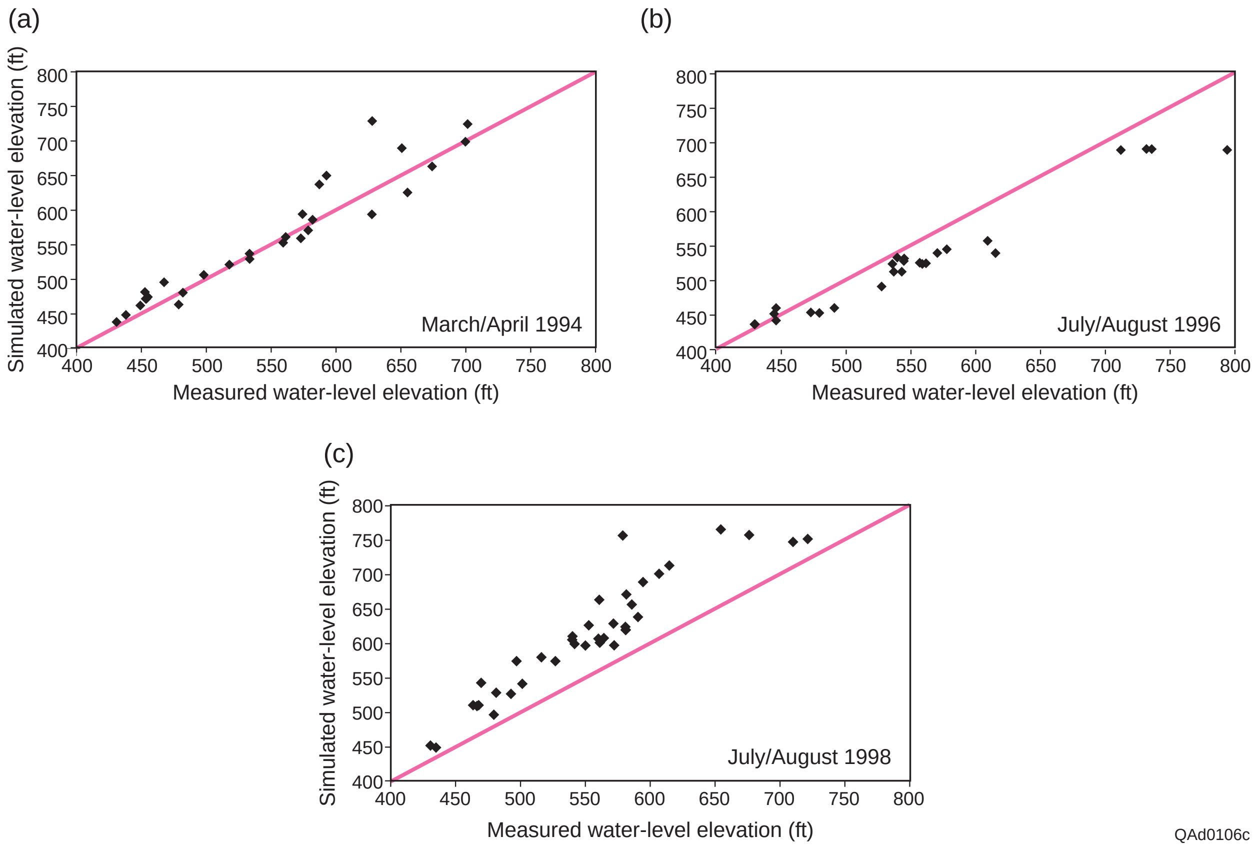


Fig. 40. Scatter plots of simulated versus measured water-level elevations for the transient simulations (a) March/April 1994, (b) July/August 1996, and (c) July/August 1998.

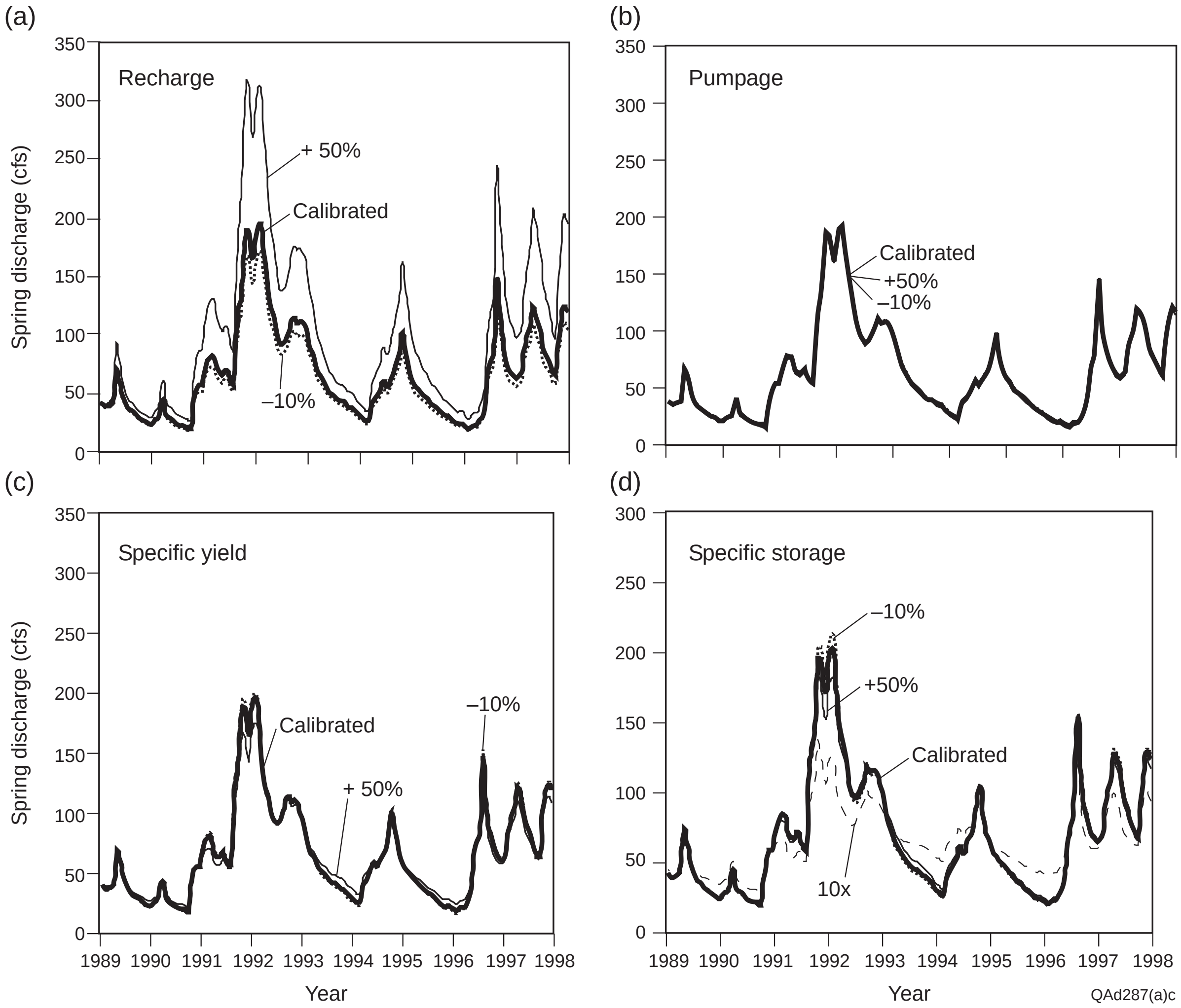


Figure 41. Sensitivity of the transient simulated spring discharge to (a) recharge, (b) pumpage, (c) specific yield, and (d) specific storage.

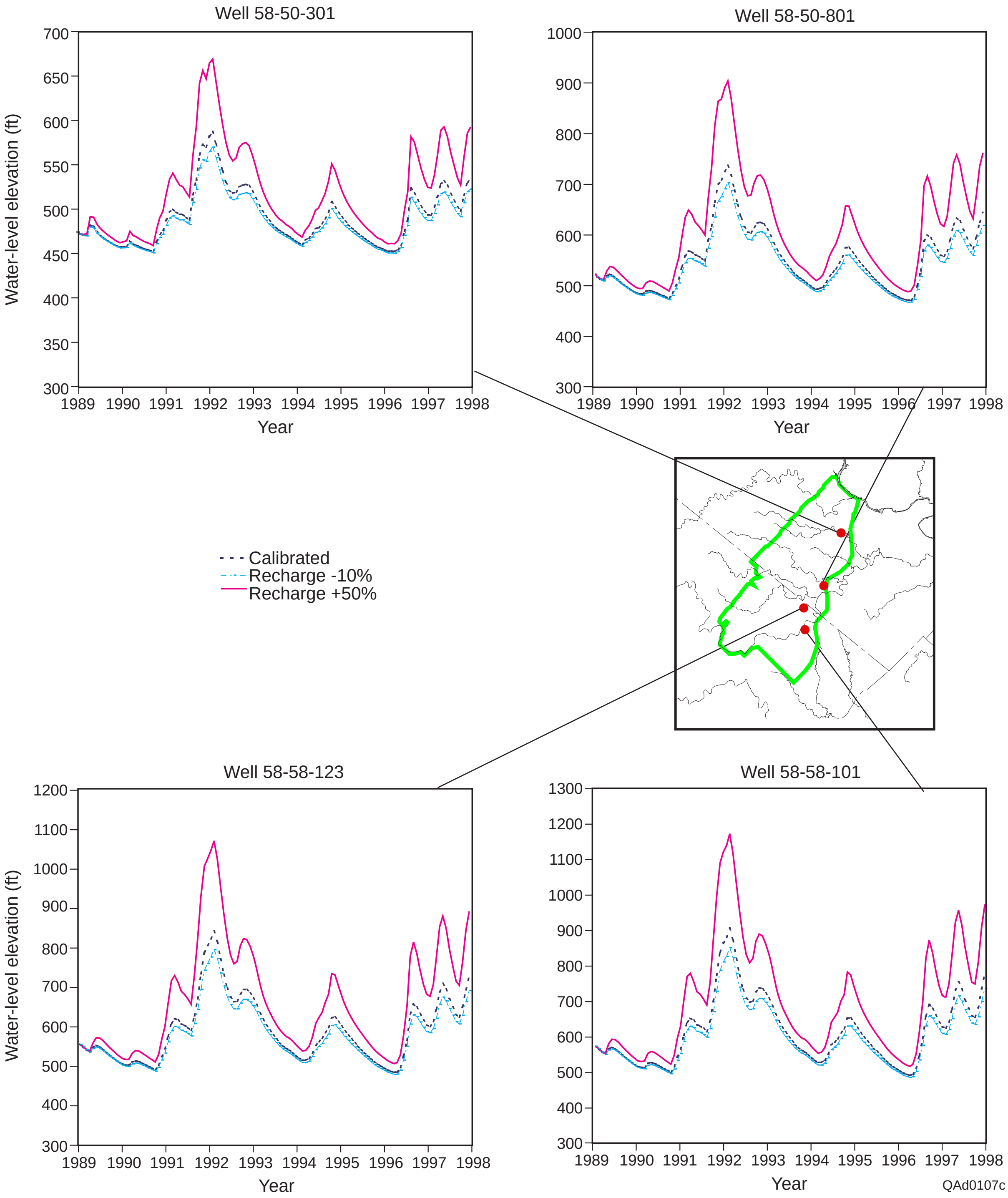


Figure 42. Sensitivity of the transient simulated water levels to recharge.

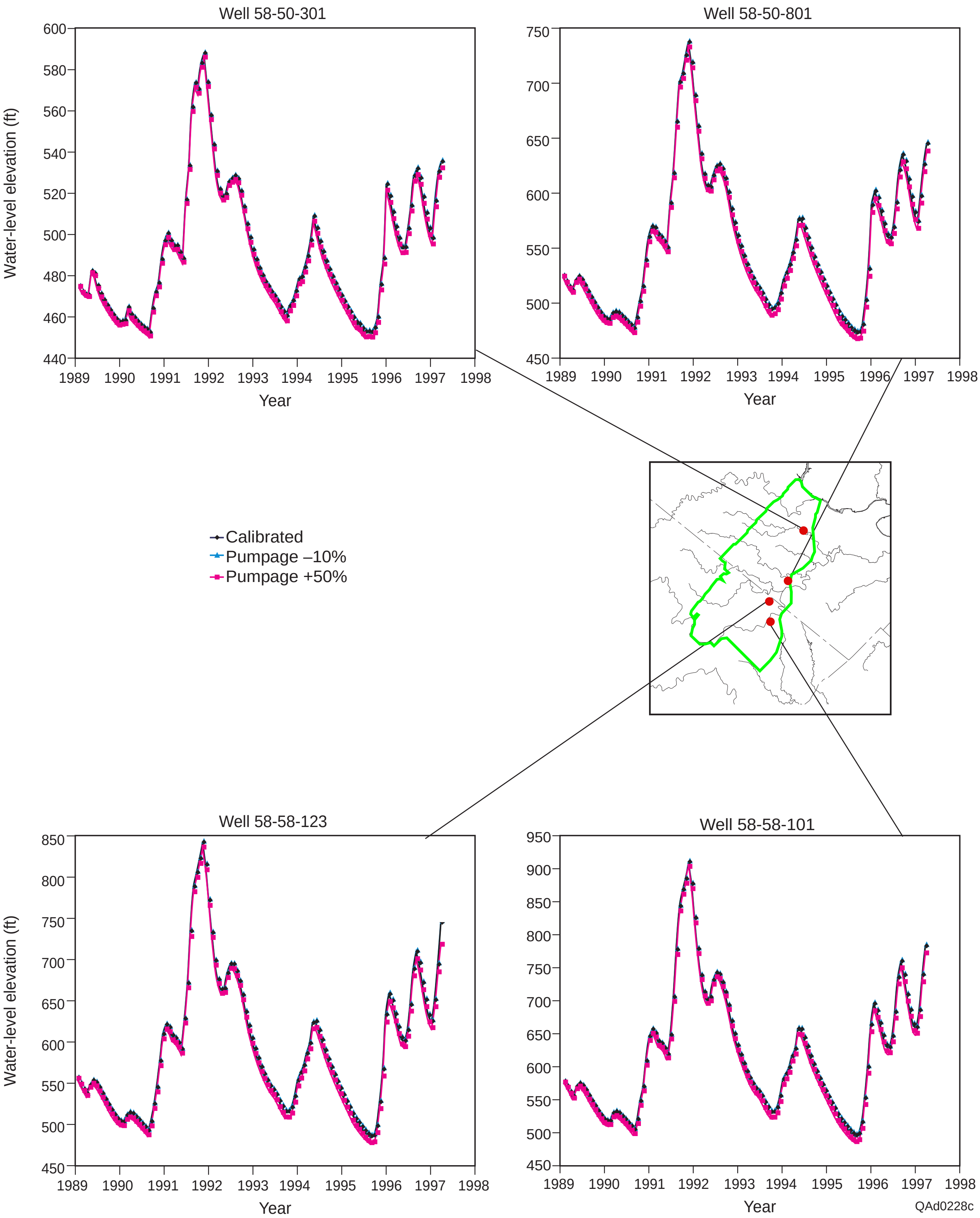


Figure 43. Sensitivity of the transient simulated water levels to pumpage.

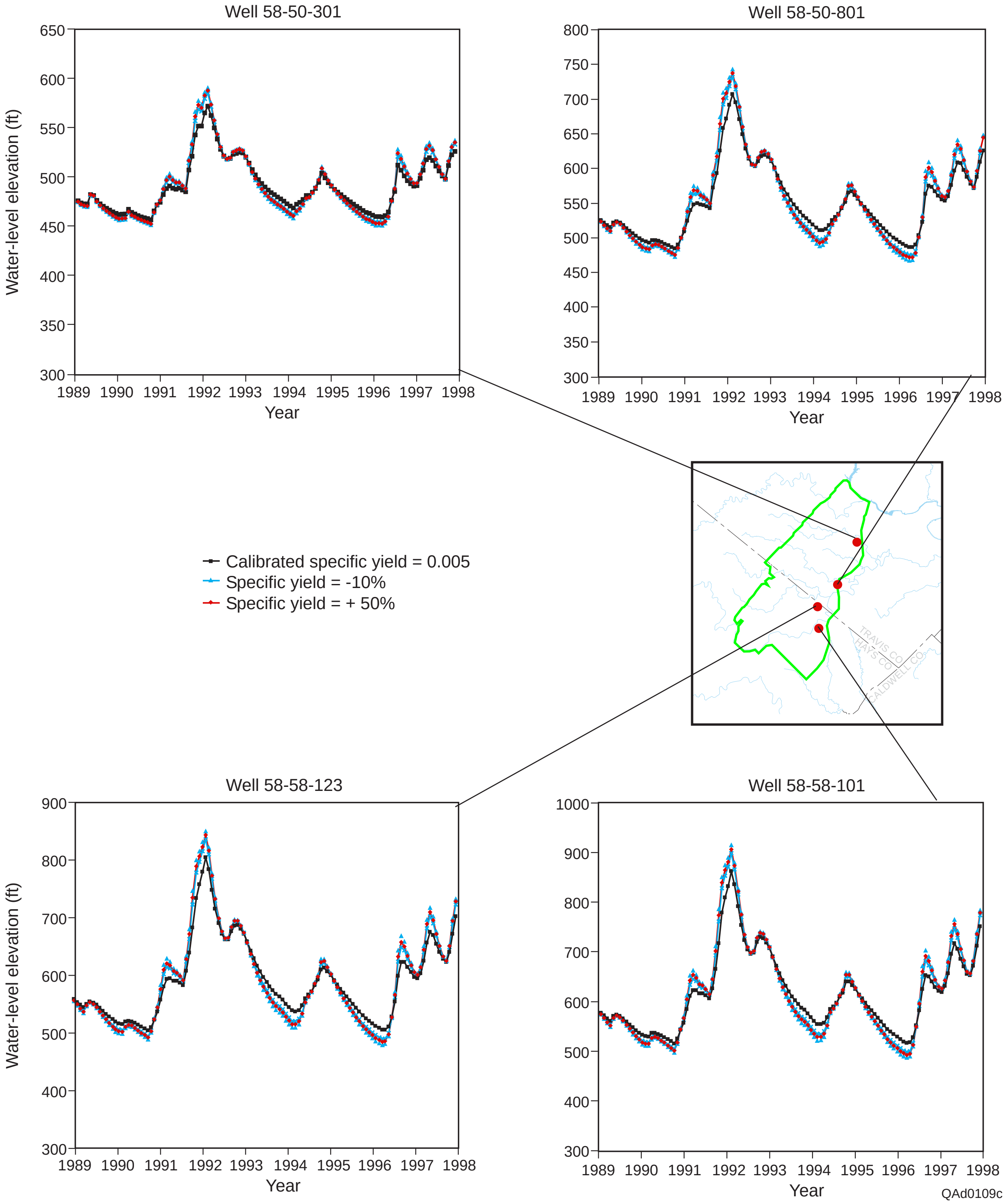


Figure 44. Sensitivity of the transient simulated water levels to specific yield.

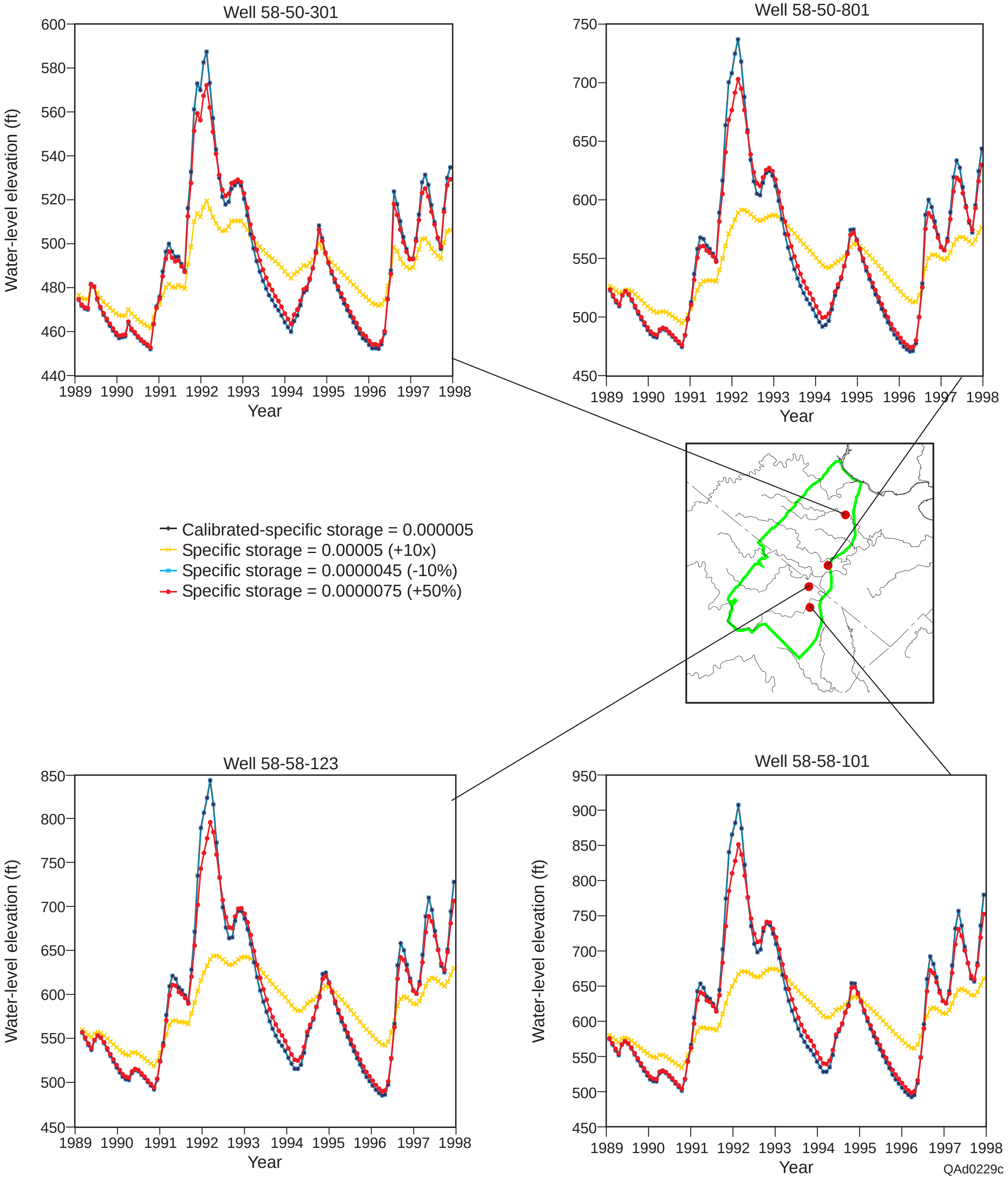


Figure 45. Sensitivity of the transient calibration water levels to specific storage.

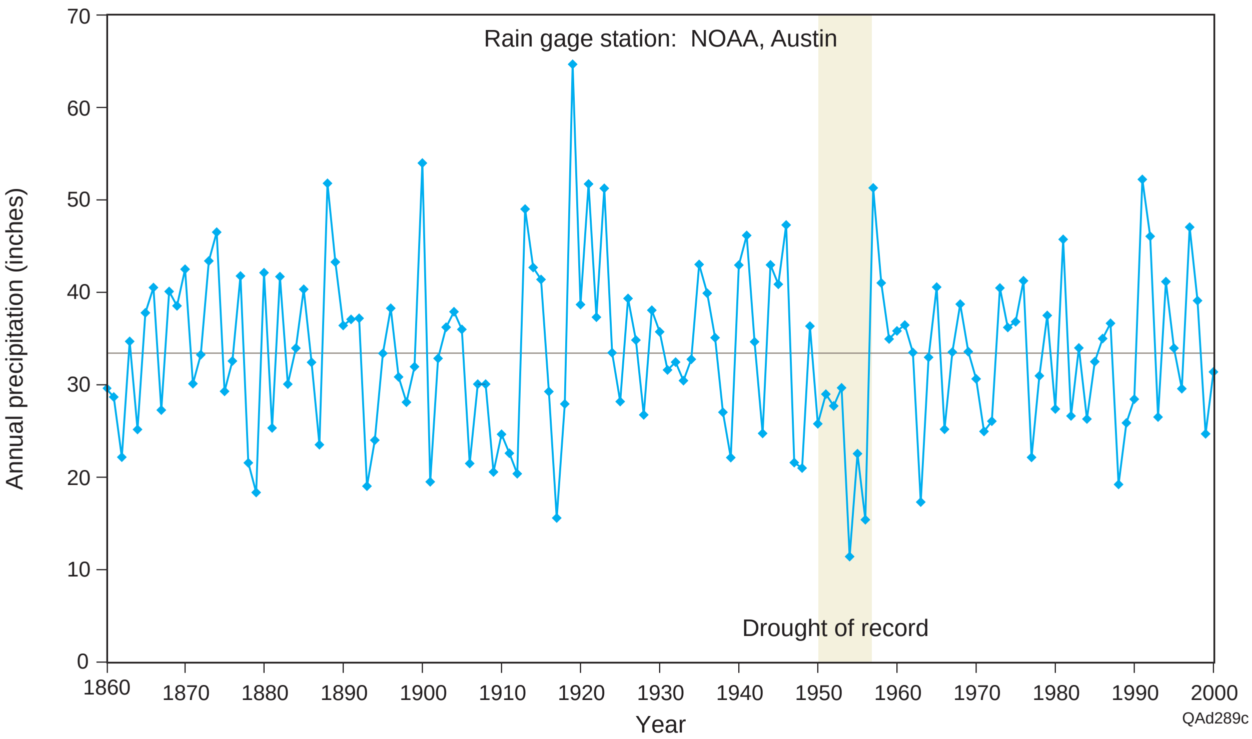


Figure 46. Precipitation from 1860 through 2000 measured at the rainfall gaging station in Camp Mabry and Mueller Airport in Austin (NOAA), showing the drought of record during the 1950's.

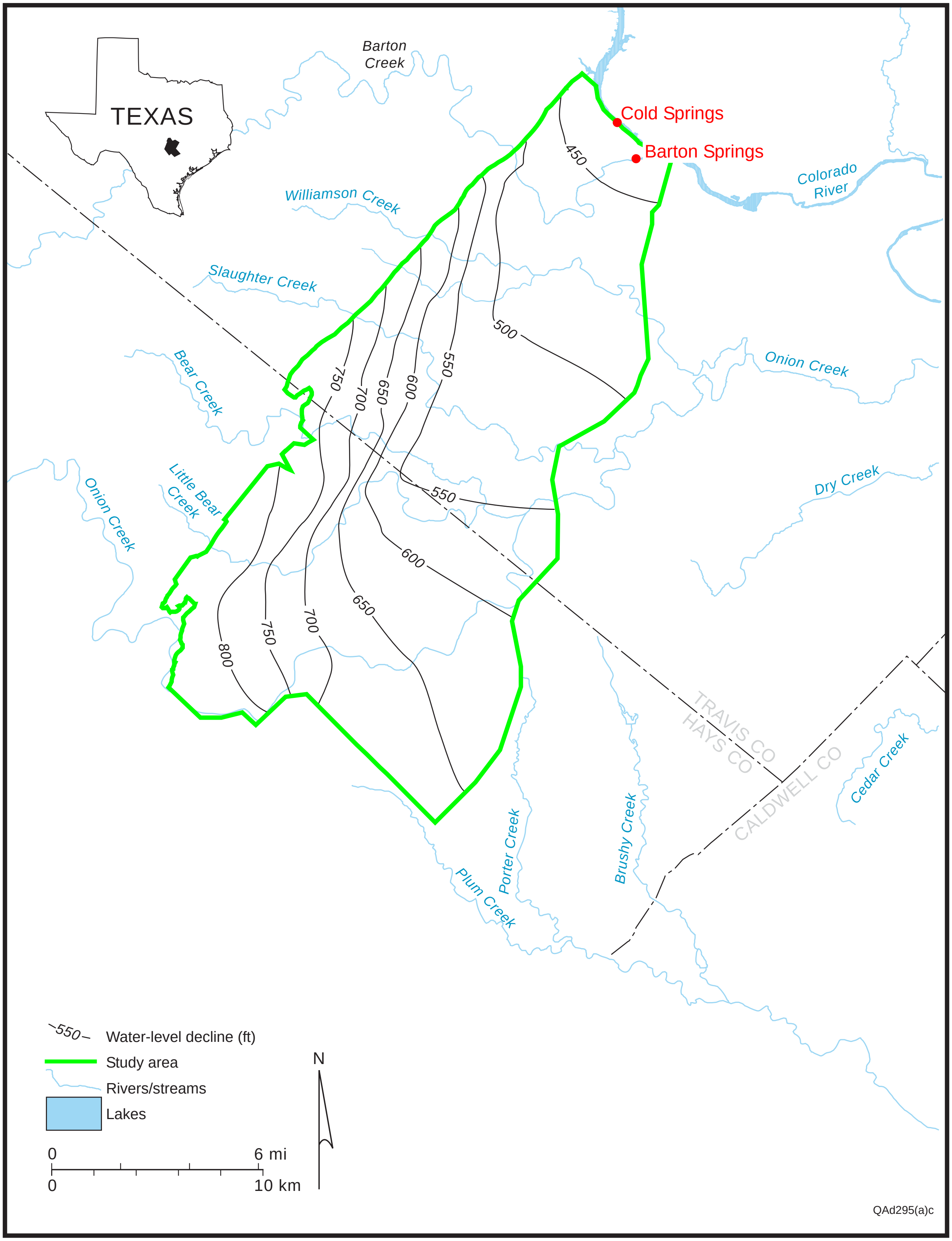


Figure 47. Baseline water levels based on average recharge (55 cfs) and current pumpage (2000) at the end of a 10-yr simulation for comparison with future simulations.

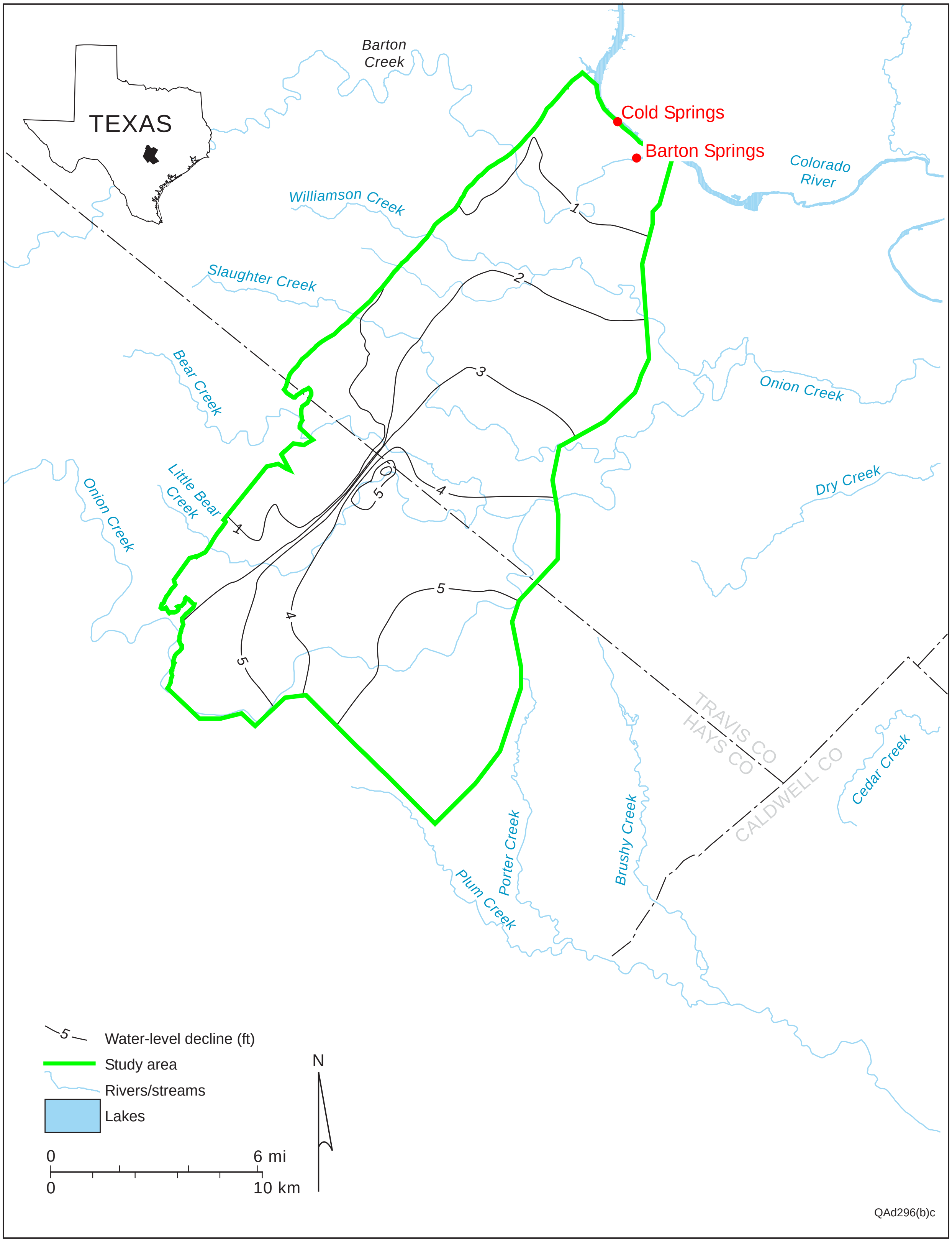


Figure 48(a). Simulated water-level declines in 2010 (relative to baseline water levels (Fig. 47)) using average recharge conditions through 2010.

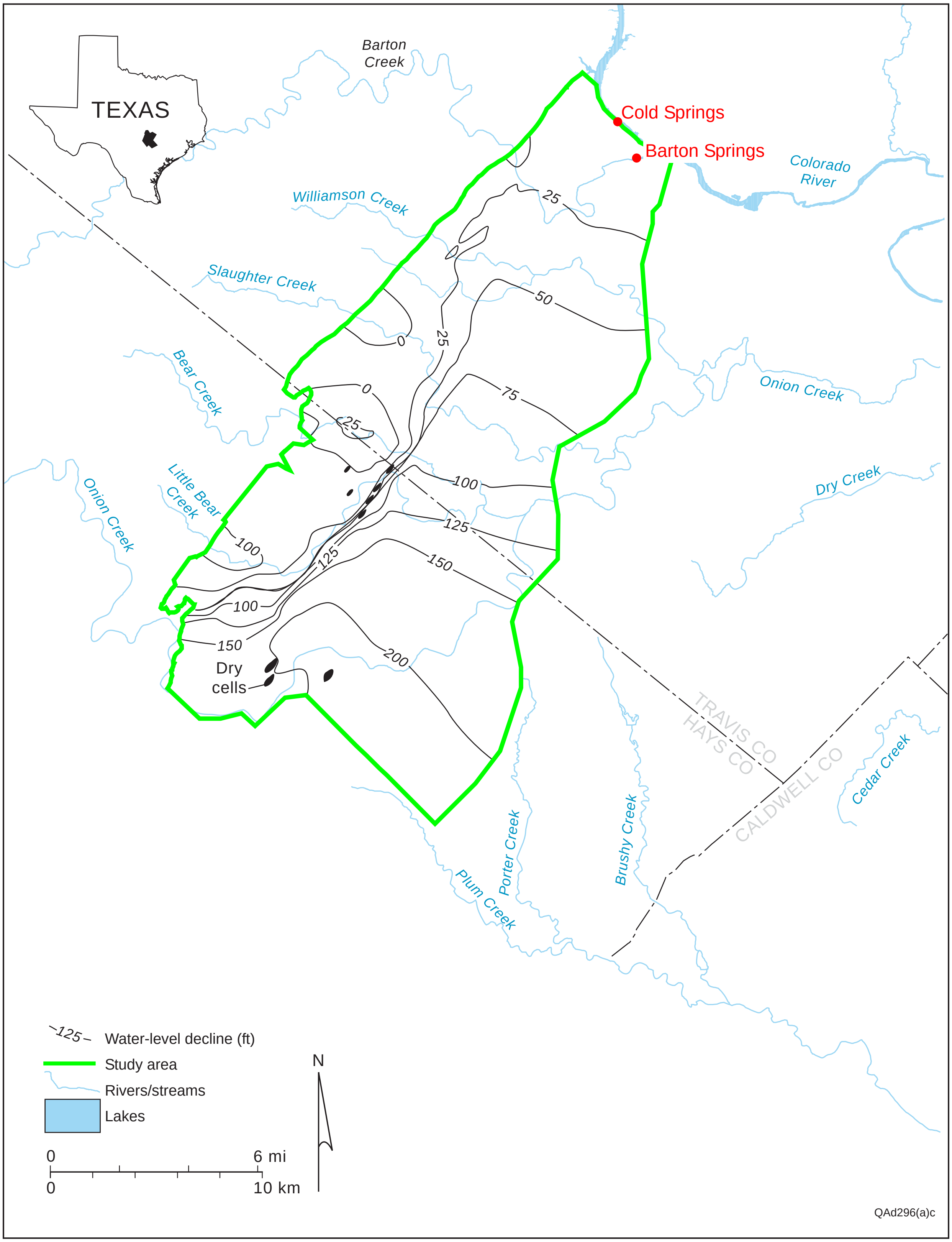


Figure 48(b). Simulated water-level declines in 2010 (relative to baseline water levels (Fig. 47)) using average recharge conditions through 2003 and drought-of-record recharge conditions from 2004 to 2010.

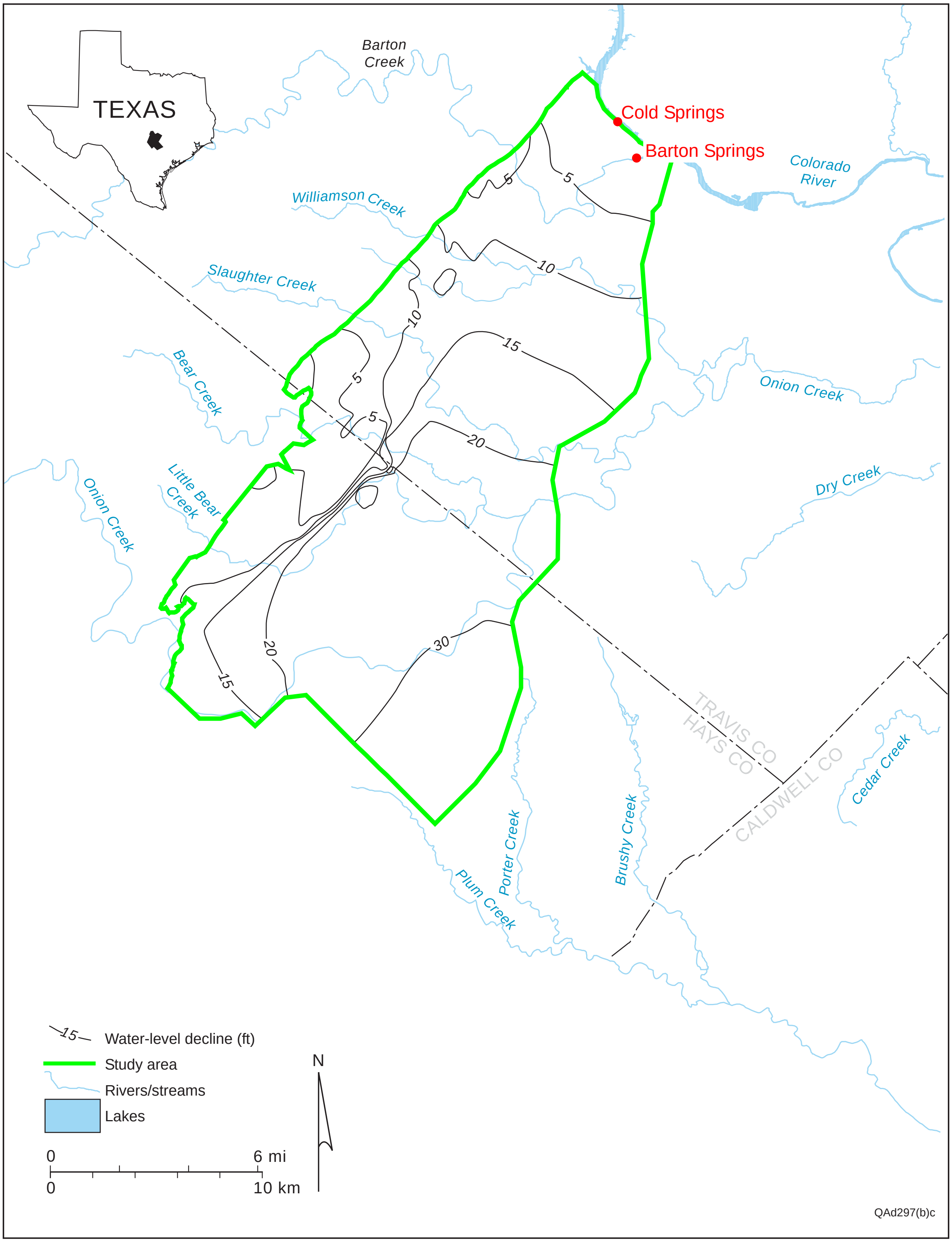


Figure 49(a). Simulated water-level declines in 2050 (relative to baseline water levels (Fig. 47)) using average recharge conditions through 2050.

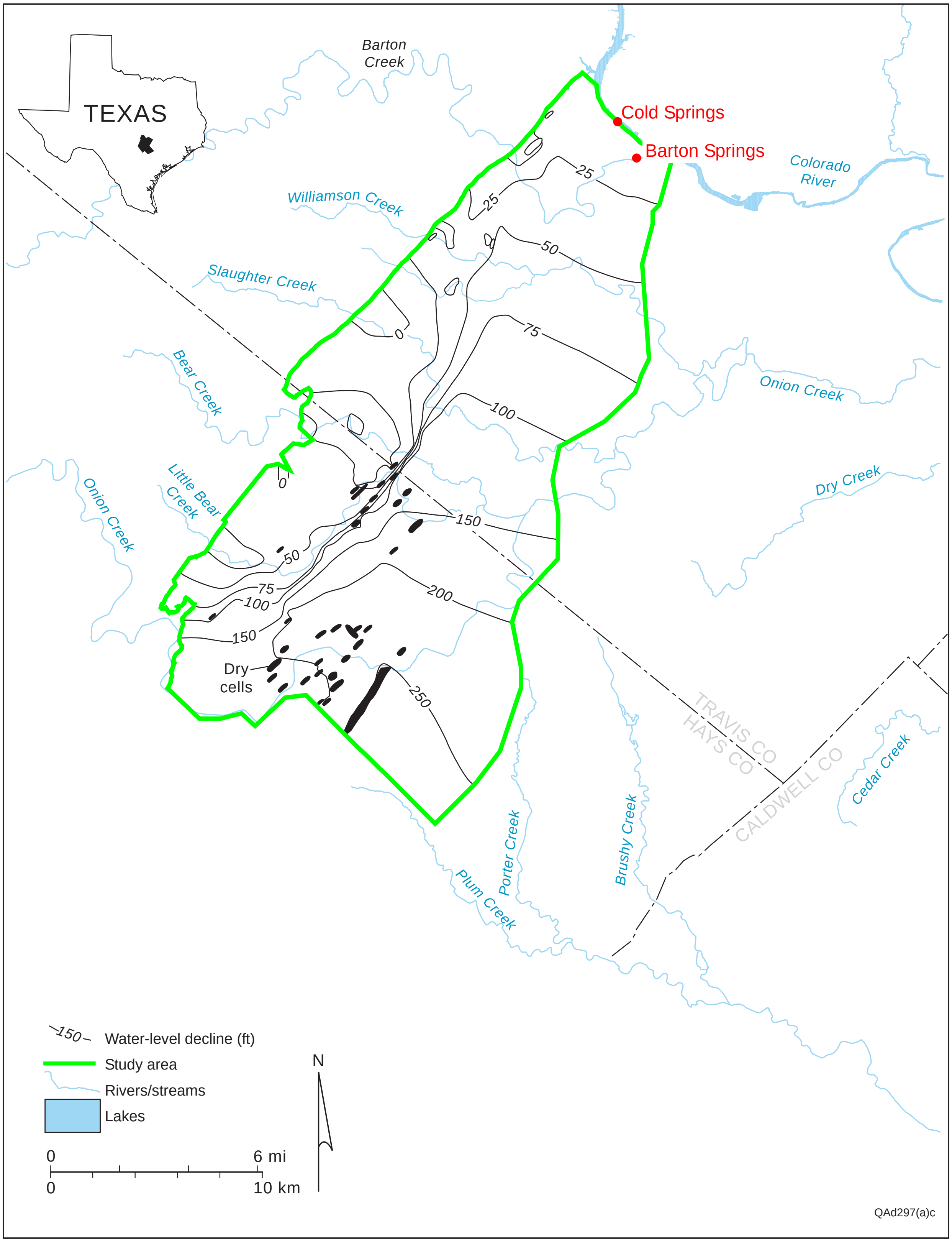


Figure 49(b). Simulated water-level declines in 2050 (relative to baseline water levels (Fig. 47)) using average recharge conditions through 2043 and drought-of-record recharge conditions from 2043 to 2050.

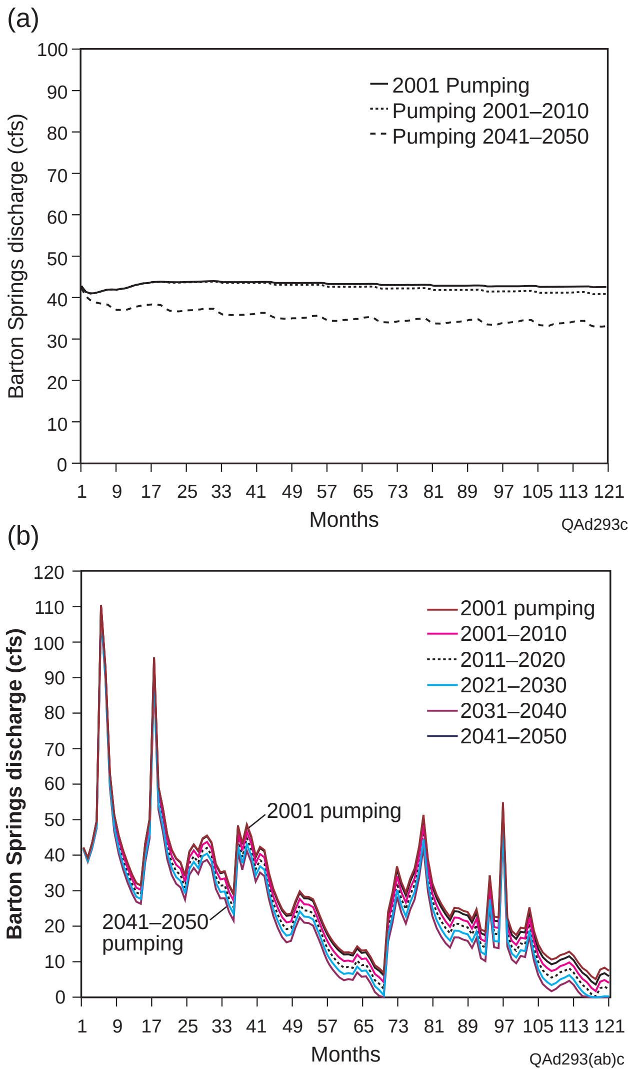


Figure 50. Simulated spring discharge for 10-yr periods using (a) average recharge conditions through 2050 and (b) average recharge conditions for the first three years and drought of record for the last seven years of each 10-yr period. The order in the legend reflects the vertical order in the line graphs.

Table 1. Stream-gauge data, including location, length of record, and maximum recharge.

Creek name	Station no.	Latitude/longitude	Upstream/ downstream	Length of gauging record	Maximum recharge (ft^3/s)
Barton (Lost Creek)	8155240	301626,0975040	Upstream	12/28/88–9/30/98	250
Barton (Loop 360)	8155300	301440, 0974807	Downstream	2/1/77–12/29/98	
Williamson Creek	8158920	301406, 975136	Upstream	12/29/93	13
Williamson Creek	8158922	301334,0975228	Upstream	3/1/93–12/29/98	
Slaughter Creek	8158840	301232,0975411		1/1/78–12/29/98	52
Bear Creek	8158810	300919,09752623		7/1/79–12/29/98	66
Onion Creek (Drift)	8158700	300458,0980027	Upstream	7/1/79–12/29/98	120
Onion Creek (Buda)	8158800	300509,975052	Downstream	7/1/79–9/30/83	

Table 2. Distribution of recharge among creeks calculated from daily data from 1/1/1980 through 12/31/1998.

	Recharge (ft^3/yr)	Total creek recharge (%)
Barton Creek	6.35E+08	29
Williamson Creek	4.95E+07	2
Slaughter Creek	1.22E+08	5
Bear and Little Bear Creeks	4.19E+08	19
Onion Creek	1.00E+09	45
Total	2.23E+09	100

Table 3. Statistical summary of hydraulic conductivity values for the Barton Springs segment of the Edwards aquifer.

n	p_{25}	p_{50}	p_{75}	x_g	x_{g+s}	x_{g--s}	s^2
24	1.3	4.9	13.8	0.6	1.4	-0.2	0.6

n—number of points
p_{25}— 25th percentile (medial) (ft/d)
p_{50}—50th percentile (median) (ft/d)
p_{75}—75th percentile (median) (ft/d)
x_g—geometric mean
x_{g-s}—geometric mean minus a standard deviation (ft/d)
x_{g+s}—geometric mean plus a standard deviation
s^2—variance $(\log[ft/d])^2$
Standard deviations are calculated from the log-normal distribution.

Table 4. Annual precipitation, recharge, pumpage, and number of reported users for the transient simulation (1989 through 1998) and predicted recharge for average conditions (2041 through 2043) and potential future drought (2044 through 2050) estimated from the 1950's drought for the future simulations.

Time (yr)	Precipitation (inches)	Recharge (cfs)	Pumpage (reported + domestic) (cfs)	Pumpage as % of recharge	Number of users
1989	25.87	28.84	5.11	18	100
1990	28.44	20.91	3.88	19	103
1991	52.21	140.98	3.92	3	116
1992	46.05	168.56	4.57	3	126
1993	26.5	66.07	5.41	8	129
1994	41.16	33.38	5.23	16	131
1995	33.97	82.86	5.29	6	136
1996	29.58	4.15	5.73	138	139
1997	47.06	127.39	5.56	4	140
1998	39.11	153.45	6.29	4	142

Table 5. Sensitivity of transient spring discharge to variations in recharge, pumpage, specific yield, and specific storage.

	Mean (cfs)	Minimum (cfs)	Maximum (cfs)	Range (cfs)	Coefficient of variation
Calibrated value	67.6	19	196	177	0.61
Recharge (-10%)	60.8	18	172	154	0.59
Recharge (50%)	102.7	26	319	293	0.68
Pumpage (-10%)	68.1	20	197	178	0.61
Pumpage (+50%)	65.4	17	194	177	0.63
Specific yield (-10%)	67.9	18	200	182	0.63
Specific yield (+50%)	66.5	23	177	154	0.52
Specific storage (-10%)	67.8	19	207	188	0.63
Specific storage (+50%)	67.1	20	178	158	0.56
Specific storage (10x)	64.2	28	133	105	0.35

Table 6. Water budget for the calibrated steady-state, transient, and predictive runs. All values are in cubic feet per second (cfs).

Model Run	Recharge	Wells	Springs	Storage
	cfs	cfs	cfs	cfs
Steady State	60.0	-5.1	-54.8	NA
Transient 89-98	82.7	-5.1	-71.9	5.7
2010	13.5	-11.2	-7.6	-5.3
2020	13.5	-13.2	-5.8	-5.5
2030	13.5	-15.3	-4.1	-5.9
2040	13.5	-17.3	-2.3	-6.1
2050	13.5	-19.4	-1.5	-7.4
2010 (no drought)	55.0	-11.2	-41.1	2.7
2050 (no drought)	55.0	-19.4	-33.7	1.9

To convert cfs to acre-ft/yr, multiply by 723.97
A positive sign indicates additions to the water budget and negative signs indicate removals.
Numbers represent fluxes for the year listed. The transient calibration model represents the average flux for 1989 – 1998.

ATTACHMENT 1
TEXAS WATER DEVELOPMENT BOARD
Review of the draft Final Report: Contract No. 2001-483-399
"Groundwater Availability of the Barton Springs Segment of the Edwards Aquifer, Texas: Numerical Simulations through 2050:

Board staff offers the following comments:

1. Report is well written and easy to read and understand

2. Cover page, need to note that Brian Smith is with BSEACD.

Brian Smith's affiliation has been noted on the cover page.

3. Page 2, 1st and 3rd sentence: It would be clearer if Barton Springs pool was defined and then described.

Sentences reordered to clarify meaning.

4. Page 2, paragraph 2: "in a computer" does not seem like correct terminology, perhaps "using" or some other word would be more appropriate.

Changed in a computer to using a computer.

5. Page 2, paragraph 2, 2nd sentence: Calibrated is introduced here but it is unclear what it means.

Model calibration is a standard process in modeling and is explained in detail in the Methods section

6. Page 3, paragraph 1, 1st sentence: The statement "(1,000 x 500 versus a minimum of 1,500 ft)" does not seem to be parallel and is hard to understand. Whether it means 500,000 vs 1500 or 1000 versus 1500 or something else entirely is not clear.

Changed sentence to indicate that minimum cell spacing of 500 ft versus 1,500 ft.

7. Page 4, geology section (and many places afterward): Comment on aquifer nomenclature. TWDB calls the aquifer the Edwards (Balcones Fault Zone) aquifer. This aquifer consists of three segments: the San Antonio segment, the Barton Springs segment, and the northern segment. In the report, you refer to the San Antonio segment as the Balcones Fault Zone segment.

Balcones Fault Zone segment renamed the San Antonio segment throughout.

8. Page 10, paragrapa 4: This statement seems to compare a description “stratigraphic thickness” to a process “thinning as a result fo normal faulting” to each other and is hard to understand.

Changed thinning to reduction in thickness.

9. Page 21, paragraph 1, equation 1: The m in hm needs to be a subscript. The i in hi should be a subscript s according to the equation.

Changes made.

10. Page 21, RMS equation: Explanation of terms in the text is inconsistent with the equation 1.

Explanation corrected to correspond to equation.

11. Page 26, paragraph 1: The use of the word recession here is confusing. Perhaps a definition should be included.

The term recession is replaced with low-flow period.

12. Pate 29, Drought of Record: “1960 through 2000’ should be 1860 through 2000’.

Change made.

13. Figures difficult to impossible to read without being in color. Impossible to address now, but will need to be looked at in Final Report.

Color figures included in report where it was difficult to decipher material in black and white.

14. Please include a budget table in the Final Report

Table included.

APPENDIX B

SENSITIVITY ANALYSIS OF SOUTHERN GROUNDWATER DIVIDE

The 2001 GAM (Scanlon et al., 2001, Appendix A) and the recalibrated GAM, described in this report, simulate the groundwater divide between the Barton Springs segment and the San Antonio segment of the Edwards Aquifer as a no-flow boundary. Groundwater divides are commonly simulated in numerical models as no-flow boundaries (Chiang and Kinzelbach, 2001; Cleary et al., 2001). To test the assumption that a no-flow boundary adequately simulates this aquifer, a sensitivity analysis was conducted by comparing the recalibrated GAM with a no-flow boundary to the recalibrated GAM with constant-head and general-head boundaries. The influence of these different boundary conditions and pumping rates on water levels was evaluated in this sensitivity analysis. Results of this analysis show that water levels will either increase or decrease, relative to the results of the recalibrated GAM, depending on water levels and hydraulic conductivity values set at the boundary. The most realistic scenario tested, which uses a general-head boundary, indicates that the increase in water levels is small compared with water levels from the recalibrated GAM with a no-flow boundary. Conditions simulated by the general-head boundary are more realistic than the constant-head boundary. Using a flow boundary for the southern boundary of the model could marginally improve the model, but additional data, such as pumping rates, water levels, and hydraulic conductivity, from the northern part of the San Antonio aquifer are needed to incorporate into the recalibrated GAM.

Boundary Changes

Scenarios were run with various conditions for the southern boundary of the model area. Figure B1 shows the part of the boundary that was modified for the sensitivity analysis. The no-flow boundary used in the 2001 GAM (Scanlon et al., 2001, Appendix A) and the recalibrated GAM was changed to constant-head and general-head boundaries for this analysis.

Constant-Head Boundary Conditions

Constant-head boundaries are used in numerical models to simulate a boundary at which water levels remain constant throughout the model run, allowing water to flow into or out of the model area, depending on relative water levels within the model area. A constant-head boundary provides an inexhaustible supply or sink of water (Chiang and Kinzelbach, 2001). Table B1 summarizes changes that were made to the recalibrated model to test the sensitivity of the groundwater divide to various boundary conditions. A constant-head boundary was set for model simulations Mod1 and Mod3 using water levels set to low levels of the 1950's drought (Slade et al., 1986).

General-Head Boundary Conditions

General-head boundaries allow flow to take place across the boundary, but the amount of flow is regulated by the water level that is set for a point or boundary at some distance outside the model area and by the conductance that is set for the area between the actual model boundary and the distant point or boundary. A general-head boundary was used in Mod2 and Mod4 with a water level of 574 ft above mean sea level (msl), which represents the elevation of the lake at San Marcos Springs. A conductance value of 112 ft^2/day was used for the general-head boundary on the basis of the distance of 80,000 ft from the model boundary to San Marcos Springs, the cross-sectional area of a model cell of 225,000 ft^2, and hydraulic conductivity of 40 ft/day. The formula to calculate conductance is:

$$C = K A / L$$

where

C = conductance of general-head boundary
K = hydraulic conductivity
A = cross-sectional area of a cell
L = distance of actual boundary to domain boundary
(Cleary et al., 2001)

Pumping Scenarios

Constant-head and general-head boundary model runs were made using low- and high-pumping scenarios to determine effects of flow and no-flow boundaries on water levels on the southeastern part of the model area.

Brune and Duffin (1983) estimated that pumping from the aquifer was about 0.66 cfs during the 1950's drought of record. To test the sensitivity of the southern model boundary to 1950's drought conditions, two scenarios (Mod1 and Mod2) were run with a pumping rate of 0.66 cfs.

The District estimates that permitted groundwater pumping plus exempt well pumping in 2004 is 10.8 cfs. To test the sensitivity of the southern model boundary to current pumping conditions, two scenarios (Mod3 and Mod4) were run with a pumping rate of 10 cfs.

Results of Sensitivity Analysis

Six model runs were made for the sensitivity analysis of the southern groundwater divide (Table B1). Water-level values from the recalibrated GAM were compared with water levels from the different boundary and pumping scenarios.

To determine the relative impacts of modified boundary conditions on water levels, water-level values from the recalibrated GAM were subtracted from water levels simulated in the scenarios with modified boundary conditions. Table B1 shows water-level differences for selected cells along a southwest-northeast transect (Figure B1) of the southern model area. Two cross sections (Figures B2 and B3) show water-level differences for each cell along this transect. The magnitude of water-level changes decreases away from the modified boundary. Water-level changes are less than 1 ft in the cells within 1,000 ft of Barton Springs.

At a low pumping rate (0.66 cfs), water levels from the constant-head and general-head boundary scenarios are slightly lower than water levels from the recalibrated GAM (Figure B2). At cell 32,77, water levels are 10 ft and 25 ft lower in Mod1 and Mod2, respectively, than in the recalibrated GAM.

At a high pumping rate (10 cfs), water levels from the constant-head and general-head boundary scenarios are greater than in the recalibrated GAM (Figure B3). At cell 32,77, water levels are 22 ft and 90 ft higher in Mod4 and Mod3, respectively, than in the recalibrated GAM.

Discussion of Results

As shown in Table B1 and Figures B2 and B3, water-level changes are small in scenarios with low rates of pumping (Mod1, and Mod2) compared with the scenario with a high rate of pumping (Mod3). Water-level changes in Mod4 are small compared with Mod3.

Mod3, with a constant-head boundary, simulates 1950’s drought conditions north and south of the divide, but does not consider drawdown from pumping south of the divide, and therefore is unrealistic. Mod4 is the most realistic of all the scenarios tested as part of this sensitivity analysis. Mod4, with a general-head boundary set to the elevation of San Marcos Springs, allows for water levels to vary at the boundary, which can occur owing to pumping of wells south of the divide, discharge to San Marcos Springs, and climatic conditions.

Judging from the well-impact evaluation described in Section 4 of this report, increases in water level of 22 ft (as simulated in Mod4) are unlikely to significantly reduce the number of wells that might be impacted by pumping and drought-of-record conditions.

Summary

Mod4, which incorporates current (2004) rates of pumping with drought-of-record conditions and a general-head boundary at the southern boundary of the model area, is the most realistic of the tested scenarios. Results of this simulation suggest that if the recalibrated GAM, currently being used by the District, was modified with a general-head boundary across a part of the southern model boundary, the potential for flow across the boundary could be addressed. Because of the small changes in water levels between Mod4 and the recalibrated GAM, model results for water levels in the model area would not improve significantly. Therefore, the recalibrated GAM, with a no-flow boundary, is an adequate model for simulating the Barton Springs aquifer. Future modeling of the Barton Springs aquifer should consider using a time-varying specified-head boundary for the southern boundary in addition to collection of hydrogeologic data near the groundwater divide. Water-level data from the USGS model for the San Antonio segment of the Edwards Aquifer (currently undergoing review) could be used to set water levels along the southern boundary.

REFERENCES

Brune, Gunnar and Duffin, Gail, 1983, Occurrence, Availability, and Quality of Ground Water in Travis County, Texas: Texas Department of Water Resources, Report 276, 219 p.

Chiang, W. H., and Kinzelbach, W., 2001, 3D-groundwater modeling with PMWIN: New York, Springer, 346 p.

Cleary, R. W., Franz, T., and Guiguer, N., 2001, The MODFLOW Course: National Ground Water Association, November 6–8, Orlando, FL.

Scanlon, B., Mace, R., Smith, B., Hovorka, S., Dutton, A., and Reedy, R., 2001, Groundwater Availability of the Barton Springs Segment of the Edwards Aquifer, Texas—Numerical Simulations through 2050: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for the Lower Colorado River Authority, under contract no. UTA99-0, 36 p. + figs., tables, attachment.

Slade, Raymond, Jr., Dorsey, Michael, and Stewart, Sheree, 1986, Hydrology and Water Quality of the Edwards Aquifer Associated with Barton Springs in the Austin Area, Texas: U.S. Geological Survey Water-Resources Investigations, Report 86-4036, 117 p.

Table B1. Results of sensitivity analysis

Model version	Boundary type	Water levels at boundary	Pumping (cfs)	Barton Springs flow (cfs)	Water-level changes*		
					Cell 32,77	Cell 50,77	Cell 67,77
Recalibrated GAM	No flow	2001 GAM initial conditions	0.66	11.3			
Mod1	CHB	D-O-R conditions	0.66	9.7	-10	-14	-11
Mod2	GHB	San Marcos Springs	0.66	9.6	-25	-22	-14
Mod3	CHB	D-O-R conditions	10	5.6	+82	+57	+30
Mod4	GHB	San Marcos Springs	10	3.5	+22	+15	+7
Recalibrated GAM	No flow	2001 GAM initial conditions	10	1.1			

* Water-level changes are relative to corresponding results of recalibrated GAM (0.66 or 10 cfs of pumping) with a no-flow boundary.

D-O-R- Drought of record

CHB- Constant-head boundary; GHB- General-head boundary

Spring flow and water-level values are from Stress Period 117, which represents the lowest flows and water levels of the drought of record.

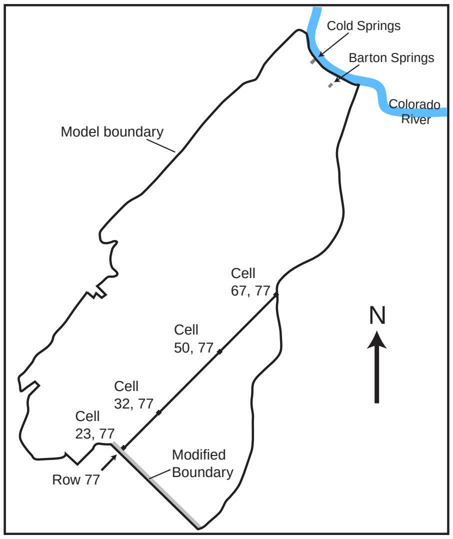


Figure B-1. Model area of the Barton Springs aquifer.

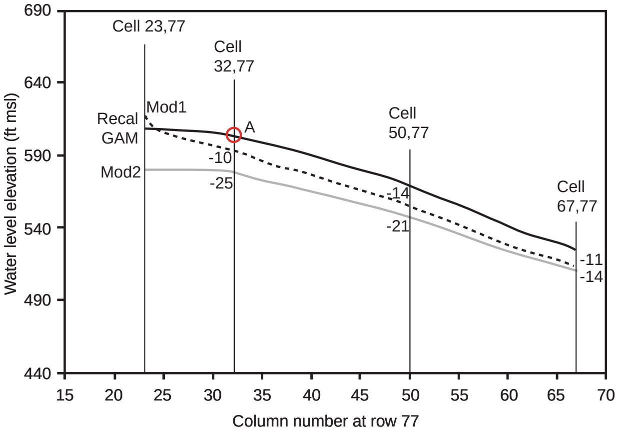


Figure B-2. Cross section of southeast model area with 0.66 cfs pumping scenarios. Head values are from stress period 117, time step 12.

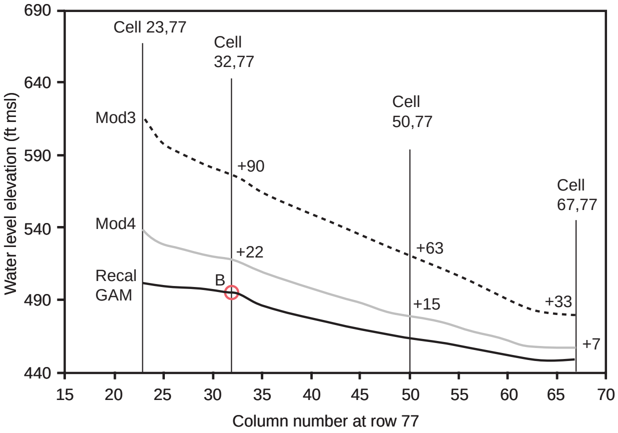


Figure B-3. Cross section of southeast model area with 10 cfs pumping scenarios. Head values are from stress period 117, time step 12.

APPENDIX C

LIST OF PARTICIPANTS AND AFFILIATIONS AT SUSTAINABLE YIELD MEETINGS AT THE BSEACD

September 10, 2003

Suzanne Pierce, UT Graduate Student
Larry Land, HDR Engineering
Rene Barker, USGS
Rick Lindgren, USGS
Raymond Slade, Consulting Hydrologist
Joe Vickers, Wellspec Co.
James Beach, LBG-Guyton Assoc.
Clarence Littlefield, Southwest Eng.
Kaveh Khorzad, Wet Rock Groundwater
John Mikels, Geos Consulting
Shirley Wade, TWDB
Robert Mace, TWDB
Nico Hauwert, City of Austin WPDRD
David Johns, City of Austin, WPDRD
Steve Musick, TCEQ
Randy Williams, TC&B
Ken Manning, LCRA
Nadira Kabir, LCRA
Ned Troshanov, EAA
Marshall Jennings, EARDC
Lendon E. Gilpin, EARDC
Bridget Scanlon, UTBEG

March 24, 2004

John Mikels, Geos Consulting
Frank Del Castillo, PBS&J
Tricia Sebes, HDR Engineering
Larry Land, HDR Engineering
Joe Vickers, Wellspec Co.
Roberto Anaya, TWDB
Ian Jones, TWDB
Andrew Backus, HTGCD
Randy Goss, LCRA
Phil Savoy, Murfee Engineering
Ned Troshanov, EAA
Hugo Elizondo, Jr., Cuatro Consulting
Nadira Kabir, LCRA
Brent Covert, LCRA
Raymond Slade, Consulting Hydrologist
Suzanne Pierce, UT Graduate Student
Ron Green, CNWRA/SWRI
Robert Mace, TWDB
John Littlefield, Southwest Eng.
Lauren Ross, Greater Edw. Aq. Alliance

APPENDIX C

Descriptions of the Habitats and the Flora & Fauna of the Barton Springs Complex

Excerpted from the City of Austin's Amended Habitat Conservation Plan for the Barton Springs Pool Operation and Maintenance (2013)

Appendix C

Detailed Descriptions of the Habitats and the Flora and Fauna of the Spring Outlets of the Barton Springs Complex

Note: This appendix contains verbatim (except formatting)excerpts of various sections of the habitat descriptions contained in the Barton Springs Pool HCP prepared by the biological staff of the City of Austin's Watershed Protection Department (Service, 2013), which should be accessed for bibliographic citations contained herein. This entire document may be found at: http://www.austintexas.gov/watershed_protection/publications/document.cfm?id=203078.

Flow Regimes and Man-made Modifications of the Barton Springs Complex

The Barton Springs complex is part of the dynamic flowing water system of Barton Creek. Parthenia Spring and Upper Barton Spring are entirely within the channel of Barton Creek, and spring water from Eliza and Old Mill flows into Barton Creek. The complex is located approximately 1,500 feet upstream of the confluence of Barton Creek and the Lady Bird Lake segment of the Colorado River. This stretch of Barton Creek is 20 to 100 feet wide and numerous smaller upland streams contributing to its flow. The natural surface hydrology of this stretch of Barton Creek varies from spates of flashy, rapidly flowing flood water to periods of slowly flowing, base flow (City of Austin 2005, 2006, 2007). At times, the only water flow in Barton Creek is spring water originating from Barton Springs.

The flow regimes of creeks and rivers are the dominant features that distinguish them from lakes and ponds (Leopold *et al*. 1992). Shallow water of streams and creeks has faster current velocity and consequently greater power to generate incipient motion of substrates and debris (Leopold *et al*. 1992), driving geomorphological changes in channels. This disturbance is an important feature of streams and rivers (Resh *et al*. 1988, Poff and Ward 1989, Gordon *et al*. 2004), and was a natural characteristic of the Barton Springs complex prior to alteration by humans. Natural variation in flow velocity drives variation in abiotic and biotic features of resilient stream ecosystems (Vogel 1994). Water flow influences every part of the aquatic ecosystem (Giller and Malmqvist 1998, Wetzl 2001), from the amount of sediment deposited (Nowell and Jumars 1984) and types of algae (Blum 1960, Reiter and Carlson 1986, Poff *et al*. 1990) to the community of invertebrates and vertebrates found there (Vogel 1994). Faster, unidirectional water flow naturally favors growth of tightly attached algae (Fritsch 1929, Korte and Blinn 1983, Stevenson 1983) and a diversity of stream-adapted invertebrates (Hynes 1972), and helps maintain high water quality (Spellman and Drinan 2001).

Historically, there were no barriers to free-flowing water in the Barton Springs complex, Barton Creek, or the lower Colorado River. Presently, the flow regimes of these systems are altered, and have been for about 150 years. All three perennial springs of the Barton Springs complex have flow regimes altered by impoundments (Figure 5). The largest spring, Parthenia Spring (also known as Main Spring), is contained within Barton Spring Pool and confined by upstream and downstream dams spanning Barton Creek. Smaller Eliza Spring (also known as Concession Spring, Polio Pit, Elks Spring, or Walsh Spring) and Old Mill Spring (also known as Sunken Garden, Paggi's Mill, or Zenobia Spring) are located on the north and south banks of Barton Creek, respectively. Old Mill Spring retains an overland outflow stream discharging directly into Barton Creek downstream of Barton Springs Pool. Outflow from Eliza Spring is directed into a buried pipe and ultimately downstream into Barton Creek. The upstream dam of Barton Springs Pool obstructs flow of Barton Creek floodwater, while base flow is diverted around Barton Springs Pool through a culvert.

Heavy rainfall in the Barton Springs Contributing and Recharge zones drives the flooding of Barton Creek that reaches Barton Springs. Based on U. S. Geological Survey measurements of discharge in Barton Creek upstream of Barton Springs (site 08155400) from 1999 – 2011, when floods exceed approximately 500 ft^3/s, Barton Creek overtops the upstream dam and flows through Barton Springs Pool. These floods occur on average 4.3 times per year, with maximum and minimum number of occurrences within a single year of 15 and 0. The median duration of floods of this or greater magnitude is 2.96 days (Table 1). Precipitation and antecedent conditions surrounding these flood conditions are highly variable in total volume, intensity, duration, and geographic distribution over the watershed.

Flow regime of Eliza Spring has been altered since 1929 (see section 2.8 and Appendix B). Natural water flow from the spring was obstructed by construction of a concrete dam across Barton Creek downstream of the confluence of Eliza Spring and the creek. The overland stream was diverted into a buried pipe, which connected with Barton Springs Pool (Figures 5, 10). This obstruction was reversed in 1974 with the redirection of water flow from Eliza Spring into the newly constructed Barton Creek Bypass Culvert (Figure 5) that carries creek water around the Pool. In the 1950s, free water flow into the spring pool was altered with the construction of a concrete floor in the amphitheater; the resulting higher elevation of surface substrate requires obstruction of free water flow from the spring pool to maintain water in surface habitat under most aquifer conditions. Presently, if gates in the downstream dam of Barton Springs Pool are open, floodwater of Barton Creek rarely travels overland into Eliza Spring.

Table C-1. Descriptive statistics for discharge of Barton Creek and flooding of Barton Springs Pool from 1999 – 2011. Presented are the average (mean), the total number of occurrences, and average duration within each discharge category. Bold text denotes data during floods of Barton Springs Pool. Gauge height data were collected at the junction of Loop 360 and Barton Creek (site 08155300) and immediately upstream of Barton Springs Pool (BSP, site 08155400), and converted to discharge by the U.S. Geological Survey. Gauge height upstream of Barton Springs Pool is influenced by capacity and obstruction of a flood bypass culvert.

	Upstream BSP			Loop 360		
Discharge (ft^3/s)	Mean	Total Number	Duration (days)	Mean	Total Number	Duration (days)
100 - 199	9.9	31	6.88	12.8	62	2.11
200 - 299	8.7	24	5.70	9.0	36	2.50
300 - 399	6.4	22	4.97	6.7	28	1.54
400 - 499	5.7	19	3.41	5.2	24	1.25
500 – 599	4.3	15	2.96	4.1	17	1.14
600 - 699	4.0	11	2.70	4.0	15	1.05
700 - 799	3.7	11	0.23	3.8	13	0.77
800 - 899	2.3	7	2.32	3.7	12	0.53
900 - 999	1.9	5	2.53	3.5	13	0.69
≥ 1000	1.9	6	1.46	3.3	13	0.71

Flow regime of Old Mill Spring has been altered since the mid-1800s (section 2.8 and Appendix B). The construction of a mill and, subsequently, an amphitheater altered Old

Mill Spring by almost completely impounding the outflow from the spring, creating a deep-water pool with low flow velocity under most aquifer conditions. Outflow was further impeded by remnants of a buried concrete pipe and the loss of the original surface stream. The natural surface outflow stream was buried beneath several feet of soil and its historic course is poorly known. The original stream channel exited the spring pool at a lower elevation than the reconstructed stream (Figure 9) and connected to Barton Creek further downstream than it does today (Figure 9). Flow of groundwater into the spring pool is obstructed by a deep layer of cobble, gravel, and sediment, which is also littered with fragments of concrete and asphalt, broken glass, rusty metal, plastic, and other trash. The exact topography of the natural limestone underlying this site is not recorded. The location and elevation of the natural fissures and caves from which groundwater is emitted to the surface is unknown. Based on anecdotal information and historical accounts (City Items 1873, as cited in Limbacher and Godfrey Architects 2008), they may be up to 10 feet deeper than the current substrate elevation. Upper Barton Spring is the only site whose surface flow regime has not been altered by dams or impoundments (Figure 5).

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Vegetation and Macrophyte Communities at/near the Barton Springs Complex

Vegetation often observed along seeps and springs in the Edwards Aquifer are maidenhair fern (*Adiantium capillus-veneris*), tuber anemone (*Anemone edwardsiana*), and southern shield fern (*Thelypteris kunthii*) (Bezanson 2000, Amos and Rowell 1988 as cited in Griffith *et al*. 2004). Many Edwards Plateau small, headwater springs have shallow water, high canopy cover (Bray 1904), fast current, and low nutrient content (Mabe 2007). These factors likely underlie naturally low abundance and diversity of aquatic macrophytes and macroalgae (Cushing and Allan 2001, Giller and Malmqvist 1998). Larger springs located within wider, higher order streams, such as the stretch of Barton Creek that contains Parthenia Spring, likely had a greater abundance of aquatic macrophytes than headwater springs because the canopy cover is less, current is slower, and nutrient load is greater (Wetzel 2001).

The Barton Springs complex is located within Zilker Park in Austin, Texas. This park is a combination of manicured gardens, trails, turf lawns, and nature trails through unmanaged native landscapes along Barton Creek near its confluence with the lower Colorado River (Lady Bird Lake). Growing throughout the manicured areas of the park are mature live oak (*Quercus virginiana*), ashe juniper (*Juniperus ashei*), pecan (*Carya illinoensis*), American elm (*Ulmus Americana*), cottonwood (*Populus deltoides*), and hackberry (*Celtis occidentalis*) trees. A number of smaller, mostly native trees have recently been planted in an effort to create a new generation of diverse, native trees in the park. The sports fields and other turf areas of the park are composed of Bermuda and Zoysia grasses. Non-native invasive species have become established throughout much of the vegetated areas, particularly Chinese tallow (*Sapium sebiferum*), Japonese honeysuckle (*Lonicera japonica*), heavenly bamboo (*Nandina domestica*), and privet (*Ligustrum* sp.). An integrated plan for removal of non-native, invasive species and reintroduction of native species around Barton Springs (Limbacher and Godfrey Architects 2008) was recently implemented by the City's Parks and Recreation Department.

Since the construction of dams and creation of Barton Springs Pool, the aquatic vegetation in the Plan Area has changed. Anecdotal reports indicate that patches of macrophytes were present sporadically; almost no aquatic macrophytes were present as of 2001 (Laurie Dries personal observations, City of Austin unpublished data). This was likely a result of frequent, intrusive maintenance methods used to control algae and remove flood debris (*i.e.*, dredging and chemical treatments). At present, the aquatic macrophyte community Barton Springs Pool is more abundant and diverse than ever recorded, largely a result of repeated reintroductions of native species, and use of less intrusive maintenance methods. Aquatic macrophyte species currently found in Barton Springs Pool include Delta Arrowhead (*Sagittaria platyphylla*), Water Primrose (*Ludwigia repens*), Water Stargrass (*Heteranthera dubia*), Southern Waternymph (*Najas guadalupensis*), Coon's Tail (*Ceratophyllum demersum*), Two-leaf Water Milfoil (*Myriophyllum heterophyllum*), Carolina Fanwort (*Cabomba caroliniana*), Water Celery (*Vallisneria americana*), Water Hyssop (*Bacopa monnieri*), Two-headed Water Starwort (*Callitriche heterophylla*), Upright Burrhead (*Echinodorus bertoroi*), Spikerush (*Eleocharis* sp.) and Knotty Pondweed (*Potamogeton nodosus*). Two vascular algae (*Chara* sp. and *Nitella* sp.), whose appearances resemble small, plants, have been observed occasionally throughout the Pool, and the aquatic moss, *Amblystegium riparium*, is common on limestone surfaces of Parthenia Spring.

Vegetation is sparse in Eliza Spring and Old Mill Spring. In the 1990s, both these sites had artificially deep spring pools (almost 10 feet), and the dominant, or only, vegetation was aquatic moss and algae. Since habitat restoration began for both springs, the water depth has decreased, creating more stream-like habitat with greater water velocities. Efforts to reintroduce native aquatic vegetation to Eliza Spring have been hampered by the concrete floor; vegetation cannot become well established even when planted in sediment pockets. Macrophytes that have been planted and established temporarily are water primrose, water hyssop, water celery, and spikerush. Aquatic moss has remained present in Eliza Spring, although at lower abundance. Loose, rocky substrate in Old Mill Spring continues to be removed as part of habitat restoration, making it difficult to establish macrophytes, but

American waterwillow (*Justicia americana*), water primrose, and water hyssop have been reintroduced and become established along the edges of the spring pool.

The current algal community in the Barton Springs complex has not been evaluated exhaustively or quantitatively, but algal species observed in each of the springs are reported in Tables C-2 and C-3. Planktonic algae are rare and in low abundance within the spring sites, likely due to phosphorus concentrations below detection limits of standard tests, and a high turnover rate of water within the springs (Barton Springs Pool daily turnover between 2 and 19 times) (Alan Plummer and Associates 2000, Herrington and Scoggins 2006). Phosphorus limitation of planktonic algal growth is common to central Texas streams (Mabe 2007), although periphytic algae are common and generally abundant in all the springs in the complex (City of Austin unpublished data, Herrington and Scoggins 2006). This suggests that nutrient availability is not the only factor influencing algal growth and abundance. The types of algae observed suggest that the algal community varies among spring sites and habitat type (Alan Plummer and Associates 2000, Colucci 2009). Habitats with higher flow velocity along the substrate, such as Eliza Spring, Upper Barton Spring, and Parthenia Spring, are dominated by tightly attached periphyton and some seasonal filamentous algal blooms, with little colonization of blue-green algae. Old Mill Spring and the deeper areas of Barton Springs Pool are more characteristic of slow moving rivers or ponds (low flow velocity and increased sedimentation) and have higher relative abundances of filamentous green algae and blue-green algae (City of Austin unpublished data).

A species of red alga, *Flintiella sanguinaria*, was collected from the mouth of Parthenia Spring (Ott 1976) and has not been reported from additional localities, suggesting possible endemism to Barton Springs. Presence of this species has not been recorded since the study of Ott (1976), but algal sampling in Parthenia Spring has been sporadic.

There is evidence from both taxonomic inventories and observations that the algal community in Barton Springs Pool varies temporally and geographically. During a period of low discharge (< 30 ft^3/s) in the spring and summer of 2000, nuisance algal abundance reached levels objectionable to swimmers and recreational users. As part of development of an algae control plan, Alan Plummer and Associates (2000) conducted a study of abundance and growth of nuisance algae in the Pool. While the study was unsuccessful in documenting algal growth rates, algae found in various locations in Pool were identified (Tables C-2 and C-3). Compared with the inventory taken during 2005-2006 by City staff, there were significantly more genera observed at Barton Springs Pool only 5 years after the Alan Plummer and Associates study. Algal community in Barton Springs Pool prior to the 1970s was heavily influenced by the use of chlorine and copper sulfate to control algal growth. Use of copper sulfate was ceased in the 1960s. Use of chlorine [ceased] in the early 1990s.

Table C-2. Genera of soft-bodied algae found from March 2005 and August 2006 in Eliza, Old Mill, and Upper Barton Spring, (summarized from City of Austin 2008b), from 2006 to 2011 in Barton Springs Pool, and reported in the Barton Springs Pool Preliminary Algae Control Plan (Alan Plummer and Associates 2000). Algae generally found attached to substrate (benthic) are denoted by the letter A, generally free-floating (planktonic) algae are denoted by the letter F. The names in bold are algae that have reached nuisance abundances in Barton Springs Pool.

	City of Austin				**Plummer**
Genus	**BSP**	**Eliza**	**Old Mill**	**UBS**	**BSP**
Green micro-algae					
Aphanochaete (A)	x				
Ankistrodesmus (F)			x		
Chlamydomonas (F)	x	x	x		
Closterium (F)		x	x		
Cosmarium (F)	x	x	x	x	
Gloeocystis (F)		x			
Oocystis (F)	x				
Pediastrum (F)					x
Scenedesmus (F)	x	x			x
Green macro-algae					
Chaetophora (A)	x				
Chaetosphaeridium (F)	x				
Chamaesiphon (A)		x			
Chara (A)	x				
Cladophora (A)	x	x	x	x	x
Dichotomosiphon (A)	x	x			

Hydrodictyon (A or F)	x	x		x		
Mougeotia (A or F)	x					x
Nitella (A)	x					
Oedegonium (A)	x					
Rhizoclonium (A or F)	x					
Spirogyra (A or F)	x	x		x		x
Stigeoclonium (A)	x	x	x			x
Tetraspora (A)		x	x	x		x
*Thamniochaete***						x
Red Algae						
Audouinella (A)	x		x			
Batrachospermum (A)	x	x	x	x	x	
Hildenbrandia (A)	x	x				
Tuomeya (A)			x	x		
Yellow-green algae						
Ophiocytium (F)			x			
Tribonema (F)	x	x				
Vaucheria (A)	x	x	x	x		
Blue-green/cyanobacteria						
Amphithrix = Homeothrix (A)	x					
Anabaena (F)	x		x			
Aphanocapsa (F)	x					
Calothrix (A)	x					
Chroococcus (A)	x	x			x	

Coelosphaerium (F)	x				
Lyngbya (A)	x	x	x		
Oscillatoria (F)	x	x	x	x	x
Spirulina (F)	x				x
Euglenoid algae					
Euglena (A)	x	x			

Another period of objectionable nuisance algal growth occurred in the summer of 2006, coinciding with low Barton Springs' discharge of approximately 30 ft^3/s. In response, native aquatic macrophytes were reintroduced into the Pool to increase competition with algae for nutrients and sunlight, to provide cover for algae-eating invertebrates and fish, and enhance dissolved oxygen concentrations. This resulted in significant increase in aquatic plants, from roughly 10% of surface area to over 50% (City of Austin unpublished data). During the subsequent drought period (Barton Springs discharge <25 ft^3/s), from the summer of 2008 to the fall of 2009, nuisance algal abundance never increased to the objectionable amounts observed during previous low discharge periods. This suggests that the establishment of aquatic macrophytes has succeeded in helping to control abundance of nuisance algae, regardless of nutrient concentrations.

Table C-3. Diatom algal genera observed between March 2005 and August 2006 in Eliza and Old Mill springs, and Barton Springs Pool (City of Austin 2008b), and algae reported in the Barton Springs Pool Preliminary Algae Control Plan (Alan Plummer and Associates 2000).

	City of Austin			**Plummer**
Genus	**BSP**	**Eliza**	**Old Mill**	**BSP**
Achnanthes	x	x	x	
Achnanthidium	x	x	x	
Adlafia	x			

Amphora	x	x	x		x
Bacillaria			x		
Brachysira	x		x		
Caloneis			x		x
Cocconeis	x	x	x		
Craticula	x				
Cymbella	x				x
Denticula	x	x	x		
Diadesmis	x				
Diatoma	x				x
Diatomella					x
Diploneis	x				
Encyonema	x		x		
Encyonemopsis		x			
Encyonopsis	x		x		
Eunotia	x				
Fragilaria	x	x			x
Geissleria	x		x		
Gomphoneis					x
Gomphonema	x	x	x		x
Gomphospenia	x				
Luticola	x				
Melosira	x	x			
Navicula	x	x	x		x

Nitzchia	x	x	x	
Psammothidium	x	x	x	
Pseudostaurosira	x			
Reimeria	x			
Rhoicosphenia	x	x	x	
Sellaphora			x	
Staurosira	x			
Staurosirella	x	x	x	
Surirella		x		
Synedra	x	x	x	x
Tabilleria				x
Terpsinoe	x			x

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Faunal Assemblages at/near the Barton Springs Complex

In addition to aquatic salamanders, records of aquatic fauna that have been or are currently found in Barton Creek and Barton Springs include 20 species of fish, 3 species of turtles and numerous invertebrates. Native fishes commonly seen in Barton Springs Pool include the Green Sunfish (*Lepomis cyanellus*), Bluegill (*Lepomis macrochirus*), Longear Sunfish (*Lepomis megalotis*), Spotted Sunfish (*Lepomis punctatus*), Largemouth Bass (*Micropterus salmoides*), Guadalupe Bass (*Micropterus treculi*), Mosquitofish (*Gambusia affinis*), and the Greenthroat Darter (*Etheostoma lepidum*). Native fishes whose ranges include Barton Creek, which are seen occasionally in Barton Springs include the American Eel (*Anguilla rostrata*), Channel Catfish (*Ictalurus punctatus*), Flathead Catfish (*Pylodictus olivaris*), Gray Redhorse (*Moxostoma congestum*), Texas Logperch (*Percina carbonaria*), Dusky Darter (*Percina sciera*), Orangethroat Darter (*Etheostoma spectabile*), Red Shiner (*Cyprinella lutrensi*), Blacktail Shiner (*Cyprinella venusta*), Texas Shiner (*Notropis amabilis*), Central

Stoneroller (*Campostoma anomalum*), and the Blackstripe Topminnow (*Fundulus notatus*). Fish residing in Eliza Spring are mosquitofish, but tadpole madtoms (*Noturus gyrinus*) have been seen for short periods of time after floods. Old Mill Spring typically has no resident fish, although some sunfish occasionally migrate in and out of the spring. The Bullhead Minnow (*Pimephales vigilax*) has been found in abundance in Upper Barton Spring when it is flowing, along with other minnows mentioned above. Non-native Mexican tetras (*Astyanax mexicanus*) were found in abundance in Barton Springs Pool and Old Mill Spring in recent decades but have appeared only sporadically in recent years. Non-native fishes currently found in Barton Springs Pool are the Redbreast Sunfish (*Lepomis auritus*) and the Rio Grande Cichlid (*Cichlasoma cyanogutatum*). A single non-native Asian Grass carp (*Ctenopharyngodon idella*) was introduced into Barton Springs Pool in the 1990s and was subsequently removed.

The community of aquatic invertebrates found in the Barton Springs complex includes *Hyalella azteca* amphipods, *Dugesia* sp. planarians, physid and planorbid snails, lymnaeid limpets, and larvae of chironomid midges, baetid and heptageniid mayfly larvae, *Helicopsyche* sp. caddisfly larvae, *Pterophila* sp. moth larvae, *Argia* and *Archilestes* odonate (damselfly) larvae, and *Psephenus* sp. beetles and larvae, and red crayfish (*Procambarus clarkii*) (Geismar and Herrington 2007). Of particular importance to *E. sosorum* is the abundance of planarians, amphipods, and chironomids, which make up the largest portion of their diet in the wild (Gillespie 2011). Periods of low salamander abundance are coincident with periods of low invertebrate abundances (Gillespie 2011). Abundances of these invertebrates vary temporally and are lower during low aquifer discharge. In addition, planarians, chironomids, and ephemeropterans also vary with season (Gillespie 2011).

Herpetofauna observed in and around Barton Springs includes several species of turtles, the Red Ear Slider (*Trachemys scripta*), Texas Cooter (*Pseudemys texana*), Texas Map Turtle (*Graptemys versa*), Eastern Box Turtle (*Terrapene Carolina*), Ornate Box Turtle (*Terrapene ornata*), Yellow Mud Turtle (*Kinosternon flavescens*), Easter Mud Turtle (*Kinosternon subrubrum*), Stinkpot (*Sternotherus ordoratus*), Common Snapping Turtle (*Chelydra serpentina*), and Spiny Softshell Turtle (*Apalone spinifera*).

Species of frogs that are common in the area include the Gulf Coast Toad (*Bufo valliceps*), Woodhouse's Toad (*Bufo woodhouseii*), Blanchard's Cricket Frog (*Acris crepitans*), Spotted Chorus Frog (*Pseudacrisclarkii*), the Southern Leopard Frog (*Rana sphenocephala*), and the Rio Grande Leopard Frog (*Rana berlandieri*). Other frog species known from Travis County include the Cliff Chirping Frog (*Eleutherodactylus marnockii*), Texas Toad (*Bufo speciosus*), Green Toad (*Bufo debilis*), Red Spotted Toad (*Bufo punctatus*), Barking Frog (*Eleutherodactylus augusti*), Cope's Gray Treefrog (*Hyla chrysoscelis*), Green Treefrog (*Hyla cinerea*), Gray Treefrog (*Hyla versicolor*), Strecker's Chorus Frog (*Pseudacris streckeri*), Southeastern Chorus Frog (*Pseudacris feriarum*), Eastern Narrow-mouthed Toad (*Gastrophryne carolinensis*), Great Plains Narrow-mouthed Toad (*Gastrophryne olivacea*), American Bullfrog (*Rana catesbeiana*), and Couch's Spadefoot Toad (*Scaphiopus couchii*),

The Western Slimy Salamander (*Plethodon albagula*) may be found within Zilker Park. Other non-neotenic species known from Travis County are the Smallmouth Salamander (*Ambystoma texanum*) and the Marbled Salamander (*Ambystoma opacum*).

Lizard species observed in and around Zilker Park are the Texas Spiny Lizard (*Sceloporus olivaceous*), Green Anole (*Anolis carolinensis*), Texas Alligator Lizard (*Gerrhonotus infernalis*), Ground Skink (*Scincella lateralis*), Ornate Tree Lizard (*Urosaurus ornatus*), Greater Earless Lizard (*Cophosaurus texanus*), and non-native Mediterranean Gecko (*Hemidactylus turcicus*). Other species known from Travis County include Six-lined Racerunner (*Aspidoscelis sexlineata*), Eastern Spotted Whiptail (*Aspidoscelis gularis*), Slender Glass Lizard (*Ophisaurus attenuatus*), Eastern Collared Lizard (*Crotaphytus collaris*), Spot-tailed Earless Lizard (*Holbrookia lacerata*), Texas Horned Lizard (*Phrynosoma cornutum*), Prairie Lizard (*Sceloporus undulatus*), Great Plains Skink (*Plestiodon obsoletus*), and Four-lined Skink (*Plestiodon tetragrammus*).

Snake species observed around Barton Springs include the Coral Snake (*Micrurus fulvius tener*), Eastern Hognose Snake (*Heterodon platirhinos*), Eastern Rat Snake (*Pantherophis obsoletus*), Checkered Garter Snake (*Thamnophis marcianus*), Western Ribbon Snake (*Thamnophis proximus*), and Diamond-backed Water Snake (*Nerodia rhombifer*). Other snake species known from Travis County include Glossy Snake (*Arizona elegans*), Eastern Racer (*Coluber constrictor*), Ringneck Snake (*Diadophis punctatus*), Chihuahuan Night Snake (*Hypsiglena jani*), Prairie Kingsnake (*Lampropeltis calligaster*), Common Kingsnake (*Lampropeltis getula*), Milksnake (*Lampropeltis triangulum*), Coachwhip (*Masticophis flagellum*), Striped Whipsnake (*Masticophis taeniatus*), Blotched Water Snake (*Nerodia erythrogaster*), Broad-banded Water Snake (*Nerodia fasciata*), Rough Green Snake (*Opheodrys aestivus*), Great Plains Rat Snake (*Pantherophis emoryi*), Gopher Snake (*Pituophis catenifer*), Texas Longnose (*Rhinocheilus lecontei*), Texas Patchnose Snake (*Salvadora grahamiae*), Ground Snake (*Sonora semiannulata*), DeKay's Brown Snake (*Storeria dekayi*), Flathead Snake (*Tantilla gracilis*), Plains Blackhead Snake (*Tantilla nigriceps*), Blackneck Garter Snake (*Thamnophis cyrtopsis*), Copperhead (*Agkistrodon contortrix*), Cottonmouth (*Agkistrodon piscivorus*), Western Diamondback Rattlesnake (*Crotalus atrox*), Blacktail Rattlesnake (*Crotalus molossus*) and Texas Blind Snake (*Leptotyphlops dulcis*).

The ranges of a large number of birds include the Barton Springs area. Native bird species commonly seen around the springs in recent years include the Belted Kingfisher, Gadwal, Coot, Mallard, Green-backed Heron, Great Blue Heron, White-crowned Night Heron, Cattle

Egret, Snowy Egret, Redtail Hawk, Red-shouldered Hawk, Barred Owl , Spotted Sandpiper, Killdeer, Yellow Warbler, Golden-fronted Woodpecker, Mourning Dove, White-winged Dove, and Great-tailed Grackle. Non-native house sparrows, starlings, and rock doves are abundant in the manicured areas of the park.

Over 100 taxa of macroinvertebrates have been documented as present in the springs (Geismar and Herrington 2007, City of Austin unpublished data). Non-insect invertebrates include aquatic earthworms, triclad flatworms of the genus *Dugesia,* glossiphoniid leeches, water mites, hydra, and crustaceans, including crayfish (*Procambarus clarkii),* ostracods, copepods, the amphipod *Hyalella azteca,* as well as three species of subterranean blind amphipods (*Stygobromus* sp.), and one species of blind isopod, *Lirceolus hardeni.* These subterranean invertebrates are rarely found at the surface. Gastropods (snails and limpets) documented in the springs are members of Physidae, Lymnaeidae, Planorbidae, Pleuroceridae, Ancylidae, and Hydrobiidae. Shells of the non-native Asian clam, (*Corbicula fluminea*) have been found in Parthenia Spring; live non-native snails (*Melanoides tuberculata*) found in Old Mill Spring were removed. *Stygopyrgus bartonensis*, a small, aquatic hydrobiid snail, was described based on an empty shell collected from Eliza Spring (Herschler and Longley 1986) although no additional specimens have been collected from Barton Springs. Representatives of at least 10 groups of aquatic insects have been observed in the springs: eight genera of ephemeropteran larvae (mayflies), 14 genera of trichopteran larvae (caddisflies), 18 genera of beetles, 5 families of odonates (dragonflies and damselflies), one genus of plecopteran larvae (stonefly), one lepidopteran (aquatic moths), 3 dipteran larvae (flies), 6 hemipterans, 1 megalopteran (alderflies), and 1 collembolan (springtails). Water pennies, amphipods, and chironomid larvae are nearly always present. Many of the taxa are commonly categorized as intolerant of pollution (TCEQ 2007b), suggesting that water quality of Barton Springs is generally good. Abundance of individuals within each taxon varies among spring sites and with aquifer discharge conditions. Abundance decreases as aquifer discharge decreases and some taxa disappear regardless of season (e.g., limpets, planarians, caddisfly larvae, baetid and heptageniid mayfly larvae).

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Human Activities Affecting Habitat at the Barton Springs Complex

The history of human activity near Barton Springs dates back at least 10,000 years based on numerous archaeological sites located near the perennial springs (Voellinger 1993, Nickels et al. 2010). The earliest known human inhabitants of Central Texas were small bands of Native Americans. In 1730, the establishment of a Spanish mission near Barton Springs marked the beginning of European settlement around Barton Springs. Detailed description of human history in Austin and around Barton Springs is presented by Limbacher and Godfrey Architects (2008). Presented below is a history of modifications of Barton Springs and is derived from Limbacher and Godfrey Architects (2008) and the Austin History Center archives.

Commercial use of Barton's springs began in 1839 with the construction of a sawmill on Barton Creek (Figure 11). At least two additional mills were built in the 1870s, one on the south bank of Barton Creek downstream of Parthenia Spring and another further downstream on Old Mill Spring (Figure 9). The sawmill was accompanied by erection of a wooden timber dam across Barton Creek (Austin History Center photos C00077-A, PICA 00975), which would be washed out during floods and subsequently rebuilt. The dam across Old Mill Spring was constructed of stone with wooden gates to control water outflow (Austin History Center C03293, PICA 000976, PICA 00986). Eliza Spring was apparently unaltered until the early 1900s (Austin History Center PICA 00987b), when Andrew Zilker constructed a concrete amphitheater around the spring pool (Figure 10) to be used as a meeting place for the Benevolent and Protective Order of Elks, Austin Lodge #201 (AHC PICA 28447, PICA 00971). In 1917, Mr. Zilker negotiated transfer of his land to the City of Austin for use as a public park. Zilker Park had been created and recreational use of the springs had begun.

Zilker Park and Barton Springs became destinations for swimming and camping, and provided drinking water during the drought of 1917. Swimming was facilitated by the annual erection of temporary rock dams across Barton Creek deepening the water (Austin History Center photo C01803), and the construction of concrete retention walls and stairways on the slopes leading to the water (Austin History Center C01818b, PICA 30171). Development of Zilker Park and Barton Springs into a formal recreation destination proceeded throughout the late 1920s and 1930s. Two permanent dams were constructed across Barton Creek upstream and downstream of Parthenia Spring (Figure 11; Austin History Center PICA 22642), creating a deep-water swimming area dubbed Barton Springs Pool. The channel downstream of Barton Springs Pool was reconfigured to place the deepest area in the middle of the new dam. The creek channel within Barton Springs Pool was widened and deepened in some areas, and uneven substrate was leveled. The natural creek banks were replaced with concrete walls, and topped with sidewalks. A flat, shallow stretch of substrate along the northwestern wall of the Pool was created to provide a beach area of "waist-deep" water for "non-expert" swimmers (Austin American Statesman September 23, 1929). A two-story bathhouse and concession stand were also constructed on the north side of the Pool (Austin History Center C01825). Finally, the outflow stream from Eliza Spring was confined to a buried concrete pipe that opened into Barton Springs Pool.

Old Mill Spring escaped further modification until 1937, when the National Youth Administration built a four-tiered amphitheater around the spring (Austin History Center PICA 20233). The innermost wall was built on top of the remains of the mill's stonework walls and across the outflow stream channel, creating a dammed, deep, swimming pool. Much of the outflow stream was diverted to a buried, underground pipe although some water flowed through small spillways to a redirected surface stream.

Prior to the mid-1940s, waters of upper Barton Creek flowed through openings in the upstream dam of Barton Springs Pool (Austin History Center PICA 01033), mingling with ground water emanating from the springs. After the large flood of 1943, a bypass system was added to Barton Springs Pool to divert floodwater into an underground concrete pipe that carried water beneath the Pool through the downstream dam into lower Barton Creek (Austin History Center PICA 20222, 20224). Sometimes during the 1950s, small concrete walls and a concrete floor were built in the shallow end to create a children's wading area separate from the rest of the Pool. Concrete was poured into large fissures of Parthenia Spring and depressions in the natural limestone substrate to create level surfaces. A concrete floor approximately one foot thick was poured on top of the natural substrate of Eliza Spring, leaving limited openings as conduits from the underground spring to the surface. The land surrounding the amphitheater was raised several feet with the addition of sand, soil, and gravel, and the height of the amphitheater walls was increased.

From 1974 to 1976, a second floodwater bypass system was built in response to lost revenue from Pool closure during flooding and concern over potential pollution of floodwater from urban development (Barton Springs Bypass Preliminary Report 1973). This system consists of a box culvert built beneath the northwestern sidewalk of the Pool extending from the upstream to the downstream dam capable of transmitting approximately 500 ft^3/s of water. The openings in the upstream dam were plugged with concrete to prevent entry of creek water into the Pool during floods, which also prevents entry of creek water during baseflow. Two spillways were added to the downstream dam. The outflow pipe from Eliza Spring was routed into the bypass culvert rather than into the Pool.

Additional modification of Barton Springs Pool occurred as part of the first Habitat Conservation Plan issued for *E. sosorum* in 1998. Plates over the openings of the downstream dam were replaced with adjustable gates, and substrate of the beach area was removed to lower its elevation. Ramps to and into the Pool were added to provide accessibility for disabled individuals. In Old Mill Spring, the buried outflow pipe was plugged to divert more water to the surface stream.

APPENDIX D

Observed Relationships Among Barton Springs Discharge, Water Chemistry, and Salamander Abundance – 2004

City of Austin Scientific Report 04-06, Turner, 2004

Watershed Protection
Development Review

Some Water Quality Threats to the Barton Springs Salamander at Low Flows

by Martha A. Turner, P.E.
Water Resource Evaluation Section
Environmental Resource Management Division

Abstract

An evaluation of salamander counts, spring flowrates, and dissolved oxygen concentrations was completed to recommend a pumping limit for sustainable yield to the Barton Springs Edwards Aquifer Conservation District. The primary purpose of the evaluation was to find correlations between flow, dissolved oxygen, and surface count data of the endangered Barton Springs salamander. If such correlation were significant, it would provide the statistical basis for setting thresholds for Barton Springs flows related to a water quality parameter commonly used in aquatic life support. In addition, this parameter was shown to be decreasing in baseflow spring water quality data (Turner, 2000). The relevance of dissolved oxygen levels to maintenance of this aquatic endangered species is also evaluated. It was determined that salamander counts decline when dissolved oxygen (DO) concentrations fall below 5 mg/L and when flow from Barton Springs falls below 30 cfs. Flows equal to or below the drought of record low flow of 10 cfs were found to be potentially harmful to the Barton Springs salamander. Dissolved oxygen levels at the same flow rates could be lower than they were in the 1950s during the drought of record in the 1950's.

Introduction

Droughts are a normal part of Central Texas weather cycles and will recur periodically in the future, causing hydrological responses in water table elevations and spring discharges. The drought of record occurred during the 1950’s with a minimum discharge of 9.6 cubic feet per second (cfs) from Barton Springs. Droughts since 1990 have resulted in spring discharges of between 15 and 20 cfs several times between January and December 1990, as low as 17 cfs in August 1996, and between 18 and 20 cfs from April through September 2000.

Current permitted and non-regulated pumping from the BSEA (Barton Springs Edwards Aquifer) is equivalent to approximately 10.5 cfs, approximately 10 cfs from permitted wells and approximately 0.5 cfs from exempt wells (private domestic or livestock wells incapable of pumping greater than 10,000 gallons per day). During a drought equivalent to the drought of record (minimum discharge of 9.6 cfs with pumpage of 0.66 cfs), the BSEACD anticipates that a low flow of 3 cfs from Barton Springs will still be available. However, this flow depends on achieving a 30% reduction in pumping through conservation measures.

The impact of this low flow on the Barton Springs salamander is uncertain. Extrapolating from the historical dissolved oxygen (DO) to flow relationships, and using available laboratory testing on similar salamanders, significant Barton Springs salamander mortality could be expected at this flow.

The historical relationship between flow, dissolved oxygen and salamander abundance is discussed below. The emphasis in the discussion will be on Barton Springs, but consequences of low flow, such as anoxic sediment and loss of habitat in Upper Barton, Eliza and Old Mill Springs will also be presented. Effects of other water quality problems at low flow were also noted although detailed evaluation of these parameters has not been completed.

Dissolved Oxygen and Barton Springs Discharge

The relationship between flow and DO at Barton Springs can be observed in the plots of data from the summers of 1996 and 2000. The average concentration of DO during the non-drought period 1997-1999 was 6.5 mg/L. During the droughts of 1996 and 2000 the DO dropped below 5 mg/L, and the low DO corresponded to periods of low spring flow. The Texas Commission on Environmental Quality has designated Barton Springs Pool as a high aquatic life use water body and therefore, to meet the Texas Surface Water Quality Standards, average DO should be greater than 5 mg/L with minimum DO of no less than 3 mg/L for the protection of aquatic life. (30 TAC 307.9).

Figure 1
Dissolved Oxygen and Flow at Barton Springs during the 1996 Drought

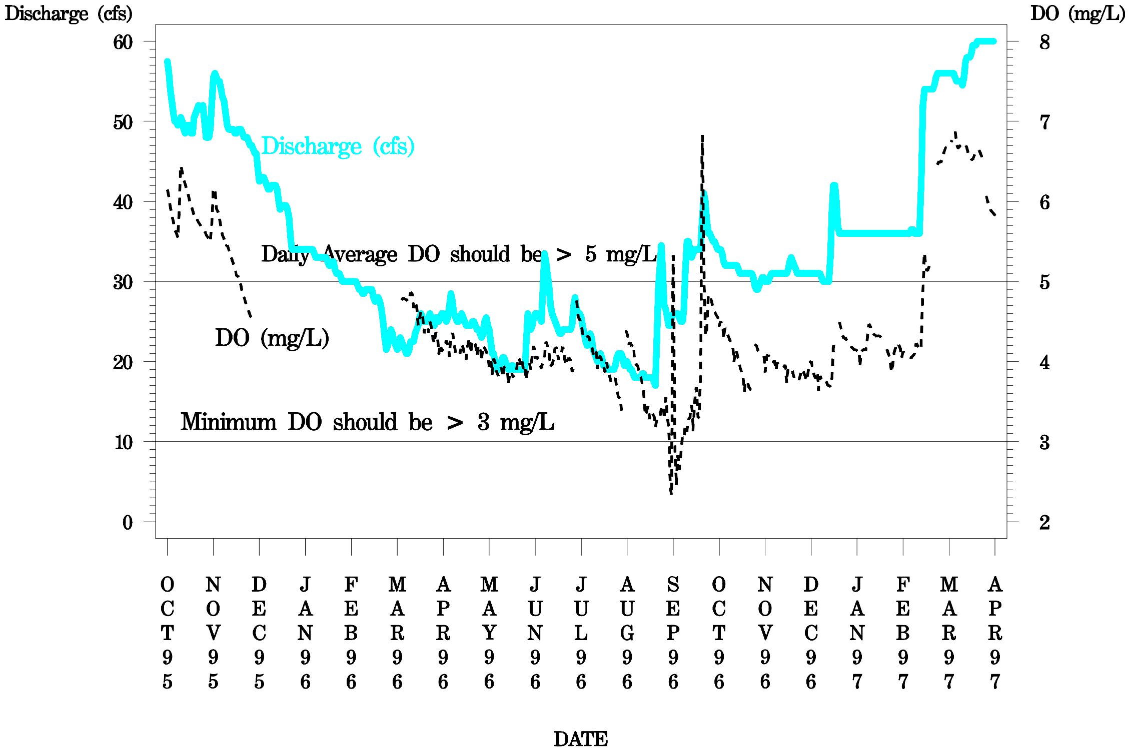
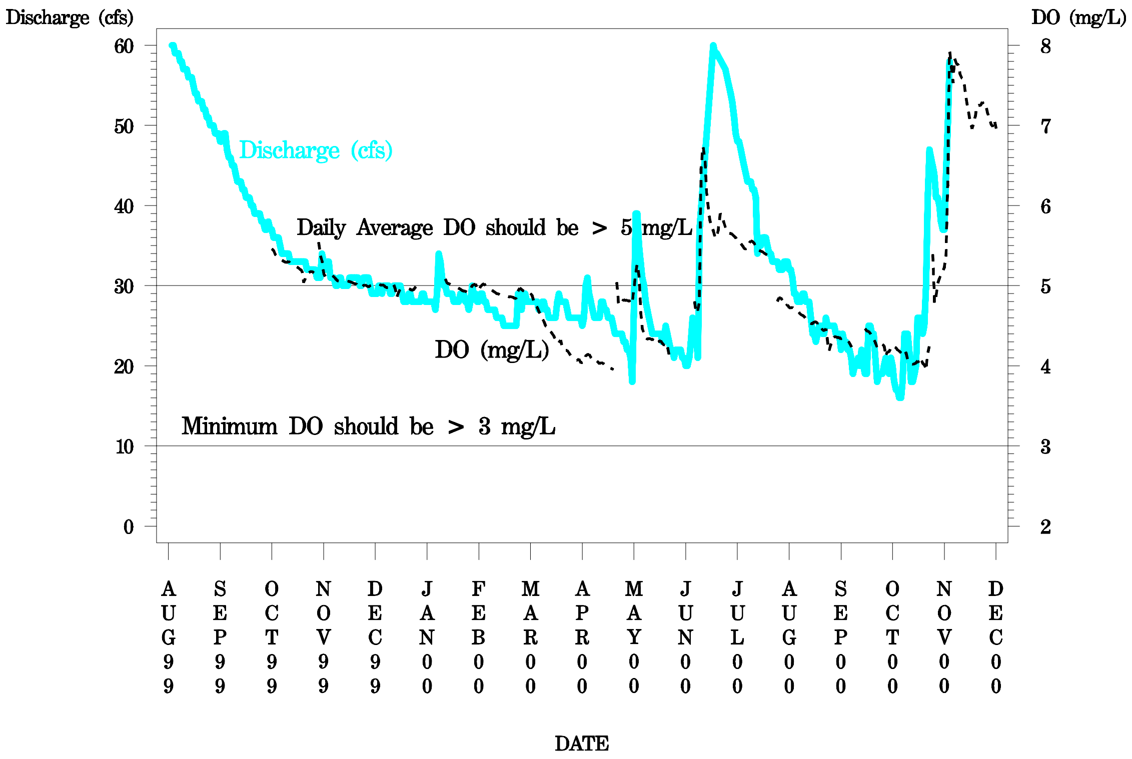


Figure 2
Dissolved Oxygen and Flow at Barton Springs during the 2000 Drought



The plotted relationship of flow to DO is confirmed by statistical analysis on both grab samples and data from Datasonde water quality probe data-loggers from 1993 through 2003. The best model of the data is a logarithmic, rather than a linear, relationship and a relatively good correlation is found or this model with R^2 values of 0.65 for the grab samples and 0.75 for the time series Datasonde data (Figures 3 and 4).

While the average DO levels are below 5 mg/L at drought flows, it has been suggested that the Barton Springs salamander can tolerate low DO concentrations because the salamander population survived the drought of the 1950's. Whereas tolerance of similar salamander species to low DO has been measured (Norris et al., 1963), the ability of the Barton Springs salamander to tolerate low DO has not been tested. However it should be noted that dissolved oxygen levels decreased by approximately 1 mg/L during the period from 1975through 2000 (Figure 5). This decline is statistically significant [Pr>F < 0.0001, R^2=0.59] (Turner, 2000). When increased pumping leads to decreased flow, the resulting dissolved oxygen levels will be lower than during the drought of the 1950's due to the decrease in oxygen levels over time. The resultant levels could be lower than the salamander requires for survival and reproduction. Table 1 shows the predicted mean dissolved oxygen for several flow levels based on the regression equation from Figure 4. No data were available below 17 cfs of discharge; therefore, the level of confidence in the predicted DO values for 14, 8, and 5 cfs is less than confidence levels at higher flows.

Figure 3
DO Data and Fitted Regression Line for 1993-2003 Grab Samples, Including an Estimate of the Average DO Levels in the 1950's.

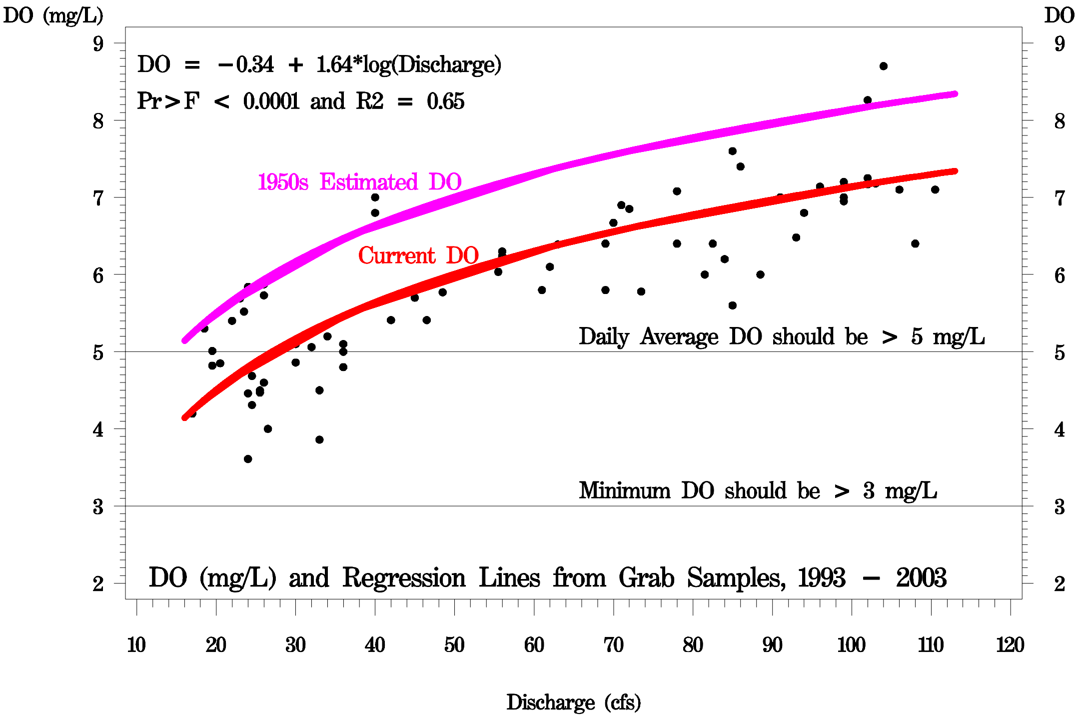


Figure 4
DO Data and Fitted Regression Line for 1993-2003 Datasonde Measurements, Including an Estimate of the Average DO Levels in the 1950's.

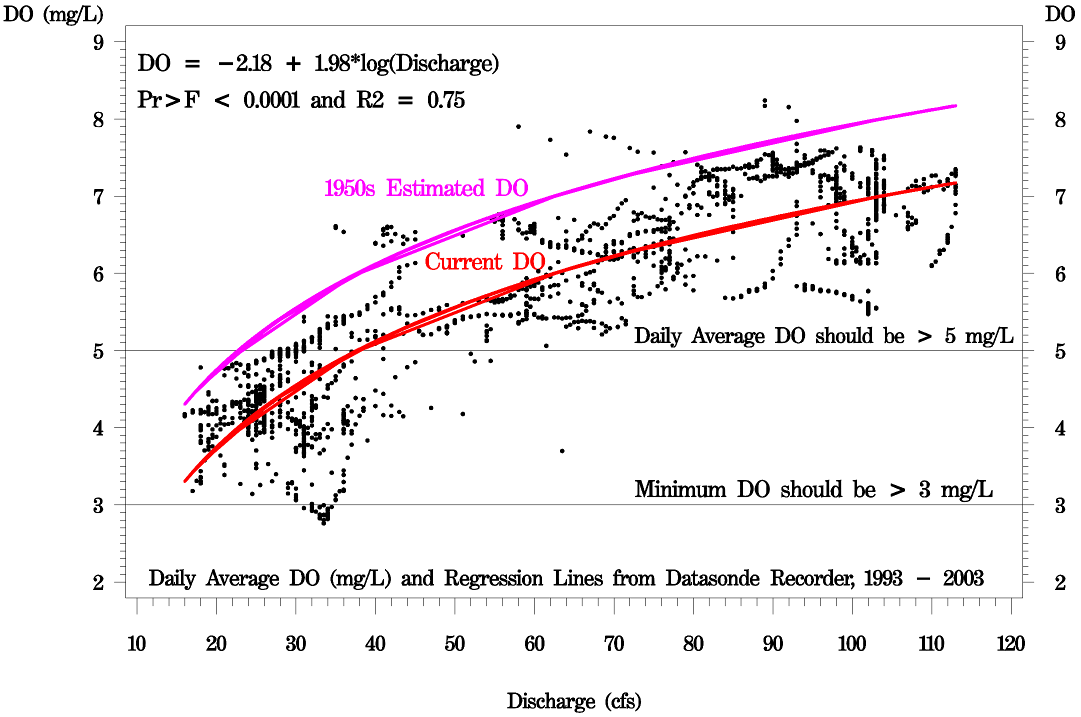
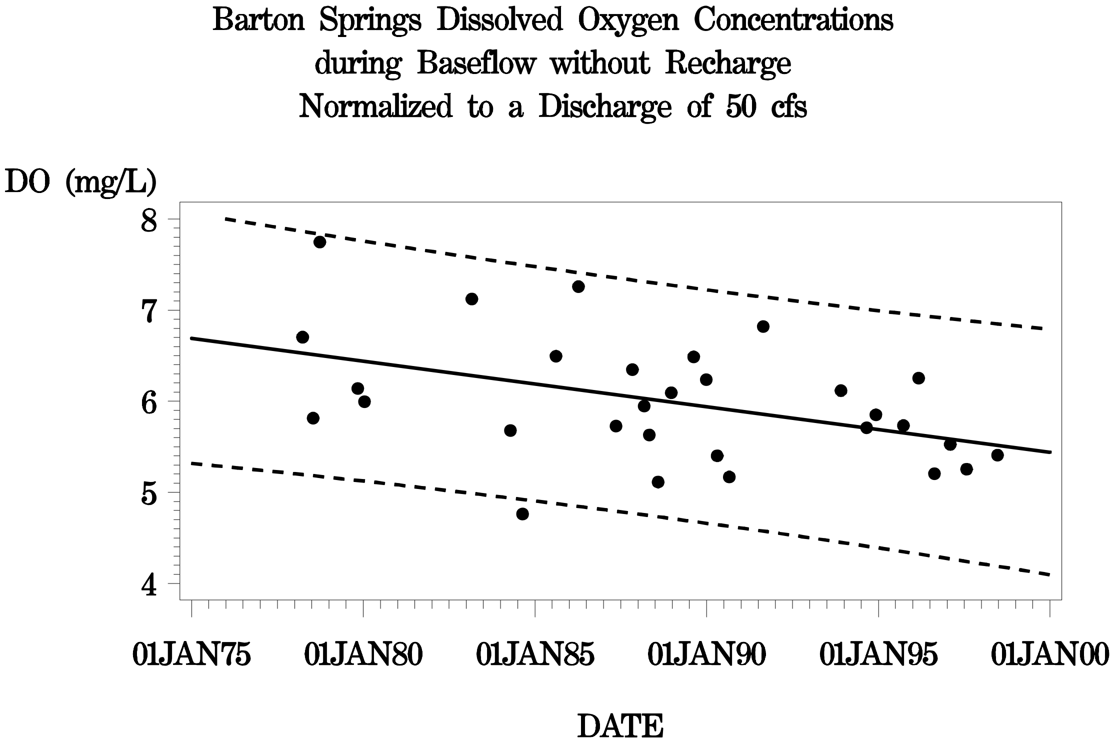


Table 1
Predicted Dissolved Oxygen for 5 Discharge Levels where DO = -2.18 + 1.98* $\log_e$(Discharge)

Discharge at Barton springs (cfs)	Predicted Dissolved Oxygen (mg/L)
38	5
23	4
14	3
8	2
5	1

Figure 5
Decrease of Dissolved Oxygen by 1 mg/L in Barton Springs since 1975.



Dissolved Oxygen and Salamander Counts at Barton Springs

Although the relationship between flow and DO is straightforward, the relationship between DO levels and salamander counts in Barton Springs Pool is more complicated. There appears to be a lag of about 6 months from periods of low DO to periods of low salamander counts. The linear relationship between salamander abundance and the DO measurements 6 months earlier is significant (Figure 6). While the regression is significant, the data may be better explained by a threshold model (Figure 7). Dissolved oxygen levels below 5 mg/L correspond to salamander counts of less than 20 individuals 6 months later. If DO levels are greater than 5 mg/L then the counts vary from 6 to over 80 individuals 6 months later, with most of the counts greater than 10 individuals. This variability is also dependent on other factors not captured in these simple comparisons.

Figure 8 shows the relationship between DO and mean salamander abundance 6 months later. Flow levels specified on the graph are from Table 1, and are intended to give a simple estimate of the expected range of flows for low DO levels. The data show a steady increase in mean number of salamanders as DO levels 6 months earlier increase. A possible reason for the lagged relationship is that when DO is low, reproduction falls off (Duellman and Trueb, 1986, Pianka, 1983), and the effects of decreased reproduction are not apparent until several months later. The percent of small salamanders in the total salamander count is the lowest for DO between 3 and 4 mg/L. This may support the hypothesis of decreases in reproduction when the adult salamanders are stressed by low DO levels, or it may be that juvenile salamanders are more sensitive to the low DO levels.

Figure 6
Relationship Between Dissolved Oxygen Levels and Barton Springs Salamander Abundance 6 Months Later

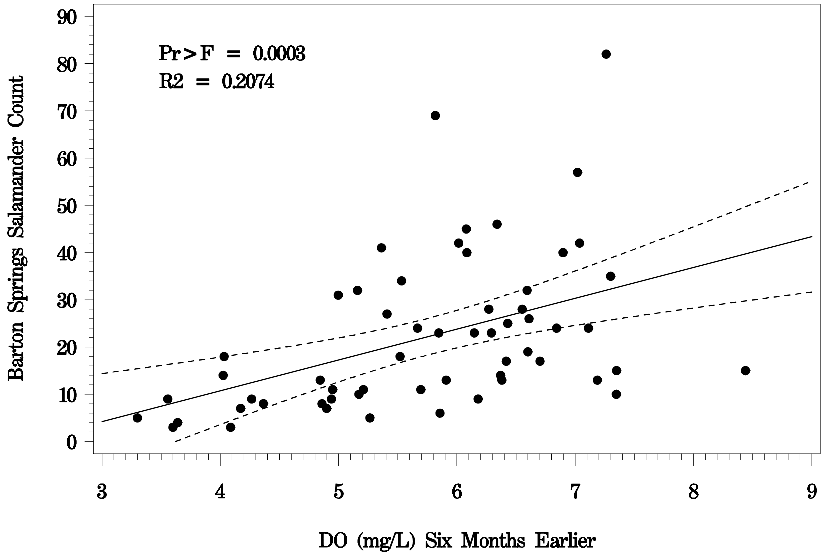


Figure7
Dissolved Oxygen Levels and Barton Springs Salamander Abundance 6 Months Later

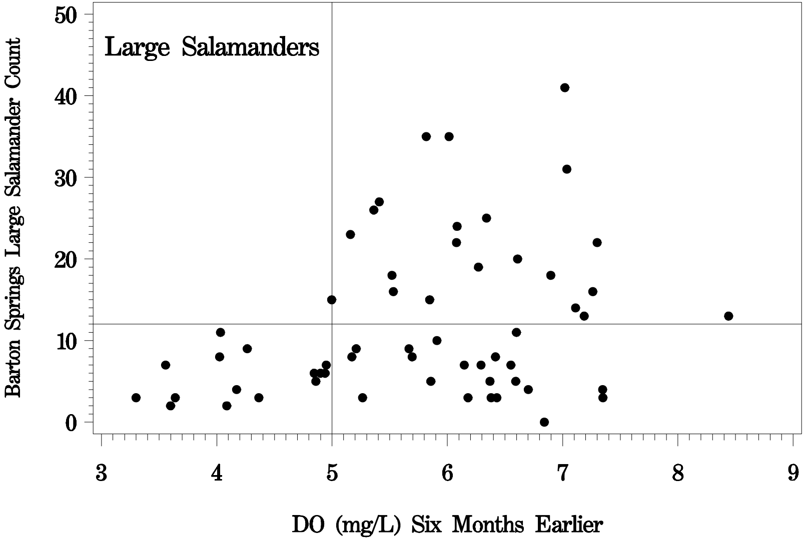


Figure 7 (continued)

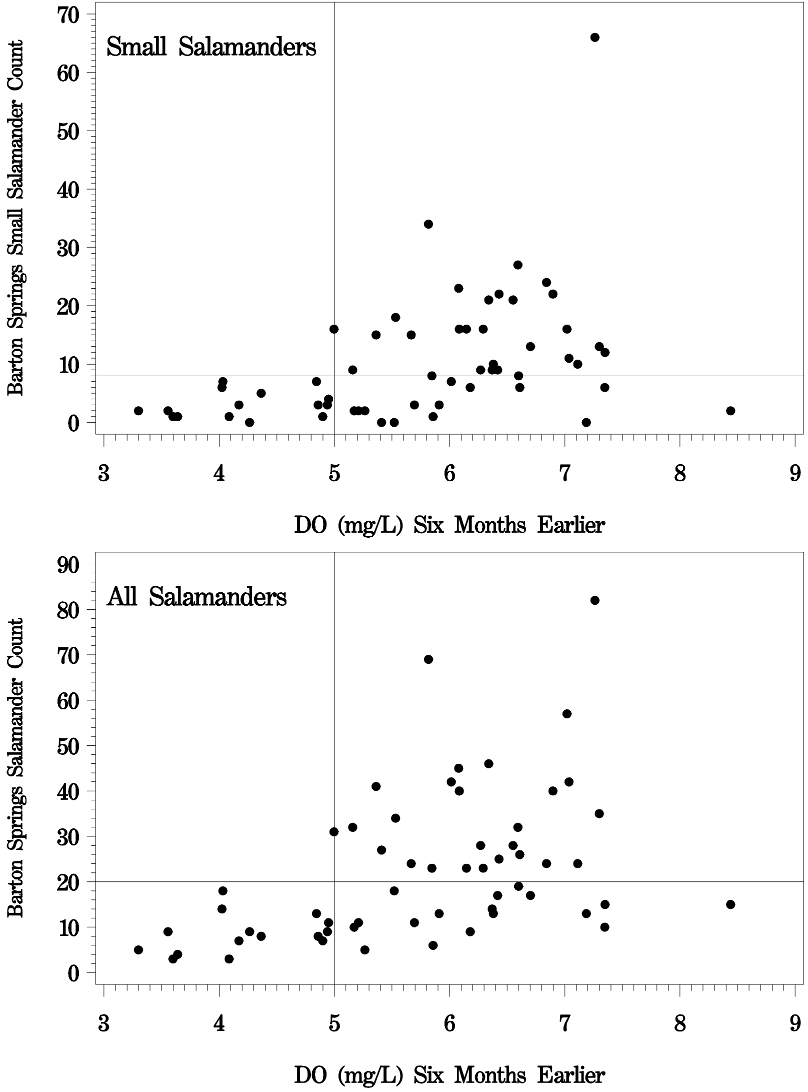
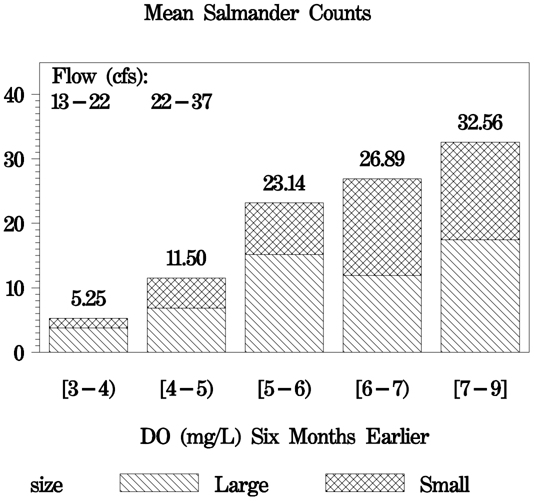


Figure 8

Grouped Dissolved Oxygen Levels and Mean Barton Springs Salamander Counts 6 Months Later



Salamander Counts during Low Flow Conditions at Eliza, Old Mill and Upper Barton Springs

Plots of water flow at Barton Springs and salamander counts at Eliza, Old Mill and Upper Barton Springs suggest a strong relationship (Figure 9). Flows below approximately 30 cfs at Barton Springs are associated with low counts at the smaller springs, which sometimes are completely or partially dry. This loss of habitat may be a serious threat to the salamander. Dissolved oxygen data from these springs are insufficient to allow direct comparisons of salamander counts to DO levels. However, anoxic sediment was observed at Eliza Spring during a low flow period. Table 2 shows apparent threshold flows below which counts are substantially lower than normal for these three springs and for Main (Parthenia) Barton Springs as well.

While it is clear that salamander counts drop at these three springs during low flow conditions it is unknown if the salamanders die, remain in the springs below where counted, or migrate to the main Barton Springs where stronger flow is present. DNA analysis currently underway may be able to answer this question by determining the genetic similarity of the populations among the springs.

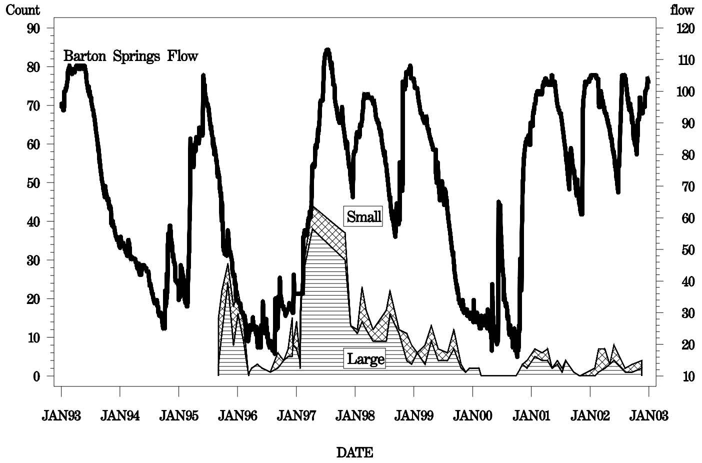
Regardless of responses at the smaller springs, the counts at the main Barton Spring also drop under low flow conditions. Therefore, the ability to migrate may not be enough to prevent major loss of salamanders during low flow conditions.

Table 2
Threshold Flows Below Which Salamander Counts are Low

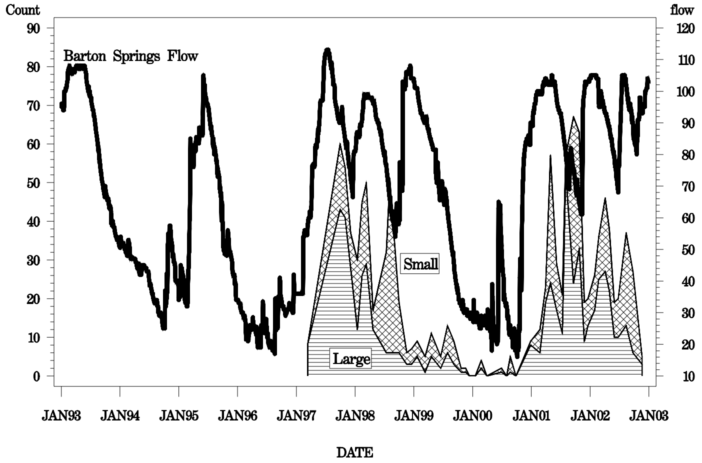
Spring	Threshold Flow	Maximum Number of Large Salamanders at flows below the threshold flow	Maximum Number of Small Salamanders at flows below the threshold flow	Number of Samples (1996-2002)	Comments	Maximum Number of Large Salamanders at all flows	Maximum Number of Small Salamanders at all flows
Eliza	<= 25 cfs	3	0	8		38	13
Old Mill	<=33 cfs	2	4	9	No samples at 34-45 cfs.	53	45
Upper Barton	40 cfs	0	0	0	Completely dry when Barton Springs is at 40 cfs.	14	4
	Threshold Flow 6 Months Earlier						
Barton	<30	11	7	17		41	66

Figure 9
Large and Small Salamander Counts at Eliza, Old Mill, and Upper Barton Springs and Barton Springs Flow vs. Time

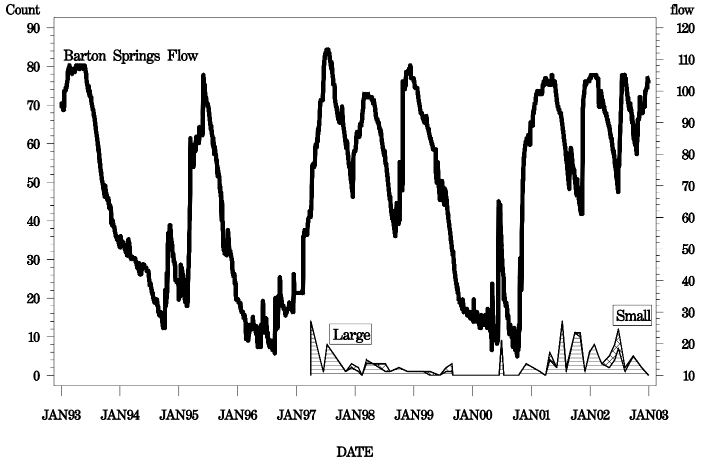
Eliza Spring



Old Mill Spring



Upper Barton Spring



Other Potential Water Quality Problems at Low Flows

Concentrations of sodium, chloride, sulfate and nitrogen increase when spring flows drop below 40 cfs and have been observed to double during recent droughts (David Johns, COA, in press). Increases in dissolved sodium and chloride generally represent leakage from the Saline or "Bad-Water" Zone, whereas increases in sulfate and strontium are generally attributed to greater leakage from the underlying Trinity aquifer (Senger and Kreitler, 1984). Aerated water from a bad water zone well has been shown to be toxic to *Eurycea nana* (San Marcos salamander), a surrogate for the Barton Springs salamander (COA 1999). The No Observed Effect Concentration (NOEC) for *Eurycea nana* was observed to be less than 6.25% of the aerated bad water zone well water. It is unknown at what flow level these water quality constituents may pose a threat to the Barton Springs salamander.

If flow levels drop significantly, water temperatures in the pool as a whole will also increase. A preliminary heat budget analysis of Barton Springs Pool, using the BSEACD proposed minimum flow of 3 cfs, shows that the pool water temperatures would increase to 25 degrees C. This is assuming no increase in the water temperature entering the pool at the spring. This temperature level may not threaten the salamanders if they are concentrated in areas where the spring flow is strong. However, temperatures any higher than 25 degrees C could be a concern due to the relationship between temperature and salamander heat tolerance, oxygen consumption, and metabolism. (Berkhouse and Fries, 1995; Feder 1978; Norris, 1963; Whitford, 1973)

Conclusions

The following conclusions were developed from the analyses discussed above:

- DO levels during future droughts will be worse than DO levels during equivalent flow periods in the past.
- DO of 5 mg/L is an apparent threshold below which salamander abundance declines.
- Flows of less than 30 cfs result in an average DO less than 5 mg/L.
- The predicted DO level of < 1 mg/L at the BSEACD-assumed low flow of 3 cfs during a drought as severe as the drought of record (1950's) could result in significant salamander mortality.
- Apparent threshold flows for Barton, Eliza, Old Mill, and Upper Barton are 30, 25, 33, and 40 cfs, respectively, below which salamander abundance declines.
- Extended periods of flow below recent drought levels (approximately 20 cfs) could result in declines in water quality could harm the Barton Springs salamander.

Recommendations

- Testing should be done to determine the sensitivity of the salamander *Eurycea nana* to low levels of dissolved oxygen
- Permitted pumpage from the aquifer is already at levels that could be detrimental to the Barton Springs salamander during critical conditions; therefore, future expansion of existing permits or approval of new permits is not recommended.
- Monitoring and periodic reassessment of both water quality trends and salamander counts is warranted annually.
- Strategies to address the decline in flow and dissolved oxygen should be formulated in both the Barton Springs Regional Water Quality Protection Plan and the Habitat Conservation Plan for the Barton Springs Salamander.

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APPENDIX E

User Conservation Plans and User Drought Contingency Plans

Specifications to Permittees as Integral Part of Production Permits (2013)

Appendix E
User Conservation Plans and User Drought Contingency Plans

The District encourages water conservation practices at all times and therefore a User Conservation Plan (UCP) is an integral part of each permit that outlines a commitment to implement certain conservation measures and practices. When the District is in a condition of No Drought, permittees operate under normal conditions, in accordance with their User Conservation Plan. The UCP of each permit is updated upon permit renewal no less than every five years. The UCP is guided by District Rule 3-6.3.

Contents of a UCP shall consider as a minimum:

- Implementation of a conservation-oriented rate structure,
- Promotion and encouragement of voluntary conservation measures,
- Promotion and encouragement, installation, and use of water saving devices,
- Promotion and encouragement of water efficient landscape practices,
- Financial measures that encourage conservation,
- Distribution of conservation information and other educational efforts, and
- Provision for ordinances, regulations or contractual requirements necessary for the permittee to enforce the UCP.

The District has developed and utilizes formatted UCP templates for the different types of water use categories. The actions described in Table E.1 are incorporated into the UCP templates of Commercial, Industrial, Agricultural and Public Water Supply permittees. The actions described in Table E.2 are specific to certain types of permittees.

Table E.1

User Conservation Plan - General Actions

Administrative Actions:

- Notify all employees of UCP.
- Post signs at all faucets, sinks, outdoor spigots, and other water sources reminding employees to use water wisely.
- During staff meetings and when appropriate, suggest ways for employees to reduce water consumption in order to promote and encourage voluntary conservation measures.
- Require employees to report all faulty fixtures or leaks to maintenance for repair.
- Assist District in the distribution of conservation and educational materials to employees and customers.
- Periodically review and evaluate this conservation plan and implement revisions to the plan as necessary.
- Develop policies to monitor, mediate and enforce compliance with this UCP.
- Promote and encourage voluntary conservation measures to employees and customers.

Operational Actions (Indoor& Outdoor):

- Implement an on-going program of system leak detection and repair which shall include the consideration and utilization of improved technology when possible.
- Require low flow/low volume fixtures to be installed in all new construction.
- When replacing old fixtures, do so with low flow/low volume products.
- Promote and utilize water-efficient landscape practices including Xeriscaping®, drip irrigation, and automatic sprinkler systems.

- Adopt a five-day watering schedule during the summer irrigation season. This may be based on a municipal or area-wide published calendar related to street addresses.
- Investigate and promote water reuse and recycling, especially the feasibility of its inclusion in water reuse systems on new construction.

Table E.2

User Conservation Plan - Specific Actions
<u>Specific to Public Water Supply Permittees</u> *For Customers* o Promote and encourage installation and use of water saving plumbing fixtures in existing homes. Promotion will take place through information mail outs and/or distribution of water saving devices. o Promote the replacement of water-using appliances with more water-efficient varieties. Promotion will take place through mail outs and creation of incentive programs. o Promote customer household leak detection and repair. o Implement a five day watering schedule during the summer irrigation season, based on street addresses of the customers. *For System Operations* o Cut off vacant houses, verify there are no leaks. o Monitor high usage customers and provide additional support and encouragement to promote efficient and effective use and application of water by those customers to reduce wasteful practices. o Limit flushing of dead-end mains and fire hydrants. • Dead-end mains—drain only as needed to prevent stale water and/or customer complaints. • Fire hydrants—open twice yearly to maintain proper operation. o Make application for a conservation-oriented rate structure in next rate case for consideration by the Texas Commission on Environmental Quality (TCEQ). o Require applicants for service from the permittee to comply with the permittee rules, plans, and regulations as approved by the District and the TCEQ. o Continue program of customer meter testing and meter replacement or repair. o Add backflow preventers on customer’s side of meter as service is required to those meters not presently equipped. *General* o Send a copy of the UCP and the UDCP to each customer. o Include drought stage and conservation information in customer billings.
<u>Specific to Domestic Use Permittees</u> o Replace faulty or unusable plumbing fixtures or appliances with water saving devices such as low-flow toilets, shower and faucet aerators, water-efficient dishwashers and clothes washers. o Choose and install water-efficient appliances and fixtures in new construction. o At least every six months check for leaks in toilets. o Repair dripping faucets and leaky plumbing promptly. o At least once each year, cease all water usage and check meter to determine if leaks exist in

underground transmission lines.
- Select vegetation from the list of appropriate native and naturalized plants compiled by the Lady Bird Johnson Wildflower Center when installing new or replacing landscape vegetation.
- Implement the five-day watering schedule promoted by the District based on street address and including watering restrictions for hose-end and underground irrigation systems.
- Wash vehicles using a hose-end sprayer with an automatic shut off or with buckets full of water and not allowing the water to continue to run from the hose when not in use.
- Use a cover on swimming pools when possible to minimize evaporative loss of water.
- When possible, consider alternative water supplies including but not limited to rainwater collection and alternative irrigation strategies including but not limited to drip irrigation to improve conservation of water on site.
- Maintain record of submitted meter readings as record for future determination of possible system leaks and to quantify success of conservation practices and steps for usage reduction during drought conditions.

Specific to Agricultural Permittees

- Investigate and implement efficient irrigation practices and utilization of alternate watering sources where possible.
- Follow a schedule of watering in morning and evening times.

A UDCP enables permittees to manage their water system and water resources during drought conditions in a conscientious, fair, and appropriate manner. Its intent is to facilitate the maintenance of an adequate supply of water in the Aquifer during the various stages of drought conditions that may occur from time to time. During drought, these efforts, if sufficiently effective, may delay the depletion of spring flows at Barton Springs and aquifer water levels until sufficient recharge is available to replenish the Aquifer.

The UDCP is guided by the Drought Contingency Plan of the District and must comply with the Drought Contingency Rules of the District, sections 3-7.5 and 3-7.6.

Contents of a UDCP shall consider as a minimum:

- A declaration of intent to comply with all District rules and permit conditions related to Drought and implement all the measures of the UDCP.
- Establishment of a permittee's baseline monthly permitted pumpage volume and target monthly pumpage volumes in accordance with mandatory reduction percentages of the two or three drought stages, as applicable, and the Emergency Response Period, if applicable.
- Voluntary compliance restrictions to achieve a 10% reduction goal during the Stage I Water Conservation Period.
- Demand reduction measures which may include prohibition of water waste, alternative and/or supplemental water supply sources, adjustment to water rates, and use of water saving devices,
- Additional demand reduction measures developed by the permittee which achieve reduction goal percentages associated with and specified by each drought stage.
- Financial measures which encourage compliance with the UDCP and UCP while maintaining financial stability of the permittee during drought stages.

- Provision for ordinances, regulations or contractual requirements necessary for the permittee to enforce the UDCP.
- Provisions for reporting pumpage.
- Special provisions for Class A,B, or C Conditional Production Permits as described in District Rule 3-7.5 A(9).

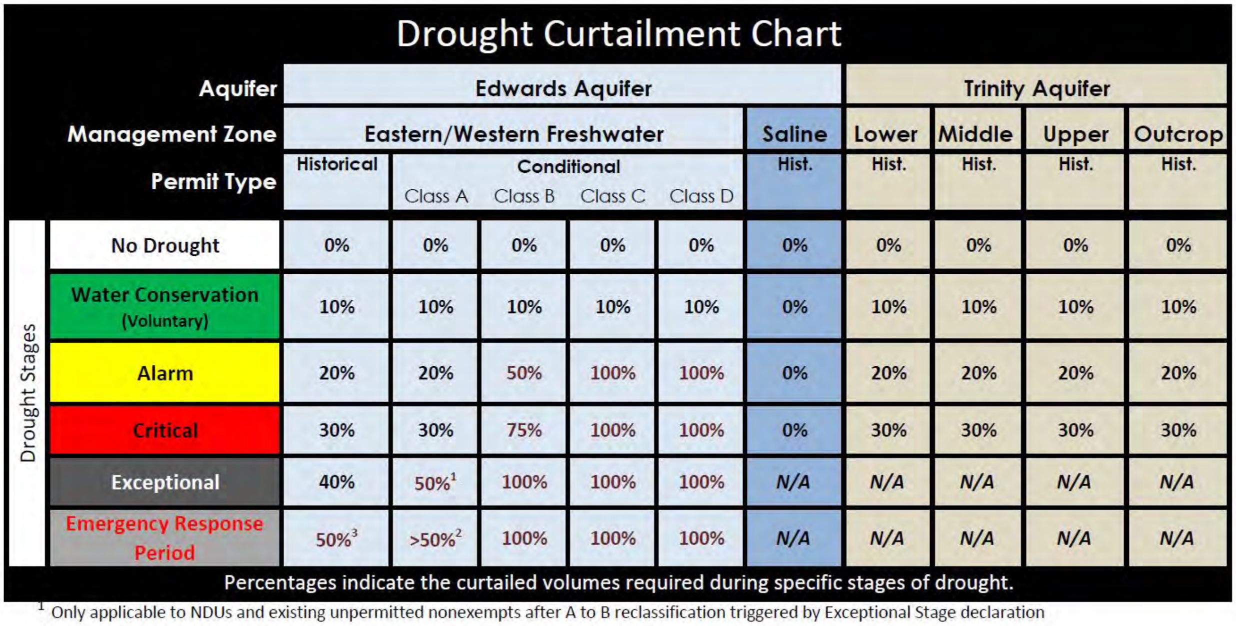
The District has developed and utilizes formatted UDCP templates for the different types of water use categories. Each UDCP will describe the permittee's Water Conservation Period and Drought Stage Responses.

For Example, the UDCP of a Public Water Supply permittee will include the following:

- Declaration of Policy, Purpose, and Intent
- Public Involvement
- Public Education
- Coordination with Regional Water Planning Groups
- Notice Requirements
- Enforcement Procedure & Plan Adoption
- Exemptions or Variances
- Drought Stage Triggers
- Alternate Water Source
- Water Conservation Period and Drought Stage Responses:

The key component of all UDCPs are the Drought Stage Responses. There are certain curtailments associated with each permit type and it is the responsibility of the Permittee to ensure that they implement the necessary actions or enforcement steps to reach those curtailments. Table E.3 shows the curtailments associated with various permit types.

Table E.3



Drought Curtailment Chart

	Aquifer	Edwards Aquifer						Trinity Aquifer			
	Management Zone	Eastern/Western Freshwater					Saline	Lower	Middle	Upper	Outcrop
	Permit Type	Historical	Conditional Class A	Class B	Class C	Class D	Hist.	Hist.	Hist.	Hist.	Hist.
Drought Stages	No Drought	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	Water Conservation (Voluntary)	10%	10%	10%	10%	10%	0%	10%	10%	10%	10%
	Alarm	20%	20%	50%	100%	100%	0%	20%	20%	20%	20%
	Critical	30%	30%	75%	100%	100%	0%	30%	30%	30%	30%
	Exceptional	40%	50%[1]	100%	100%	100%	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*
	Emergency Response Period	50%[3]	>50%[2]	100%	100%	100%	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*

Percentages indicate the curtailed volumes required during specific stages of drought.

[1] Only applicable to NDUs and existing unpermitted nonexempts after A to B reclassification triggered by Exceptional Stage declaration

[2] Curtailment > 50% subject to Board discretion

[3] ERP (50%) curtailments become effective October 11, 2015. ERP curtailments to be measured as rolling 90-day average after first three months of declared ERP.

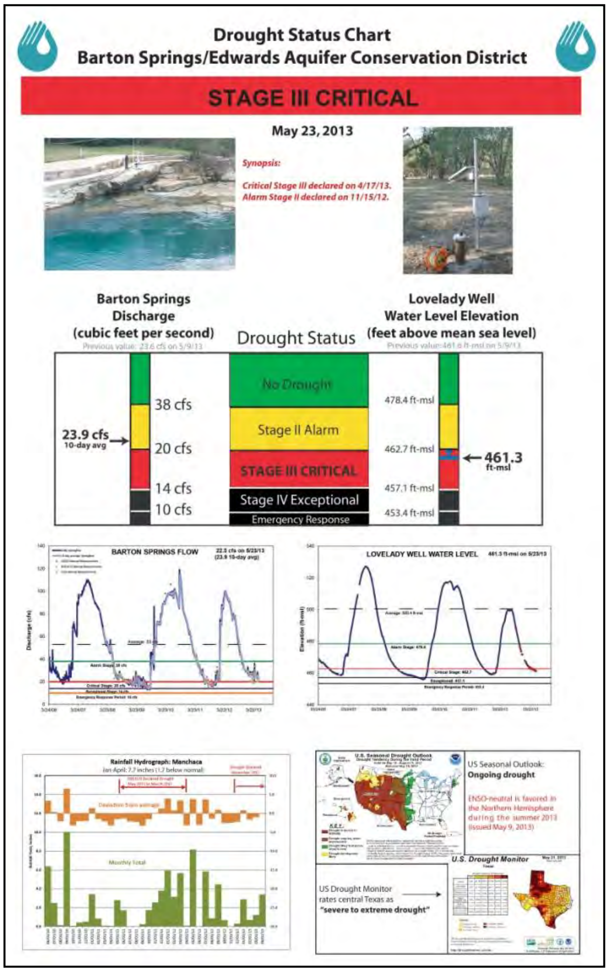
APPENDIX F

The District’s Drought Trigger Methodology for the Barton Springs Aquifer

BSEACD Report of Investigations 2013-1201, Smith et al., December 2013

Barton Springs
Edwards Aquifer
CONSERVATION DISTRICT

Drought Trigger Methodology for the Barton Springs Aquifer, Travis and Hays Counties, Texas



Drought Status Chart
Barton Springs/Edwards Aquifer Conservation District

STAGE III CRITICAL

May 23, 2013

Synopsis:

Critical Stage III declared on 4/17/13.
Alarm Stage II declared on 11/15/12.

US Seasonal Outlook: **Ongoing drought**

ENSO-neutral is favored in the Northern Hemisphere during the summer 2013 (issued May 9, 2013)

US Drought Monitor rates central Texas as **"severe to extreme drought"**

BSEACD Report of Investigations 2013-1201

December 2013

Barton Springs/Edwards Aquifer Conservation District
1124 Regal Row
Austin, Texas

Disclaimer

All of the information provided in this report is believed to be accurate and reliable; however, the Barton Springs/Edwards Aquifer Conservation District and the report's authors assume no liability for any errors or for the use of the information provided.

Cover Page: Image of the BSEACD's Drought Declaration Poster.

Drought Trigger Methodology for the Barton Springs Aquifer, Travis and Hays Counties, Texas

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BSEACD Report of Investigations 2013-1201

December 2013

Barton Springs/Edwards Aquifer Conservation District
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PREFACE

A statutory mandate charges the Barton Springs/Edwards Aquifer Conservation District (BSEACD) with the responsibility of conserving, protecting, and enhancing groundwater resources of the Barton Springs segment of the Edwards Aquifer (herein, the Barton Springs aquifer). A drought trigger methodology (DTM) is an important tool to achieve this goal and ensure drought management measures are implemented in an equitable and effective fashion.

The BSEACD's Board of Directors (Board) tasked the Aquifer Science staff with conducting an evaluation of the DTM for the Barton Springs aquifer. Staff began evaluations in early 2005 and periodically made status presentations to the Board. Detailed presentations were given to the Board on August 25, 2005, and October 27, 2005. Final results of the evaluation were presented to the Board in November 2005. The DTM was adopted in the District rules and became effective on January 26, 2006. The DTM at that time contained five drought-management stages: No Drought, Conservation Period (May-Sept), Alarm, Critical, and Emergency Response Period.

Since that time the BSEACD has experienced two major droughts in 2009 and 2011 and has made some minor changes to the initial DTM adopted in 2006. To better match Barton Springs flows with the depth to water in the Lovelady well, the Stage II Alarm Drought threshold was changed in 2008 from 181 ft to 175 ft, and Stage III Critical Drought threshold was changed from 187.2 ft to 192.1 ft. In 2009, additional deeper drought triggers (Stage IV Exceptional and the Emergency Response Period, ERP) were included into the DTM for Barton Springs. Corresponding Stage IV and ERP triggers were established for the Lovelady well in 2011. Stage III Critical threshold was changed from 192.1 ft to 190.7 ft to better correlate to Barton Springs on the basis of additional information from the severe droughts. In 2012, all triggers in the Lovelady well were converted from a depth to water (ft) to a water level elevation (ft-msl). This report documents the DTM as of December 2013.

ACKNOWLEDGMENTS

Much of what we understand about the Edwards Aquifer and its hydrodynamics was brought about by many dedicated scientists over many decades. Don G Rauschuber, P.E., a BSEACD consultant, formulated an initial DTM for the aquifer shortly after the BSEACD became fully operational in 1990, which provided a foundation for ensuing DTM initiatives. A decade later, Rauschuber and Ron Fieseler, a BSEACD employee at the time, performed the first comprehensive assessment of that initial DTM and made recommendations for its improvement, some of which are found in the current DTM. We also owe the Technical Advisory Team (TAT), formed in association with the conduct of the BSEACD's Habitat Conservation Planning grant, a special thank you for their input and contributions to this study. The TAT met periodically throughout 2005 to provide critical input and comments throughout the DTM evaluation process. Technical meetings were held on June 1, 2005, August 23, 2005, and November 7, 2005. TAT members included:

Charlie Krietler, LBG-Guyton
James Beach, LBG-Guyton
Charles Tang, LBG-Guyton
Nico Hauwert, City of Austin
David Johns, City of Austin
Raymond Slade, Consulting Hydrologist
Kent Butler, Planning Consultant and University of Texas
Roy Frye, Hicks and Associates
Jack Sharp, Jackson School of Geosciences, University of Texas

The DTM methodology was subsequently also presented to a broader technical audience. A poster was presented on March 6, 2006, at the Austin Geological Society's annual poster meeting at the Bureau of Economic Geology in Austin, Texas. A talk with published abstract was given on April 26, 2006, at the National Groundwater Association's Groundwater Summit meeting in San Antonio, Texas (Smith et al., 2006) and has been a topic of discussion with other technical specialists in those and many subsequent technical meetings.

Finally, we appreciate the long-term cooperation of the U.S. Geological Survey's Texas Water Science Center and the City of Austin's Watershed Protection Department in making many of the physical spring flow discharge measurements, which along with other measurements made by BSEACD staff members underpin much of the current DTM. Their work and willingness to participate in many fruitful technical discussions of the results, significance, and problems associated with these measurements is gratefully acknowledged.

(Left) Photograph of the Lovelady (58-50-301) well with U.S. Geological Survey equipment. The USGS took over continuous monitoring in August 2013. The USGS site name and number is 301237097464801 YD-58-50-301 (Lovelady). (Right) A) Photograph of USGS staff measuring flow about 250 ft downstream of Barton Springs Pool dam using a FlowTracker ADV®. Note the rock wall creating turbulence. B) USGS staff check equipment and make a manual stage measurement in the USGS Barton Well. More information on the Barton Springs discharge methods are discussed in Hunt et al., 2012.

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Drought Trigger Methodology for the Barton Springs Aquifer, Travis and Hays Counties, Texas

Brian A. Smith, Ph.D., P.G., Brian B. Hunt, P.G., W. F. (Kirk) Holland, P.G.
Barton Springs/Edwards Aquifer Conservation District

ABSTRACT

Previous studies of the Barton Springs segment of the Edwards Aquifer have shown that with uncurtailed pumping at 2004 rates and a recurrence of drought-of-record conditions, flow from Barton Springs could cease for brief periods, and up to 20% of the water-supply wells could have availability problems. A drought trigger methodology (DTM) was devised to improve declarations of drought and drought-management measures. Such measures, including mandatory pumping reductions, are a primary means of protecting groundwater levels and spring flow.

Three guiding principles were established as the basis for developing a DTM: 1) drought stage declarations must be made with sufficient time to achieve benefits of curtailment and education measures; 2) representative of aquifer-wide conditions; and 3) simple to implement. Principal components of the hydrologic cycle (recharge, storage, and discharge) were evaluated using historical data on drought indices, rainfall, stream flow, pumping, water levels, and spring flow.

Conduit and diffuse flow are the basic elements of the groundwater flow system in the Barton Springs aquifer that can influence the amount of water stored in the aquifer. The DTM established in this report utilizes flow from Barton Springs and water levels in the Lovelady monitor well to indicate overall storage and drought status of the aquifer. The DTM contains six stages as outlined in the table below. Barton Springs is the primary natural discharge point and is a good measure of the overall health of the aquifer system. Barton Springs is a good measure of groundwater storage, but is highly sensitive to the conduit flow system (very transient storage), responding quickly to minor and major recharge events. The Lovelady well is also a good measure of storage but is more representative of the diffuse flow system and has a muted response to major recharge events. This suggests that the Lovelady well is not directly connected to the karst aquifer's conduit system. By using both the Lovelady well and flow from Barton Springs to signal drought stages, it is likely that a serious drought can be recognized early enough for drought management measures to be implemented and continued long enough to minimize the impact on water supplies. These measures will help maintain water levels, adequate flow at Barton Springs, and aid in protecting the endangered salamanders at the springs. To exit a drought stage, both spring flow and water level must rise above their respective drought trigger values.

Although developed specifically for the Edwards Aquifer, the DTM reflects regional hydrologic response to drought and consequently has a good correlation to the Middle Trinity Aquifer in the area. The DTM presented in this report is, therefore, a reasonable measure of drought severity for making drought declarations for the Trinity Aquifer in the Barton Springs/Edwards Aquifer Conservation District. Based on the DTM study, a new drought trigger policy was adopted by the District's Board of Directors on January 26, 2006.

Summary of Drought Trigger Methodology (2006 DTM) components:

DTM Components	**Lovelady (depth to water, feet)**	**Lovelady (elevation, ft-msl)***	**Barton Springs 10-day average (discharge**, cfs)**	**Comment**
No Drought	< 175.0 ft	> 478.4	> 38 cfs	
Water Conservation Period (Every May 1st – September 30th	N/A	N/A	N/A	Voluntary reduction every year, similar to City of Austin's summer conservation program
Stage II-Alarm	≥ 175.0 ft	≤ 478.4	≤ 38 cfs	Upper Barton Springs ceases flow, major ion chemistry changes at springs; ~25th percentile of data
Stage III-Critical	≥ 190.7 ft	≤ 462.7	≤ 20 cfs	~5th percentile of data; inflection on hydrograph
Stage IV-Exceptional	≥ 196.3 ft	≤ 457.1**	≤ 14 cfs	Old Mill Spring ceases flow
Emergency Response	≥ 200 ft	≤ 453.4**	≤ 10 cfs	Lowest (1950s) historical value; 10-day average for both Barton Springs and Lovelady.

*based upon survey elevation of 653.4 ft-msl
**10-day average

INTRODUCTION

Study Area and Aquifers

The prolific karstic Edwards Aquifer system lies within the Miocene-age Balcones Fault Zone (BFZ) of Texas and provides water for more than 2 million people in the region. Hydrologic divides separate the Edwards Aquifer into three segments (**Figure 1**). The reader is referred to Slade et al. (1986), Ryder (1996), and Lindgren et al. (2004) which provide detailed regional information on the Edwards Aquifer as a whole. The Barton Springs segment of the Edwards Aquifer is the smallest segment (~155 mi^2; Slade et al., 1986) and is the subject of this paper. More than 60,000 people depend on the Barton Springs aquifer as their sole or primary source of drinking water. Barton Springs also serves as habitat for federally-listed endangered species and provides water to Barton Springs Pool, a major recreation location in Austin.

The Trinity Aquifer is stratigraphically beneath the Edwards Aquifer and is increasingly the target of groundwater production in the BSEACD. The Trinity Aquifer is juxtaposed west of the Edwards Aquifer (and BFZ) and is beneath the Edwards Aquifer within the BFZ. The Trinity is subdivided into the Upper, Middle, and Lower Trinity Aquifers. The reader is referred to Wierman et al., 2010, for more information on the Trinity Aquifer in central Texas. Recent studies have shown there is not a hydrologic connection between the Edwards and Middle Trinity Aquifers in the study area (Smith and Hunt, 2011; Wong et al., 2013).

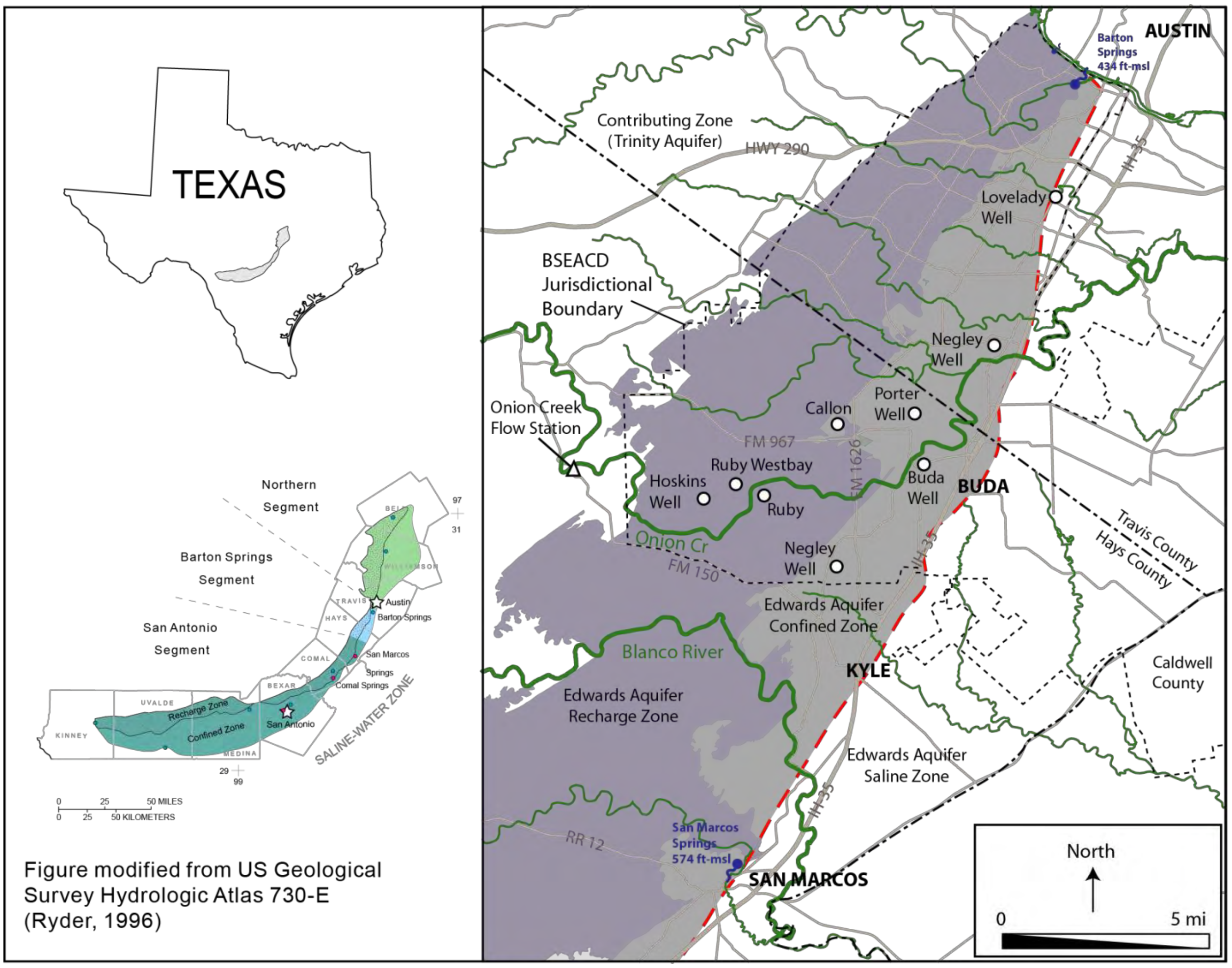

Figure modified from US Geological Survey Hydrologic Atlas 730-E (Ryder, 1996)

Figure 1. *Location map of the Edwards Aquifer, hydrologic zones, and monitor wells referenced in this study. The USGS "Driftwood" gaging station on Onion Creek is noted as Onion Creek Flow Station.*

Problem

Historical data show that during the 1950s drought of record, flow from Barton Springs reached historic monthly-average lows (about 11 cfs). Water levels in wells in the area also reached historic lows, with the Lovelady water level declining to 453.4 ft above mean sea level (3/5/1957). Modeling indicates that pumping and a repeat of 1950s Drought of Record (DOR) conditions will cause negative impacts to water-supply wells and the episodic cessation of flow at Barton Springs (Smith and Hunt, 2004).

As part of the BSEACD's groundwater permitting program, user drought contingency plans and drought declarations are the principal drought management tools for the BSEACD. Upon issuance of a declaration of drought, permittees are required to implement their contingency plan measures. These measures are the primary means of protecting groundwater levels and spring flow during a drought. The BSEACD has employed a Drought Trigger Methodology (DTM) as a means of declaring drought since 1991 (Rauschuber, 1990). However, that 1990 method has proved to be problematic in recent years for the following reasons:

- The method, which used multiple wells and triggers, was perceived as confusing and difficult to communicate to the public,
- Many of the wells became highly influenced by nearby pumping wells or operation of Barton Springs Pool,
- Some of the wells were redundant,
- The method indicated entry into drought too frequently, leading to lack of credibility and ultimately poorer response by the public.

Purpose

The purpose of this study is to define simple yet meaningful drought indicators and triggers that can take into account the complexity of a karst aquifer system and improve the certainty of drought declarations and effectiveness of communication of drought status. Such a system will improve conservation and demand-reduction measures by groundwater users, thereby helping to maintain water levels and springflow during drought conditions. The guiding principles of this study are to devise a DTM that: 1) allows for drought declarations to be made in a timely manner so that drought management measures could have an impact, 2) is representative of aquifer-wide conditions, and 3) is simple to implement.

PREVIOUS DTM STUDIES

Previous drought-management studies have been conducted for the Barton Springs aquifer, including Tillman (1989), Rauschuber (1990), and Fieseler and Rauschuber (2001). A brief discussion of each study is summarized below.

Tillman (1989)

The first study to identify a drought index well for storage and springflow in the Barton Springs aquifer was performed by Tillman (1989). In that report Tillman used linear regression analysis to determine that there is a good hydraulic continuity among wells in the artesian area and Barton Springs (R^2= 0.68 to 0.85). In the report, regression equations are presented and observations at the Buda well (State Well Number, SWN, 58-58-101) were used to predict other water levels and springflow.

Rauschuber (1990)

A study by Rauschuber (1990) was conducted to develop a Drought Contingency Plan for the BSEACD. This was essentially the framework of the first DTM developed and is hereafter referred to as the 1990 DTM. That plan discussed the guidelines and procedures for declaring droughts in the BSEACD and established the indicators and triggers for drought declaration. The report presents seven artesian well hydrographs and simple statistics for each well evaluated. Ultimately, five wells were recommended to be triggers in a drought action plan, although the Barton Springs well, which was included in the 1990 DTM, was not included as one of the wells evaluated in the 1990 study. The Rauschuber (1990) report was the framework for the 1990 DTM of the BSEACD and the primary elements include:

- Three stages of drought (Stage I/Alert, Stage II/Alarm, Stage III/Critical) with a corresponding pumping reduction of 10, 20, and 30 percent, respectively;
- Five wells used for drought declaration (Barton Well, Lovelady, Dowell, Buda, and Negley);
- Thresholds at any two of the five wells can trigger drought declarations;
- Drought stages are triggered by median, lower quartile, and historic low values for each corresponding well;
- 14-day period to enter or leave drought stage.

The 1990 DTM described in the report was largely adopted into the BSEACD's Drought Rules on August 12, 1991 (**Table 1**) and applied until January 26, 2006, when a new DTM was adopted based on the initial findings of Smith et al., 2006.

Table 1:*Historic BSEACD drought indicators and triggers 1991-2005 (1990 DTM)*

Well Name/No.	**LSD (ft-msl)**	**Alert Water Level Elevation (ft-msl)/Depth to Water (ft)**	**Alarm Water Level Elevation (ft-msl) / Depth to Water (ft)**	**Critical Water Level Elevation (ft-msl)/ Depth to Water (ft)**	**Noted Problems**
Barton Springs Well 58-42-903*	462.34	431.9	430.0	426.7	Only minor fluctuations in the water level; highly influenced by the level of Barton Springs Pool.
South Austin (Lovelady) 58-50-301	640.0	463.4 / 176.6	452.8 / 187.2	431.0 / 209.0	Critical drought level likely from drilling of well and not representative of drought—too low.
San Leanna (Dowell) 58-50-801	662.0	564.6 / 97.4	541.2 / 120.8	505.9 / 156.1	Highly influenced by PWS, IRR, and DOM wells.
Buda (Franklin) 58-58-101	707.2	599.8 / 107.4	580.2 / 127.0	550.7 / 156.5	Highly influenced by Buda PWS pumping wells; often does not fully recover.
Mountain City (Negley) 58-57-903	822.0	596.8 / 225.2	584.4 / 237.6	554.0 / 268.0	Redundant well to South Austin (Lovelady).

*formula to convert USGS reported gauge height to elevation: 462.34 – (52.84 – Max Gauge Height). Not identified as a drought indicator by Rauschuber 1990. LSD = Land Surface Datum (elevation in feet above mean sea level) as established by Rauschuber 1990.

Evaluation of 1990 DTM

As a prelude to this report, the 1990 DTM was evaluated to identify its weaknesses. Hydrographs for all drought trigger wells were plotted with historic data through 2005. Dates were noted where water levels crossed drought trigger levels, and using the 1990 DTM, a tabulation of droughts back to 1949 was generated and presented in **Table 2**. When applied to the period of record, the 1990 DTM indicates that the aquifer would be in either Stage I or II Drought conditions about 46% of the time, which is judged to be too frequent for eliciting public action. On the other hand, Stage III would not be triggered until drought conditions and impacts were worse than experienced in the 1950s drought. The 1950s drought is the benchmark for planning and management, the goal being to minimize the impacts experienced during a repeat of similar conditions. Stage III would be triggered too late to implement curtailment and conservation measures to help sustain water levels and springflow.

Prior to 1977, the 1990 DTM triggered drought with a nearly equal distribution among the indicator wells. However, this method exhibits a bias toward the Buda and Dowell wells after 1977, with those two wells triggering drought 83% of the time, and the Buda well involved about 96% of the time. Since 1977, groundwater use has increased dramatically, coinciding with the installation of the Buda Public Water Supply well (58-58-106), which is in close proximity to the Buda monitor well (about 300 ft). Since 1993, daily data exist for most monitor wells. The Buda and Dowell monitor wells triggered 100% of official BSEACD drought declarations since the onset of drought declarations by the BSEACD in 1993 (**Appendix 1**). **Figure 2** is a hydrograph of the 1990 DTM drought triggers illustrating some of the problems with the wells used as drought indicators. For example, the Buda (58-58-101) and Dowell (58-50-801) wells are impacted by localized pumping, which can draw down the water level up to 50 feet a day. The pumping of these two wells caused the premature entry into Stage II and the erratic entry and exit into Stage II. Although the method of using the daily minimum depth to water helps minimize the localized pumping issue (interference), there are times when the water level is not able to fully recover owing to peak demands.

Table 2. *Summary of drought frequency and duration using the 1990 DTM.*

	Percentage of time in drought stage			
	Stage I	Stage II	Stage III	Combined
Lovelady, Buda, Dowell, Negley				
Period of Record: 1949-2005	18%	28%	0%	46%
DOR: 1949-1958	19%	77%	0%	96%
Post DOR: 1958-2005	16%	16%	0%	32%
Daily Data: 1992-2005	19%	18%	0%	37%
Lovelady				
Period of Record: 1949-2005	16%	16%	0%	32%
DOR: 1949-1958	10%	33%	0%	43%
Post DOR: 1958-2005	17%	13%	0%	30%
Dowell				
Period of Record: 1942-2005	24%	17%	0%	41%
DOR: 1942-1958	19%	44%	0%	63%
Post DOR: 1958-2005	17%	17%	0%	34%
Buda				
Period of Record: 1938-2005	21%	30%	0%	51%
DOR: 1938-1958	25%	51%	0%	76%
Post DOR: 1958-2005	20%	21%	0%	41%
Negley				
Period of Record: 1949-2005	21%	20%	0%	41%
DOR: 1949-1958	26%	49%	0%	75%
Post DOR: 1958-2005	20%	14%	0%	34%

The Barton Springs well (58-42-903) was not part of the Rauschuber (1990) study; however it was adopted as one of the BSEACD's indicator wells for drought declaration (**Table 1**). Historically, the data have been reported as depth to water, and later as a gauge height, with uncertainty of how to correlate the datum for each measurement. More importantly, this well is problematic because the level in the well is highly influenced by the artificial water level and operation of Barton Springs Pool. Errors associated with the Barton Springs well data can be greater than natural water level changes for that well. Accordingly, the Barton Springs well (58-42-903) is omitted from further evaluations and discussions as it is clear that its water levels from this well will no longer be included as an indicator of drought.

Since maintaining springflow is an important aspect of any DTM, it is also important to note that there is a poor correlation of the 1990 DTM to Barton Springs discharge. Using data since 1978, Stage I was declared while Barton Springs flow ranged from 26 to 80 cfs, and Stage II Drought was declared when Barton Springs flow ranged between 26 and 80 cfs.

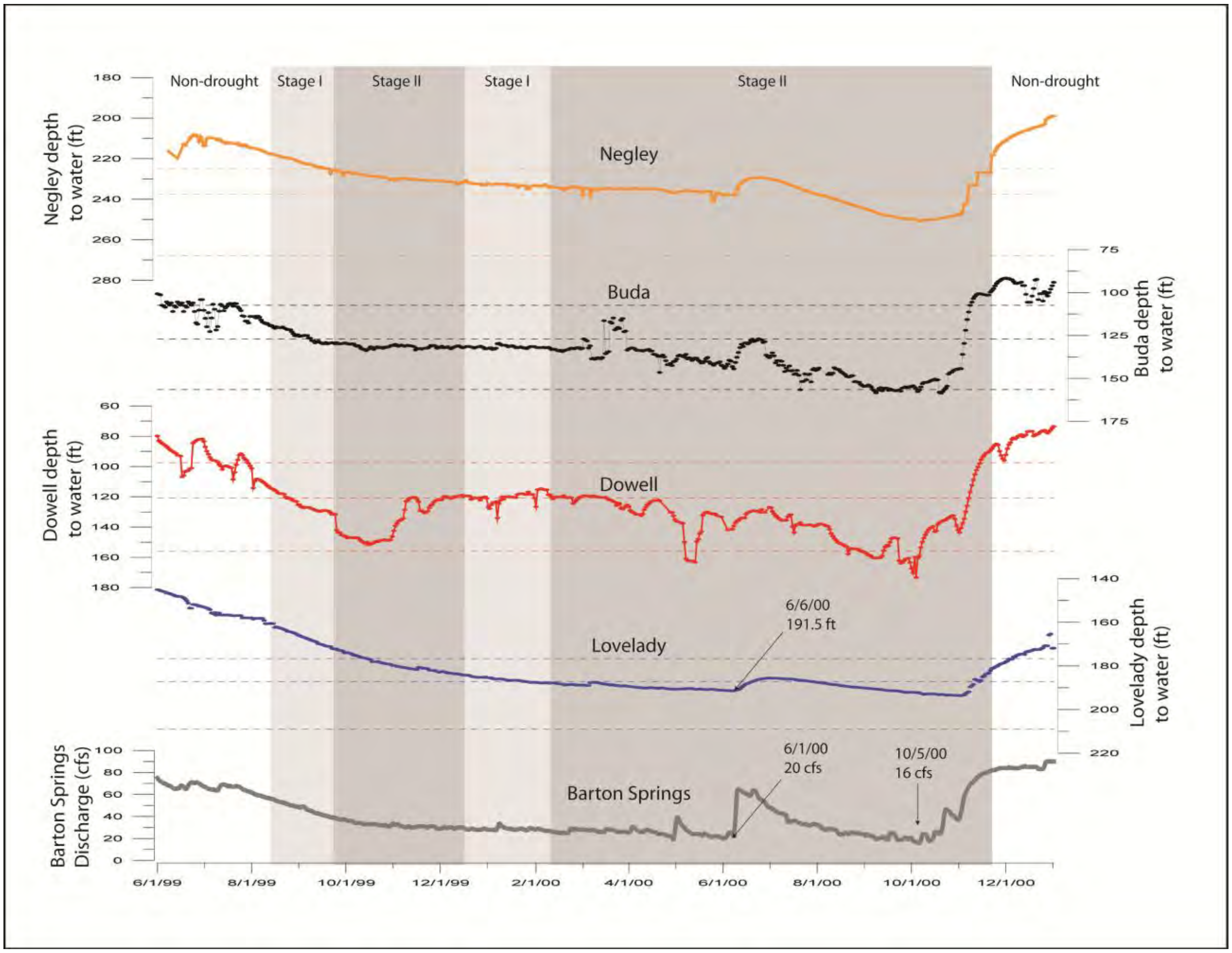

***Figure 2**. Hydrograph of the 2000 drought and the DTM devised by Rauschuber, 1990 (1990 DTM). For the time period in the hydrograph the depths to water in the Lovelady and Negley wells correlate very well to each other (R^2= 0.97) and to Barton Springs discharge (R^2= 0.88). The Buda and Dowell wells are impacted by the local effects of pumping and have a poor correlation to the Lovelady well (R^2= 0.43 and R^2= 0.53, respectively). The 5th drought indicator well, the Barton Springs well, is not shown.*

Fieseler and Rauschuber (2001)

Fieseler and Rauschuber (2001) discuss some of the problems of the 1990 DTM and describe it as being confusing, cumbersome, and perceived by permittees as unfair. The authors noted that every drought declared by the BSEACD since 1991 was triggered by the Buda and Dowell wells. Statistical evaluations of the data revealed a good correlation among the wells evaluated. They note that for the drought period of 1999-2001 the Lovelady well (58-50-301) correlates very well to Barton Springs flow (R^2= 0.88) and to the Negley well (58-57-903) (R^2= 0.97). The report also noted that the pre-1989 data biased the triggers toward lower elevations; however, they recommended that the triggers remain unaltered. The report also discussed some alternative drought trigger methodologies and suggests using a single well, namely the Lovelady (58-50-301) well, as the sole drought index well. Primary elements of proposed DTM as discussed by Fieseler and Rauschuber (2001) included:

- Annual seasonal Stage I drought declaration (June-September) to increase summer conservation awareness,

- Stage II triggered by 14 days at or below 449.3 feet msl (190.7 ft depth to water) in the Lovelady well and corresponds to a Barton Springs discharge of about 30 cfs,
- Stage III triggered by 14 days at or below 432.0 feet msl (208.0 ft depth to water) in the Lovelady well and corresponds to a Barton Springs discharge of about 13 cfs.

BACKGROUND

Climatic and Physiographic Setting

The physiographic and climatic setting of the study area greatly influences the meteorology and droughts impacting the Edwards Aquifer. The Barton Springs aquifer is located within the Balcones Fault Zone (BFZ) of central Texas. The BFZ defines the eastern margin of the Texas Hill Country (Edwards Plateau) and the western margin of the gently rolling Blackland Prairies of central Texas. The BFZ is an escarpment created by a system of northeast-trending normal faults. Land surface altitudes increase abruptly at the BFZ, rising hundreds of feet (400 to over 1000).

The climate of the study area is considered humid subtropical, characterized by hot summers and dry mild winters (Larkin and Bomar, 1983). The climate of the study area is also characterized as having protracted wet and dry periods (Diaz, 1983). This is reflected in the ranges in annual rainfall, from a high of 64.7 inches (1919) to a low of 11.4 (1954). Potential evaporation is greater than precipitation. Annual average rainfall for Austin's Camp Mabry is 33.4 inches (1856-June 2010). Although rainfall is fairly evenly distributed throughout the year, peak rainfall generally occurs in May, with a secondary peak occurring in September (and sometimes October) (**Figure 3**). The El Nino/Southern Oscillation (ENSO) strongly influences rainfall in central Texas and is discussed below (Drought section).

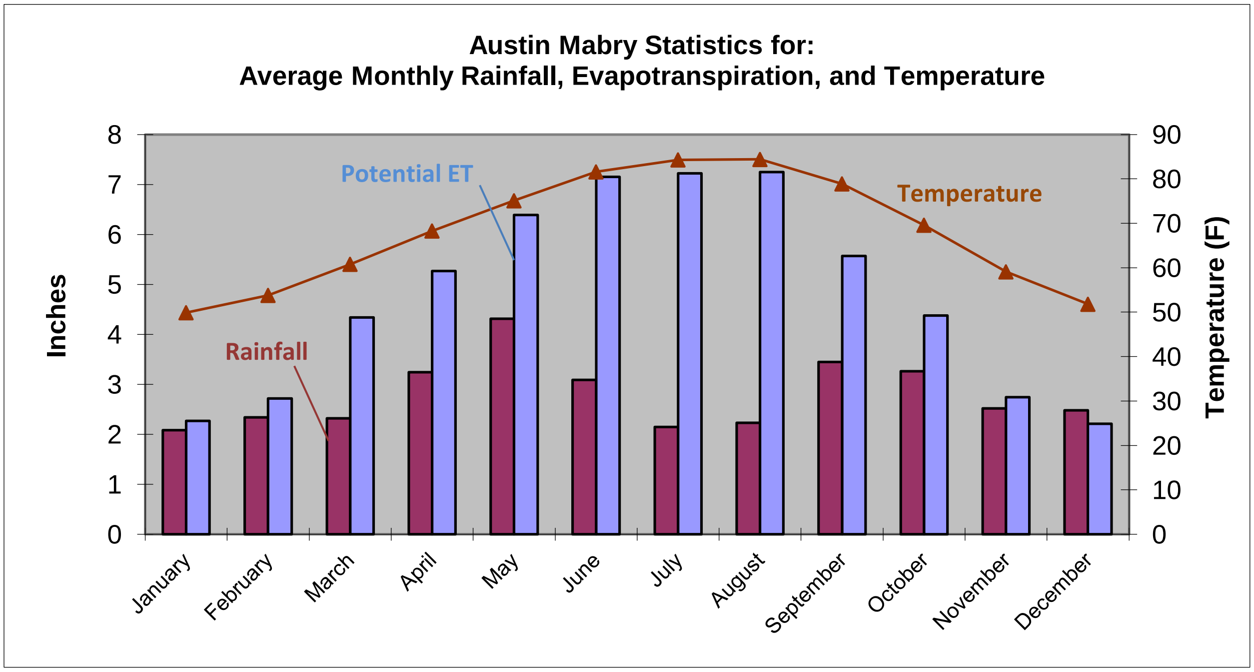

***Figure 3**. Histograms of monthly average rainfall, potential evapotranspiration (Pot. ET), and temperature from Austin's Mueller/Camp Mabry station representing 157, 75, and 155 years of data, respectively.*

Large rainstorms (May-July) are caused by warm and cold fronts encountering moisture-laden air from the Gulf. Tropical storms, depressions, and hurricanes originating in the Gulf and oceans typically occur in September and October. However, storms can also occur during summer months as was the case in 2010 (Hurricane Alex and Tropical Storm Hermine). Annual streamflow peaks occur during hurricane season (June through November) (Slade and Chow, 2011). The triggering of large storms by meteorological conditions is also aided by the orographic effect of the Balcones Escarpment (Slade, 1986). Consequently, the study area has some of the most intense rainfall per drainage area in the world and flooding is greater in the Hill Country than in any other region in the U.S. Factors contributing to flooding include: the intense (though non-uniform) storms, rapid runoff due to steep slopes, and limited infiltration due to exposed bedrock with relatively thin soils and sparse vegetation (Caran and Baker, 1986).

Conceptual Hydrogeologic Model

A detailed discussion of the hydrogeologic functioning of the Edwards and Trinity Aquifers is beyond the scope of this report. Readers are referred to Slade et al., (1986); Barker and Baker (1994); Ryder (1996); Mace et al., (2000); Smith et al., (2004); Lindgren et al., (2004), and Wierman et al., (2010). The Lower Trinity Aquifer is not addressed in this study.

Recent studies document that the Edwards and Middle Trinity Aquifers are not in hydrologic connection, at least within the BSEACD, and can be managed (e.g. pumping permits) as separate systems (Smith and Hunt, 2010; Kromann et al., 2011; and Wong et al.,2013). A portion (~100 ft) of what is known as the Upper Trinity Aquifer (Upper Glen Rose) in the Texas Hill Country is in hydrologic communication with the Barton Springs aquifer. However, the majority of the Upper Trinity Aquifer behaves as an aquitard between the Edwards and Middle Trinity Aquifers in the BSEACD area (and BFZ). Although independent aquifer systems, both the Edwards Aquifer and Middle Trinity in the BFZ are fractured karstic aquifers that have a strong interconnectivity of surface and groundwater in their respective recharge areas. The following discussion outlines the overall hydrogeologic processes of both of these aquifer systems.

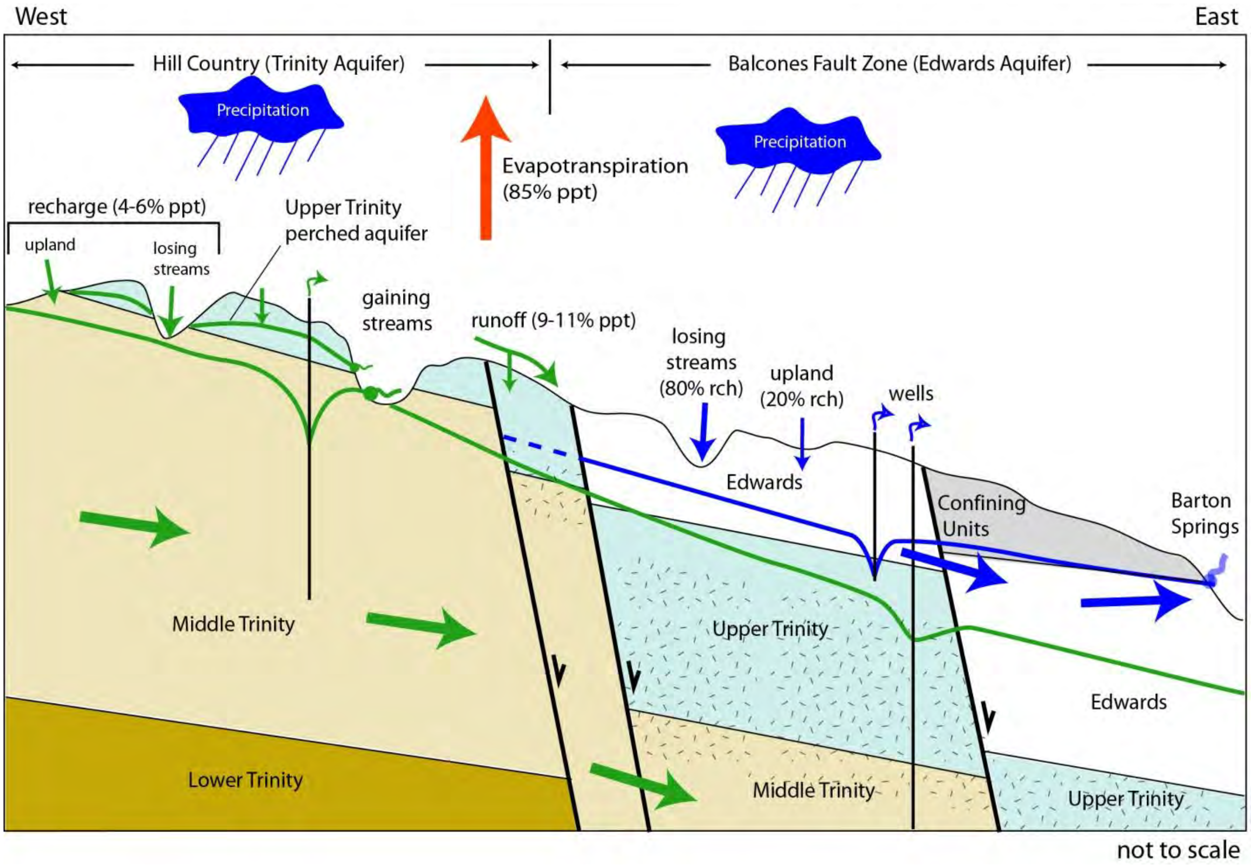

Figure 4. *Conceptual hydrogeologic model of the Edwards and Trinity Aquifer systems in the central Texas Hill Country and Balcones Fault Zones (Hays and Travis Counties). Stippled pattern represents zones of evaporites and low permeability.*

Recharge and Groundwater Flow

Figure 4 illustrates the overall conceptual model of the Edwards and Trinity Aquifer in the central Texas Hill Country and BFZ (Hays and Travis Counties). The majority (~85%) of annual precipitation falling within the Hill Country is lost to evapotranspiration (ET) (Banta and Slattery, 2011). About 4 to 6% of annual rainfall is recharged into the undifferentiated Trinity Aquifer (Jones et al., 2011). The remaining 9-11% percent of annual precipitation generates runoff into the creeks that flow through the Hill Country. The Upper Trinity Aquifer (Upper Glen Rose limestone) of the Hill Country is primarily a perched aquifer and recharged by direct precipitation where the units are exposed, or through the thin units of Edwards (Fort Terrett Fm.) that cap some hills. The Upper Trinity discharges primarily as intermittent springs and seeps, maintaining baseflows to the Blanco River and Onion, Barton, and other creeks in the Hill Country. The argillaceous nature of the rocks limits vertical flow to (and from) deeper geologic units. Locally in the Hill Country the Upper Trinity Aquifer is a good aquifer (such as in Dripping Springs). The Middle Trinity Aquifer is recharged by a combination of direct precipitation and losing streams, where these fractured and karstic units are exposed at the surface. For this region, the Blanco River in the Wimberley Valley is a primary area of recharge for the Middle Trinity. Minor recharge (downward leakage) to the Middle Trinity in the Hill Country may occur from the overlying Upper Trinity (Upper Glen Rose) (Wiermann et al., 2010). In Hays County, Middle Trinity groundwater generally follows along structural dip, from west to east. However, some groundwater flow in northern Hays and western Travis counties is to the northeast toward the Colorado River. In Hays County (Blanco and Onion watersheds), lateral flow within the Middle Trinity enters into the BFZ, but is thought to remain with the Middle Trinity (Smith and Hunt, 2011). Faulting does not appear to limit lateral flow due to the structural geometry and style of relay-ramp faulting. Groundwater flow velocities in the Middle Trinity, in the Wimberley Valley, are locally dominated by karst conduits and are thought to be quite high. Jacob's Well is a good example of the localized conduit nature of the Middle Trinity Aquifer. Despite the karstic nature of the Middle Trinity, lateral flow in the BFZ (e.g. in the deeply confined setting) is relatively slow compared to the Wimberley Valley. This is evidenced by the relative ages of Middle Trinity groundwater (Hunt and Smith, in preparation).

The majority of recharge to the Barton Springs aquifer is derived from streams originating west of the recharge zone in the Texas Hill Country. Recent studies have shown the Blanco River is a significant contributor during drought conditions (Smith et al., 2012). Water flows onto the recharge zone and recharges into numerous caves, sinkholes, and fractures along ephemeral to intermittent losing streams. For the Barton Springs aquifer, Slade et al. (1986) estimated that as much as 85% of recharge to the aquifer is from water flowing in these streams. A re-analysis incorporating recent data indicates that streams provide about 80% of the recharge to the Barton Springs aquifer (Slade, personal communication, April 26, 2013), more or less confirming the previous study's findings. The remaining recharge (15-20%) occurs as infiltration through soils or direct flow into recharge features in the upland areas of the recharge zone (Slade et al., 1986). Hauwert (2009) indicates that upland recharge may constitute a larger fraction of recharge (>25%), at least in some portions of the spring shed. Both studies recognize that a significant amount of recharge to the Edwards Aquifer is from flow in the creeks that cross the recharge zone. Groundwater in the Barton Springs aquifer generally flows from west to east across the recharge zone, converging and merging with preferential groundwater flow paths, subparallel to major faulting, then flows northeast toward Barton Springs. Groundwater tracing and other studies demonstrate that a significant component of groundwater flow in the Edwards Aquifer is discrete, occurring in an integrated network of karst conduits, caves, and smaller dissolution features (Hauwert et al., 2002a; Hauwert et al., 2002b; Hunt et al., 2005; Johnson et al., 2011). Rates of groundwater flow along preferential flow paths, determined from dye tracing, can be as fast as 4 to 7 mi/day (6 to 11 km/day) under high-flow conditions or about 1 mi/day (1.6 km/day) under low-flow conditions (Hauwert et al., 2002a).

Storage

Water levels in the Middle Trinity Aquifer have been steadily declining over the past thirty years in the Hill Country. Water-level data show a decrease of about 2 to 4 feet per year and have a trend slope of -3% over the period of record for some wells in the Hill Country (Wierman et al., 2010; Hunt et al., 2012). Water levels in the Edwards Aquifer 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 have essentially reached a new equilibrium in the Lovelady well since the climatic change of the 1960s (Hunt et al., 2012). Water levels and discharge at Barton Springs respond very quickly to recharge events and then decline at variable rates, influenced by both conduit and matrix permeability and storage (Slade et al., 1986; Mahler et al., 2006). However, the maximum amount of water in storage in the Barton Springs aquifer after each of the last three severe droughts has been successively smaller, as seen in the hydrographs of both Barton Springs and especially the Lovelady well, suggesting that these may well be larger-scale variations within a longer-term mega-drought like the 1950s drought of record.

Discharge

Discharge of the Middle Trinity in the Hill Country occurs as springs, such as Pleasant Valley Spring or Jacob's Well, and pumping from wells. Pumping in the Middle Trinity in the Hill Country for Hays County was estimated at 5,600 ac-ft/yr, and about the same for western Travis County (Hutchison, 2010). Pumping of the Middle Trinity within the BFZ (in the BSEACD) is only 285 ac-ft/yr (2013 data). Natural discharge of the Middle Trinity in the Hill Country is reported to be the Colorado River in Travis County

(Jones et. al., 2011). Natural discharge from the Middle Trinity Aquifer within the BFZ is unknown and could occur vertically into overlying units, or deeper into the sedimentary basin. As part of Groundwater Management Area 10, a desired future condition (DFC) was established for the undifferentiated Trinity Aquifer. The DFC expressed was defined as: "regional average well drawdown during average recharge conditions that does not exceed 25 feet" (Thorkildsen and Backhouse, 2011). This equates to about 1,288 acre-ft/yr of pumping.

Discharge of the Barton Springs aquifer occurs as springflow from Barton Springs (and also Cold Springs) and as pumping from wells. Peak pumpage occurs during the summer months (July and August), with up to twice the volume used during that time as during winter months (Hunt et al., 2006). Sustainable yield evaluations indicate that water levels and springflow are significantly affected by 1950s drought conditions and increased pumping rates. Simulations indicate that a nearly 1:1 relationship between pumping and springflow exists under drought conditions. In addition, pumping and drought conditions affect the amount of water in storage and can cause negative impacts to water-supply wells (Smith and Hunt, 2004). The Barton Springs segment provides water for about 60,000 people and currently has about 8,400 acre-ft/yr (2.7 billion gallons; 11.6 cfs) of authorized (on uncurtailed basis) pumping from 95 permit holders. The DFC expressed by the BSEACD's Board of Directors for the Barton Springs aquifer under drought conditions is to maintain 6.5 cfs of Barton Springs flow (Hutchison and Oliver, 2011). To achieve the DFC, current permitting (historic versus conditional permits) and pumping limits during drought conditions (drought declarations and conservation) will have reduced the maximum amount of water pumped during extreme drought conditions to 4.7 cfs (or about 3,700 ac-ft/yr) from all permittees.

DROUGHT

Recurrent drought episodes are a common feature of the climate of much of Texas, including the study area (Diaz, 1983). Drought produces a complex web of impacts that are the third most significant geologic hazard in terms of economic losses, ranking only behind floods and frost damage (Driscoll, 1986). Agricultural and hydrologic impacts from drought are felt throughout the economic, environmental, or social fabric (National Drought Mitigation Center, NDMC, 2003). Social impacts involve public safety and health. This section discusses drought in general and then defines specific types of drought relevant to the Barton Springs aquifer.

Drought is a normal and recurrent feature of natural climatic variability that, by definition, cannot occur a majority of the time (NDMC, 2003). For example, the cumulative frequency for severe drought ranges from 5 to 10% (Steinmann et al., 2005). The definition of drought must be regional- and impact-specific because it is a relative phenomenon occurring in both low- and high-rainfall areas (Wilhite, 2005). On average, 14% of the U.S. is experiencing drought annually (Wilhite, 2005). Finally, drought must be distinguished from seasonal (summer) aridity. Many general definitions of drought exist, but they all have basically the same concept as defined by Moreland (1993):

Drought: "a period of drier-than-normal conditions that result in water-related problems."

Although all droughts originate with the absence of rainfall for a prolonged period of time, and affect the entire hydrologic cycle, drought is often discussed in terms of three physical effects characterized as meteorological, agricultural, and hydrological. Owing to the nature of the hydrologic cycle, these three components are typically not affected at the same time or with the same severity. All droughts originate from a prolonged deficiency of rainfall, called a meteorological drought. Agricultural drought occurs when there isn't enough soil moisture to meet the crop needs and generally follows a meteorological drought. A hydrological drought refers to deficiencies in surface water and groundwater supplies measured as streamflow, lake elevations, and groundwater levels. Hydrologic droughts generally lag in time behind meteorological and agricultural droughts. A severe drought will eventually have adverse impacts on all these components (NDMC, 2003). Criteria for measuring hydrological droughts often focus on surface water rather than groundwater. Droughts that affect the Barton Springs aquifer can be best characterized as hydrological, but more specifically a groundwater drought. Groundwater droughts are a type of hydrologic drought and are defined by Peters and Van Lanen (2000):

<u>Groundwater drought:</u> "a groundwater drought occurs if in an aquifer the groundwater heads have fallen below a critical level over a certain period of time, which results in adverse effects."

Causes of Drought

Understanding the cause of drought is important for making predictions and developing DTMs. However, the cause for "drier-than-normal conditions" is never the result of a single factor. The immediate cause can be attributed to a large-scale persistent high (atmospheric) pressure that disrupts the global atmospheric circulation increasing sunshine, evaporation, and inhibiting the influx of moisture (Mo et al., 1997). Multi-year droughts, such as that of the 1930s and 1950s, have been linked to several ocean-atmospheric processes such as El Niño/Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and other processes (Barlow et al., 2000; Schubert, 2003; Mauget, 2003; Fye et al., 2004; NOAA, 2006).

The El Niño/Southern Oscillation (ENSO) is a naturally occurring irregular cycle (occurring every 2-7 years) of the ocean-atmosphere system in the tropical Pacific Ocean. In particular, El Niño conditions arise during a warming of tropical Pacific sea surface temperatures, which contribute to a wetter than average period in Texas by influencing the position of the jet streams and thereby promoting the influx of moisture (**Figure 5**). La Niña conditions arise during a cooling of the tropical Pacific sea surface temperature and generally contribute to drier than average conditions in Texas (Barlow et al., 2000; Schubert, 2003). The strength, duration, and frequency of ENSO conditions have been found to vary greatly over the 20th Century (Rajagopalan et al., 2000) and are expected to be highly variable owing to the influences of global warming (IPCC, 2007). Several months advance notice of impending El Niño or La Niña conditions is currently possible (Gershunov, 1998; NOAA, 2006). Recent study of ENSO effects for the Texas Hill Country by Slade and Chow (2011) reveal that greater rainfall occurs during La Niña summer months, while greater rainfall occurs during other months for El Niño conditions. ENSO does not appear to influence streamflow peaks, but total runoff volumes are slightly larger for El Niño than La Niña conditions in the northern Hill Country (Slade and Chow, 2011).

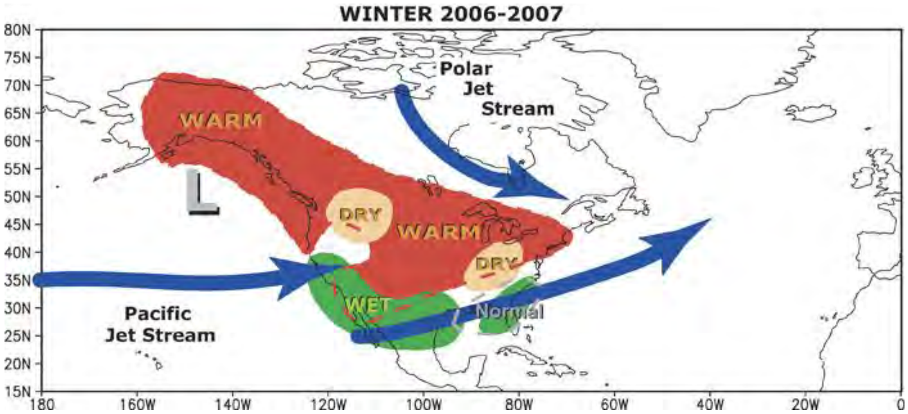

Figure 5. *Map showing the position of the jet streams and climate impacts due to ENSO. This map illustrates El Niño conditions and the general climatic impact to regions in the U.S. Map from NOAA.*

Drought cannot be viewed solely as a natural event because the impacts often result from the combined effects of the natural event itself and the demand people place on a water supply. People often influence the timing and duration, and exacerbate the impacts of drought (NDMC, 2003). Indeed, even without drought conditions groundwater pumping can have profound negative effects on aquifers and surface waters (Glennon, 2002). Studies of the Barton Springs aquifer have shown that increasing levels of pumping during drought-of-record (1950s) conditions will exacerbate drought conditions and have increasingly negative impacts on water levels and Barton Springs (Smith and Hunt, 2004). **Figure 6** illustrates the influence of pumping on springflow during drought conditions using numerical modeling.

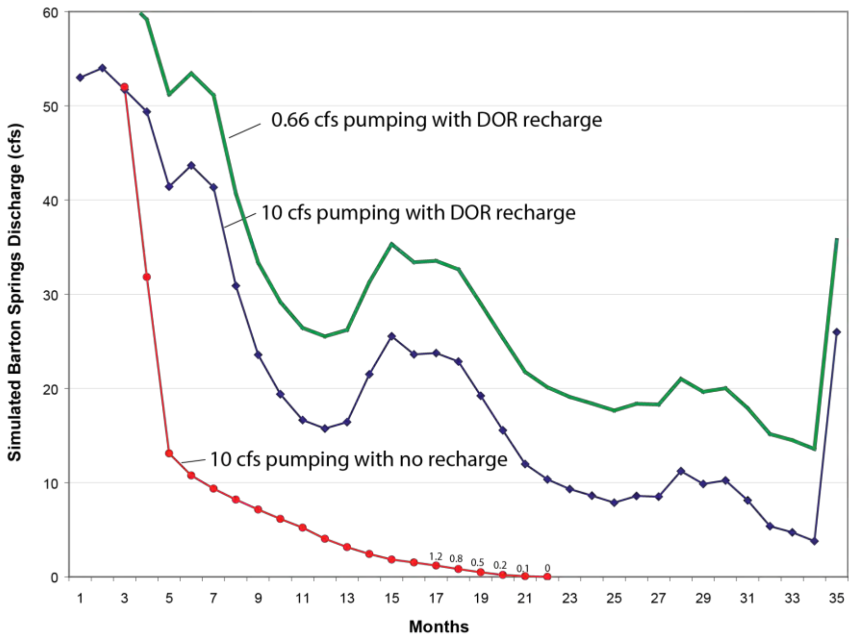

Figure 6*. Hydrograph of simulated Barton Springs discharge for 0.66 cfs and 10 cfs pumping with DOR recharge, and 10 cfs pumping and no recharge. Simulations were performed using the recalibrated GAM model (Smith and Hunt, 2004). The period used is from the first 3 years of the 7-year DOR.*

Drought Indicators and Triggers

The purpose of this study is to develop meaningful drought indicators and drought-management triggers for the Barton Springs aquifer. Ward (2013) provides a detailed review of indicators, indices, and triggers. Some introductory information is provided in this section.

Drought Indicators "are variables that describe the magnitude, duration, severity, and spatial extent of drought" (Steinemann et al., 2005).

Drought Triggers "are threshold values of an indicator that distinguish a drought level (stage), and determine when management actions should begin and end" (Steinemann et al., 2005).

Single indicators of drought are often inadequate to characterize a drought. Many indicators may need to be integrated or combined into a single indicator, called a drought index (Moreland, 1993; NDMC, 2003; Steinman et al., 2005). Common drought indices include the Standardized Precipitation Indices (SPI) and the Palmer Drought Severity Indices (PDSI). Ward (2013) deemed these as good regional indicators for Texas. These indices are meteorological and agricultural drought indicators. The Palmer Hydrologic Drought Index (PHDI) is a variation of the PDSI that accounts for streamflow, storage, and groundwater.

Drought is a slowly developing phenomenon, therefore the onset and end of drought are often difficult to define and determine (Wilhite, 2005). Accordingly, indicators need to reflect the type of drought of concern (Steinmann, et al., 2005). Groundwater is largely ignored as an indicator, or diluted by other factors, in most drought indices. The exceptions are a few European countries that monitor groundwater levels with triggers based on a time-dependent frequency distribution (Peters and van Lanen, 2000).

The BSEACD is concerned with monitoring a hydrologic or groundwater drought. For groundwater droughts, the three processes that characterize the hydrology of the aquifers are recharge, storage, and discharge. Therefore, indicators of drought in the Barton Springs aquifer are hydrologic in nature and could include stream flow, water levels, and springflow.

The beginning of a drought is generally established somewhat arbitrarily, rather than based on a precise relationship to specific impacts (NDMC, 2003; Wilhite, 2005). Drought trigger (threshold) values must be considered relative to a long-term average, often characterized as "normal" conditions for a particular area.

Historical Droughts of Central Texas

Evaluation of the hydrologic responses to past droughts is critical to the development of indicators and triggers. Each drought is unique in its climatic characteristics, intensity, duration, spatial extent, and impacts (Wilhite, 2005). **Figure 7** illustrates the years with significant droughts using the annual average hydrograph from Barton Springs as a general drought indicator. Generally speaking, when Barton Springs discharge was below 40 cfs, a drought occurred. When Barton Springs was below 20 cfs, a severe drought occurred.

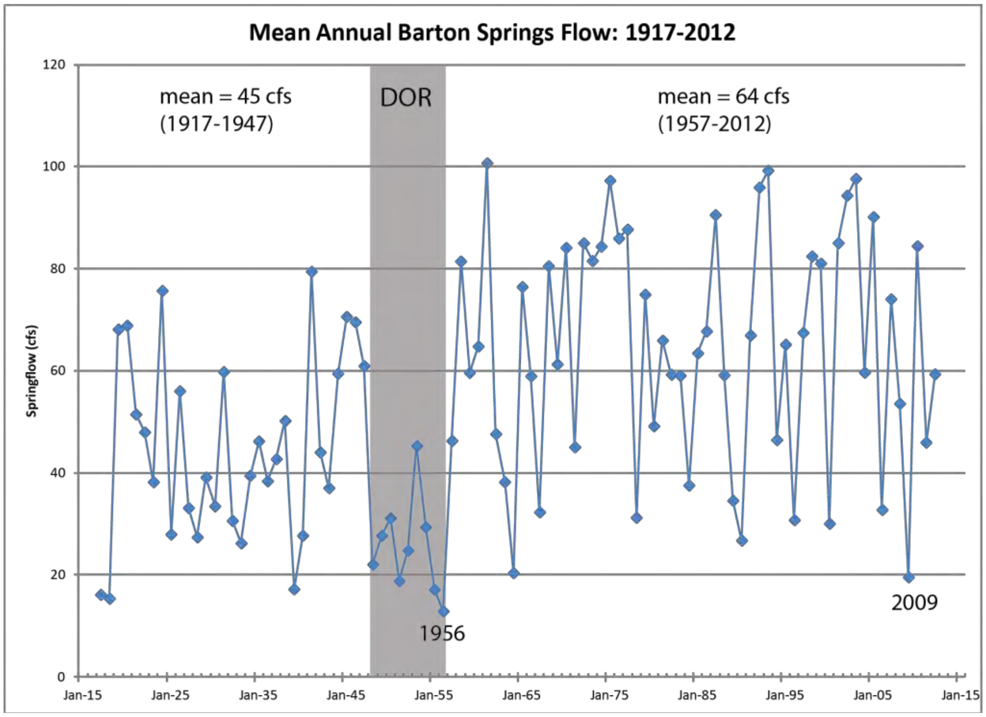

Figure 7. *Mean annual discharge hydrograph for Barton Springs illustrating major droughts over the period of record. During most years considered a drought the discharge at Barton Springs was below the annual average of 40 cfs. A significant shift in the long-term annual average discharge is noted after the drought of record that occurred from 1947 through 1956. Data from the U.S. Geological Survey.*

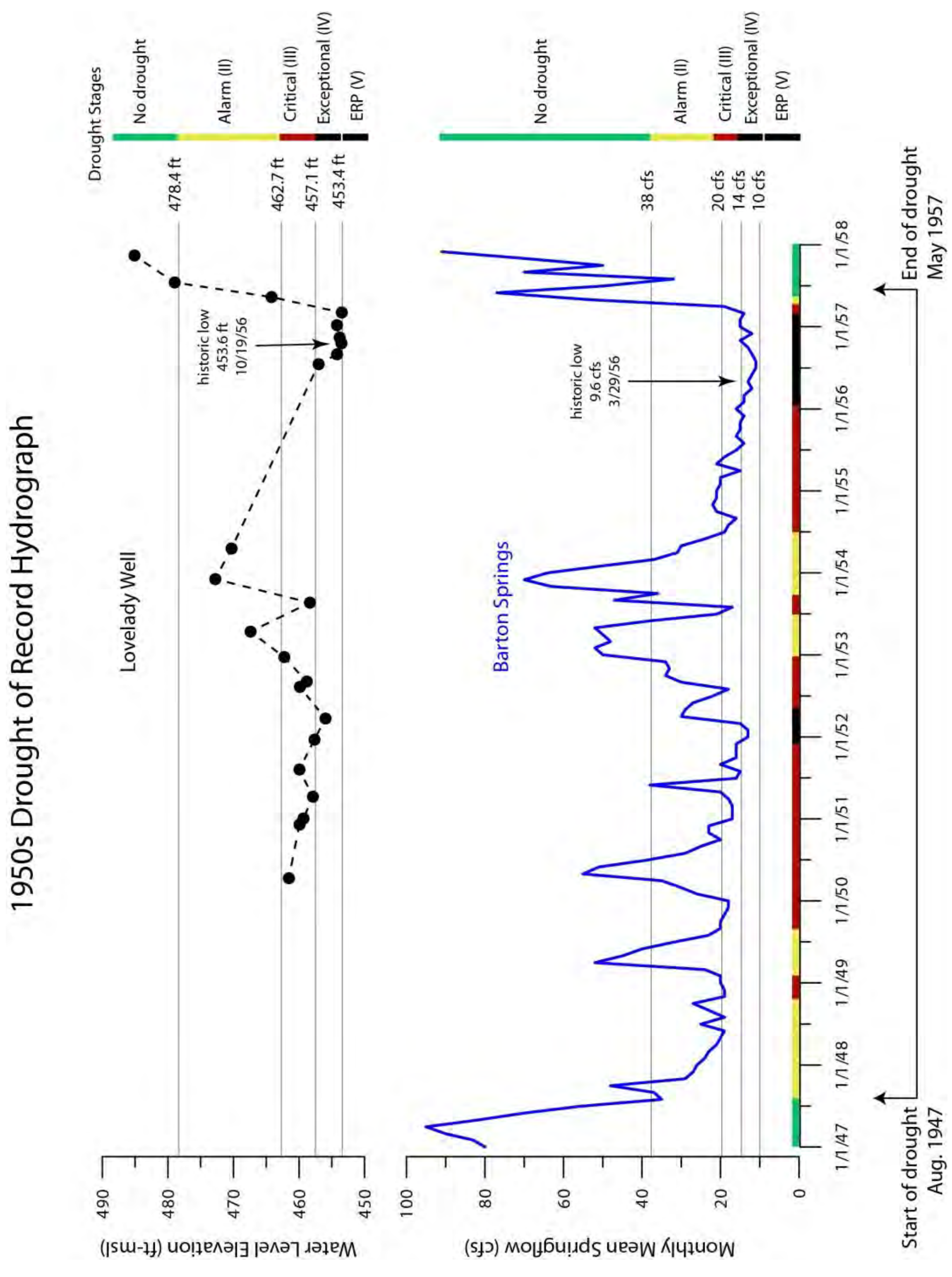

Figure 8. *1950s drought of record hydrograph showing mean monthly springflow at Barton Springs and water levels for the Lovelady Well—drought triggers shown for each indicator.*

Droughts of the 1930s and 1950s were the most severe of the 20th Century in the U.S. (Andreadis et al., 2005). Central Texas' worst drought on record occurred from 1950-1956 (Lowry, 1959; **Figure 7**). **Figures 7 and 8** illustrate that the drought should actually be defined as starting in 1947, making the worst drought about 10 years in duration rather than 7 years. However, the 1950-56 time period is used for scientific studies and aquifer management (Scanlon et al., 2001; Smith and Hunt, 2004). During the 1950s drought, water levels and springflow reached historic lows at Barton Springs, and springflow ceased altogether at Comal Springs (Guyton, 1979). The 1950s has the lowest total rainfall of any decade on record for the Austin (Camp Mabry) station. The lowest annual rainfall total during that time was 11.42 inches in 1954. The annual mean discharge for Barton Springs was 13 cubic feet per second (cfs) in 1956, with the lowest monthly mean discharge of 11 cfs occurring in July and August of 1956. The lowest measured spring discharge value was 9.6 cfs on March 26, 1956 (Slade et al., 1986).

Droughts after 1956 appear shorter in duration than droughts before 1956 (**Figures 7**). As shown on **Figure 7,** the Barton Springs aquifer has experienced about 11 years below 40 cfs since 1957, or about 20% of the time. This statistic is in contrast to the preceding 40 years of data that showing the Barton Springs aquifer experienced 23 drought years, or about 60% of the time. Moreover, in the last 50 years the population and demand for groundwater have increased substantially. Demand for water and other resources have likely exacerbated more recent droughts. However, there is an apparent shift in the overall water budget with more springflow (and pumping) after 1960 (Smith and Hunt, 2010). The mechanism and implications for this apparent increase in the overall water budget since 1960 are likely due to a climatic shift to wetter conditions. However, additional recharge from urbanization is also a component (Sharp et al., 2009). Flow from Barton Springs had a mean increase of 19 cfs after the 1960s (**Figure 7**). However, despite the increasingly wet conditions since the 1960s, baseflows in streams and low springflow values have remained unchanged over the period of record, and declining over the past 40 years (Hunt et al., 2012). Although droughts have been shorter in duration since the DOR, the 2011 drought was more intense (drier and hotter) than previous historic droughts (Nielson-Gammon, 2012). Barton Springs reached a low of 16 cfs during the 2011 drought. The 2009 drought was not as intense as the 2011 drought, but lasted longer, and springflow reached a daily low value of 13 cfs.

Recent tree ring studies (Cleaveland, 2006) have confirmed the severity of the 1950s DOR relative to a long drought chronology. However, the same study indicates that droughts more severe and protracted than the 1950s DOR have occurred in the past. This raises the question whether the 1950s DOR is the correct benchmark for planning for drought (North, 2008; Woodhouse, 2008).

APPROACH

Developing a DTM must be done in the context of an understanding of the regulatory framework of the BSEACD, and the nature of the hydrologic system. Data evaluated include previous droughts, historic drought declarations, and hydrologic data. Multivariate analyses established the best indicators of drought for the system. Further detailed evaluation of the data occurred with simple statistics and linear correlations between historic data sets. Multivariate hydrographs also helped illuminate the hydrological processes, correlations, and responses of the system.

SUMMARY OF RESULTS

The final DTM and its components are summarized in **Table 3**. Results of the multivariate analysis and detailed evaluations of hydrologic data are presented as supplemental information in **Appendices A-2 and A-3**. **Appendix A-4** presents the current Drought Stages and Rules adopted by the BSEACD (October, 2012) based on these findings.

Table 3. *Summary of Drought Trigger Methodology (2006 DTM) components*

DTM Components	**Lovelady (depth to water, feet)**	**Lovelady (elevation, ft-msl)***	**Barton Springs 10-day average (discharge**, cfs)**	**Comments**
No Drought	< 175.0 ft	> 478.4	> 38 cfs	
Water Conservation Period (Stage I): May 1st – September 30th	N/A	N/A	N/A	Voluntary reduction every year, similar to City of Austin's summer conservation program
Stage II-Alarm	≥ 175.0 ft	≤ 478.4	≤ 38 cfs	Upper Barton Springs ceases flow, major ion chemistry changes at springs; ~25th percentile of data
Stage III-Critical	≥ 190.7 ft	≤ 462.7	≤ 20 cfs	~5th percentile of data; inflection on hydrograph
Stage IV-Exceptional	≥ 196.3 ft	≤ 457.1**	≤ 14 cfs	Old Mill Spring ceases flow
Emergency Response	≥ 200 ft	≤ 453.4**	≤ 10 cfs	Lowest (1950s) historical value; 10-day average for both Barton Springs and Lovelady.

*based upon survey elevation of 653.4 ft-msl LSD
**10-day average

Drought Indicators: Barton Springs and the Lovelady Well

LBG-Guyton (2005) used multivariate and other analyses to demonstrate that the aquifer contains both conduit and diffuse flow/storage (**Appendix A-2**). It was determined that the best measure of these components is a combination of the discharge from Barton Springs and the water level in the Lovelady monitor well. Barton Springs discharge is a measure of the overall condition of the aquifer with dynamic responses integrating combined conduit, fracture, and matrix flow from the system. In other words, discharge at Barton Springs integrates all measures of storage and flow in the system. However, under certain recharge or high-flow conditions, the conduit (transient) aspect of the system can dominate the discharge. Water levels in the Lovelady well are muted, less influenced by conduit flow, and more indicative of diffuse flow and the overall amount of water in storage. In addition, the Lovelady well was chosen as the best index well because of its long period of record and easy access. Overall, there is a good correlation (R^2=0.84) between Barton Springs and the Lovelady well during drought conditions (**Figure 9**).

The BSEACD should also consider other hydrologic factors that may have some relevance to the urgency of declaring a drought, or that may indicate that a drought is likely to continue regardless of spring discharge or water levels. Those factors include: rainfall, stream flow (especially the Blanco River), regional drought indices, and water levels in other wells (**Appendix A-4**).

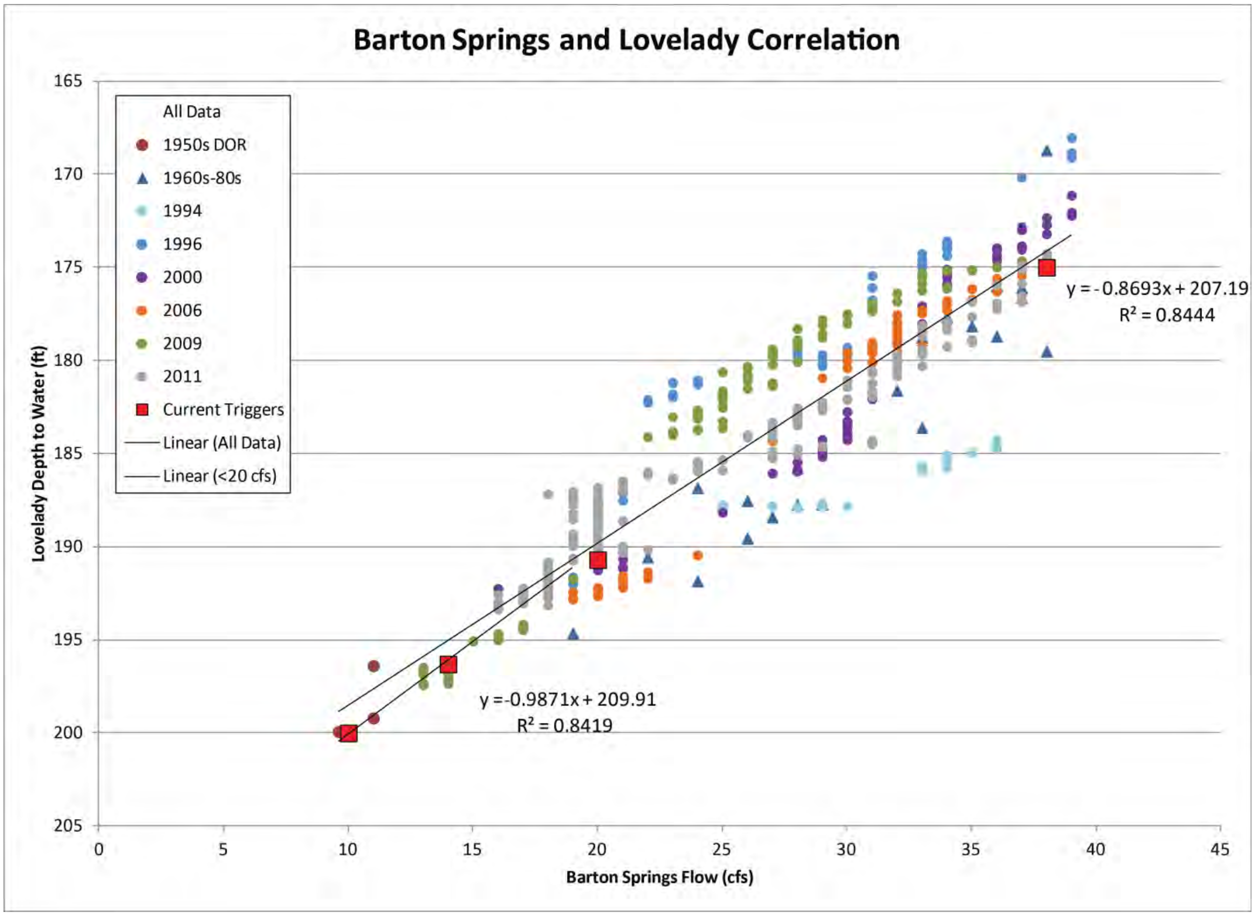

Figure 9. *Barton Springs and Lovelady correlation and regression chart.*

Drought Triggers

Barton Springs flow was the primary controlling factor for setting drought triggers or thresholds. Once springflow triggers were established, a corresponding water level was correlated to the Lovelady well. There is a good correlation between Lovelady and Barton Springs flow under drought conditions (**Figure 9**). **Table 3** summarizes the DTM with its key elements and rationales for the drought triggers. Owing to the spikes in springflow in response to minor rain events, and the inaccuracies of flow measurements, a ten-day average of springflow is used for the trigger for Barton Springs. Although the water levels in the Lovelady well are more stable than flow from Barton Springs, a 10-day average water level elevation is also used for the Lovelady well during the Emergency Response Period. This is because small variations in instrument precision and other cyclical effects such as barometric pressure changes can significantly affect small differences in the water level measurements at the Lovelady well.

Stage I-Water Conservation Period

Corresponds to the time of highest levels of pumping during the hot summer months from May-September (**Figure 3**). This is a voluntary reduction every year, similar to City of Austin's summer conservation program, and is meant to raise general awareness about water conservation. It is calendar-driven and because there is no trigger based on aquifer conditions, it is not considered an actual groundwater drought stage *per se*.

Stage II-Alarm Drought

Corresponds to the 10-day running average of Barton Springs flow equal to or less than 38 cubic feet per second (cfs); or when the water level elevation in the Lovelady monitor well is ≤ 478.4 feet above mean sea level. This trigger generally corresponds to levels when overflow springs (Upper Barton Springs) within the Barton Springs complex cease flowing, and precedes a prominent decrease in the springflow recession slope. This also correlates to "low flow" conditions and when major ion chemistry changes at Barton Springs (Johns, 2006). These levels represent approximately the 25th percentile of data for both Barton Springs and the Lovelady well.

Stage III-Critical Drought

Corresponds to the 10-day running average of Barton Springs flow equal to or less than 20 cubic feet per second (cfs); or when the water level elevation in the Lovelady monitor well is ≤ 462.7 feet above mean sea level. Critical drought trigger levels were set with sufficient margins so that these measures would be taken well before aquifer conditions reach historic DOR levels that could threaten the endangered salamanders at Barton Springs. However, BSEACD-sponsored studies recently showed that "take" of the salamanders begins at about this threshold (Woods, et al, 2010). These levels generally correspond to the 5th percentile of data for both Barton Springs and the Lovelady well.

Stage IV-Exceptional Drought

Corresponds to the 10-day running average of Barton Springs flow equal to or less than 14 cubic feet per second (cfs); or when the 10-day running average water level elevation in the Lovelady monitor well is ≤ 457.1 feet above mean sea level. This level is equivalent to the lowest flow measured since daily values have been collected at Barton Springs beginning in 1978. At this level, Old Mill Springs, within the Barton Springs complex, is near zero cfs discharge (BSEACD, 2007).

Emergency Response Period (ERP)

Corresponds to the 10-day running average of Barton Springs flow equal to or less than 10 cubic feet per second (cfs); or when the 10-day average water level elevation in the Lovelady well is ≤ 453.4 feet above mean sea level. This is the lowest recorded value at Barton Springs that occurred during the DOR, although as noted above, other droughts have been more severe and have not extirpated the salamander population or prevented its recovery in the wild. The ERP, which is a defined period in the deepest part of a Stage IV-Exceptional Drought, is the last drought declaration the current rules provide. Specific measures to be implemented to reduce groundwater demand during ERP will be determined by the Board, but they generally include the most stringent curtailments for all permittees.

Criteria for exiting a drought stage are the reverse of those for entering the stage, except both Lovelady and Barton Springs must be above their respective trigger levels. Because flow at Barton Springs is very sensitive to minor rain events, it is necessary to use Lovelady water levels as additional confirmation of the end of a drought. Additional factors will be monitored for consideration by staff for verification and validation of drought status. Those factors include: rainfall, regional stream flow, regional drought indices, and water levels in certain other wells (**Appendix A-4**).

Evaluation of the Drought Trigger Methodology: 2006, 2009, and 2011 droughts

The current DTM is simpler to implement and communicate to the public and users-at-large; and focuses on Barton Springs, a well-known, very visible, and highly valued feature; is representative of aquifer-wide drought conditions; and improves the timing of entering into drought stages. The best way to understand the functioning of the DTM is to review its implementation during recent droughts (**Table 4**; **Figure 10**).

The DTM as applied to these recent droughts appears to be functioning in a representative and consistent manner. Barton Springs and the Lovelady well entered their respective Stage II-Alarm thresholds ranging from about 40 days to 2 days. Lovelady data during the drought periods was much more stable than Barton Springs which tended to jump temporarily above its triggers during each of the three droughts due to minor rainfall events.

The Lovelady well was the indicator that consistently took the BSEACD out of drought stages. Due to its karstic nature, Barton Springs typically exits its respective drought triggers up to 2.5 months before the Lovelady well.

Figure 10 highlights that there is up to about a month of delay between crossing a drought threshold and the official declaration. Often that is caused by the frequency and timing of Board Meetings combined with the uncertainty and revisions of springflow data. Thresholds were chosen to take into account this delay. In addition, the various triggers have been changed slightly over the years as noted in the Preface of this report.

Table 4. *Table of recent droughts applying the 2006 DTM.*

Drought Years	Official Declaration Date	Drought Status	Duration (Months)	Comments
2006-7	February 6, 2006	Alarm	7.3	New drought trigger methodology adopted by Board on 1/26/06. Alarm drought declared 10-days later when 10-day average was below trigger
	September 14, 2006	Critical	4.4	Barton Springs daily mean low of 19 cfs (Sept-06)
	January 24, 2007	Alarm	1.9	
	March 22, 2007	No Drought	15.3	Third wettest year on record
	June 23, 2008	Alarm	5.7	
2008-9	December 11, 2008	Critical	10.5	Barton Springs daily mean low of 13 cfs (Sept-09)
	October 22, 2009	Alarm	1.9	
	December 17, 2009	No Drought	16.6	Hurricane Alex and Tropical Storm Hermine
2011-12	April 28, 2011	Alarm	4.4	
	September 8, 2011	Critical	5.6	Driest and hottest year on record; Barton Springs daily mean low of 16 cfs (Nov-11)
	February 23, 2012	Alarm	0.9	
	March 22, 2012	No Drought	7.9	
2012-13	November 15, 2012	Alarm	5.1	
	April 17, 2013	Critical	6.3	
	October 24, 2013	Alarm	0.9	Wet September and wettest October on record
	November 19, 2013	No Drought		

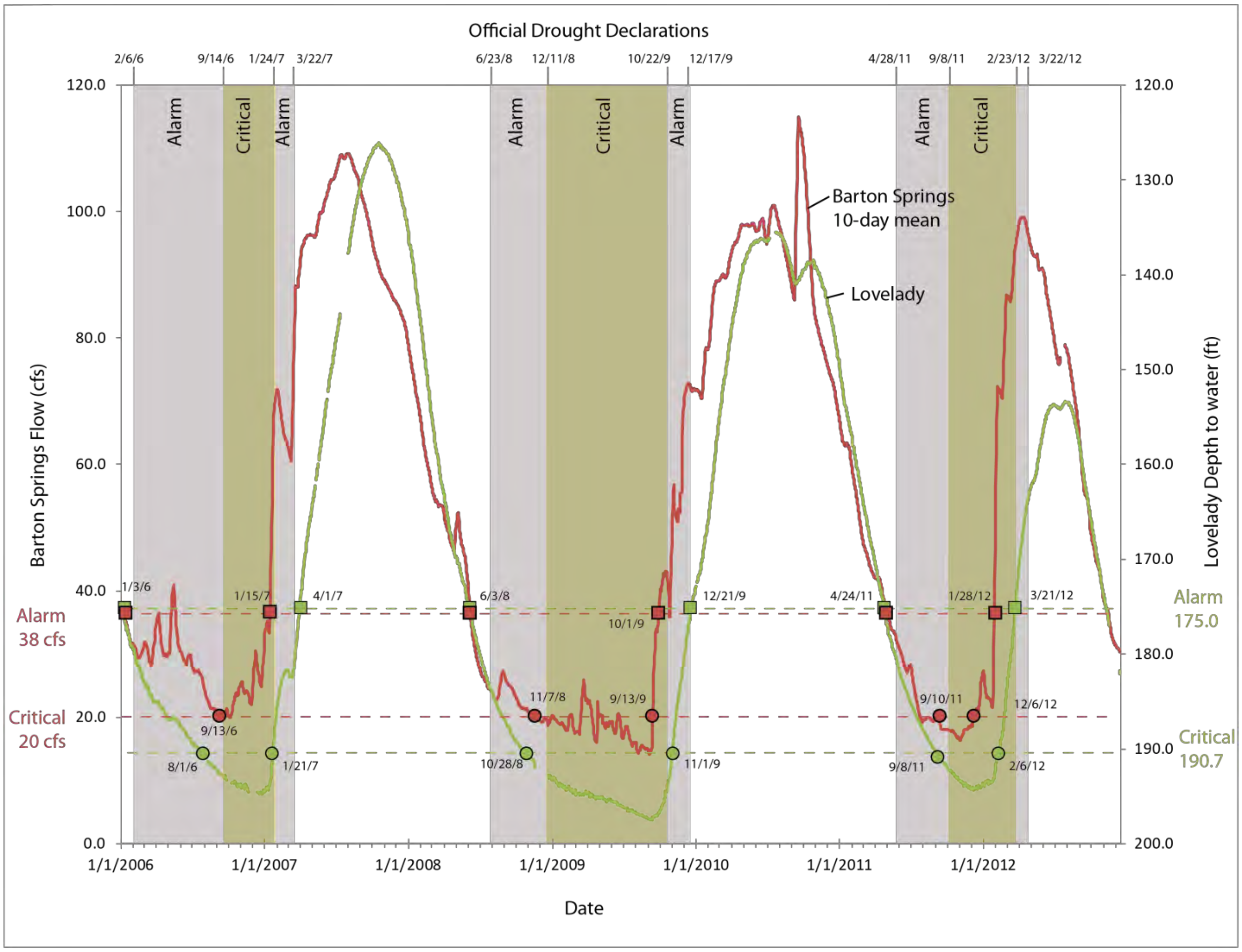

Figure 9. *Hydrograph drought indicators for the 2006-7, 2008-9, and 2011-12 drought periods. Only Alarm and Critical stages have been declared to date (December 2013). Shaded areas indicate official drought periods with dates indicated at top. Circles and squares indicate date at which each indicator crossed its respective threshold. Lovelady triggers shown as depth to water (ft).*

Middle Trinity Aquifer

The Middle Trinity Aquifer is an increasingly utilized aquifer system within the BSEACD. However, insufficient historical data exist to generate a drought index well specifically for managing the aquifer system in the BSEACD. Other data from Middle Trinity wells in the Hill Country show a decreasing trend of water levels and suggests that setting a static threshold for water levels would not work. However, **Figure 11** illustrates that both the Edwards and Middle Trinity Aquifers respond similarly to regional drought indices (PHDI). Accordingly, when the Edwards water levels (or springflow) indicate drought, water levels are also lower within the Middle Trinity Aquifer. Until future studies focused on the Trinity suggest otherwise, the DTM outlined in **Table 3** should be used to trigger drought declarations for both the Edwards and Trinity Aquifers within the BSEACD.

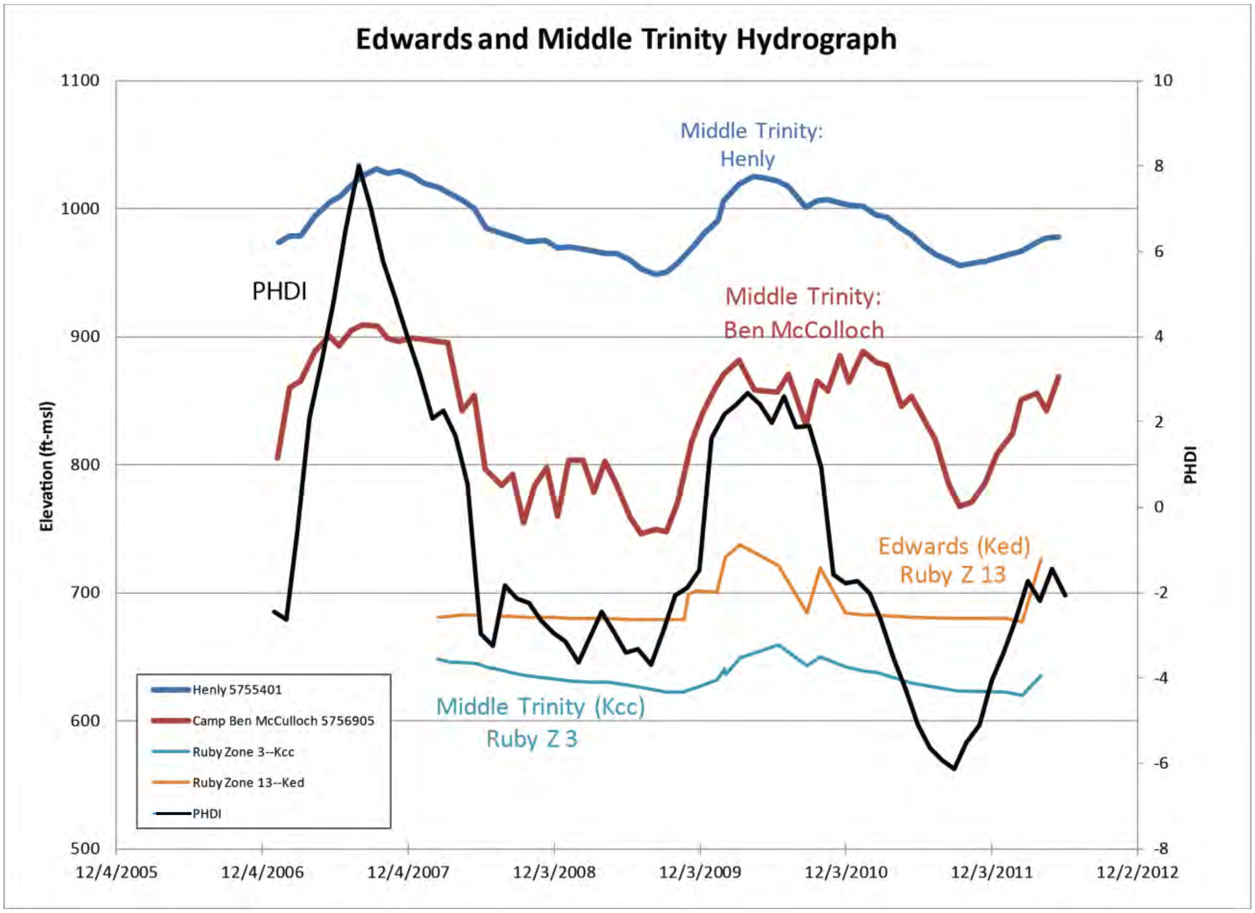

Figure 11. *Hydrograph of the Edwards and Middle Trinity Aquifers compared to a regional drought index, the Palmer Hydrologic Drought Index (PHDI). Edwards and Trinity water levels from the BSEACD's Ruby Ranch multiport monitor well contain both the Edwards and Middle Trinity levels. Other Middle Trinity well data are from west of the BSEACD in the HTGCD. All data reflect the regional hydrologic indices (PHDI).*

DISCUSSION

The DTM outlined in this report is an effective system for declaring groundwater droughts and managing groundwater resources in the BSEACD. However, a number of uncertainties with this, or any DTM that is used by the BSEACD, will remain. Any change in the overall aquifer water budget will affect how the aquifer needs to be managed, and thus any DTM in practice. Some of these areas of uncertainty include climate change, other sources of recharge (urban, cross-formational; boundary conditions), endangered species habitat requirements, and accurate Barton Springs discharge data.

Climate Change

The International Panel on Climate Change (IPCC) has determined that warming of the global climate is unequivocal, and emissions of greenhouse gases emitted by humans are largely responsible for the warming over the past 100 years (IPCC, 2007). In the future, the net global effect of the warming, even if no additional greenhouse gases are emitted, will be increased precipitation, though with variable distribution and intensity. Extreme weather events, such as, heat waves, flooding, and drought, will continue to increase in frequency and intensity (IPCC, 2007; UT, 2008).

While Global Circulation Models (GCMs) are a key tool for predicting and analyzing climate change, and regional predictions for Texas are reported (Seager et al., 2007), GCMs are not yet accurate enough for predicting and assessing impacts in many regional areas such as Texas. For example, rainfall is a key variable to assess environmental impacts (Leung, 2008); however, rainfall predictions from GCMs have the lowest confidence of simulated results and a lot of variability. Most GCM models suggest a "general drying" for Texas (Washington, 2008), but this is not consistent with Texas' regional rainfall and streamflow trends (Nielson-Gammon, 2008; Singh, 2008; Leung, 2008; Hunt et al., 2012). The last 30 years have been warming faster than the global average, and have been accompanied by an unusually wet period in Texas, punctuated with more extreme events that are expected to continue into the future (Nielson-Gammon, 2008; North, 2008).

Texas will get hotter and climate change will exacerbate stresses already imposed upon water resources (Hayhoe, 2008). Climate in Texas continues to change, although current impacts from those changes have not been observed as they have in the U.S. Southwest such as Arizona (Woodhouse, 2008). It is expected that rapidly responding aquifers, such as the Edwards Aquifer, will be more sensitive to changes in climate (Mace, 2008). However, to date, no trends have been observed, in recharge since the 1930s for the larger San Antonio segment of the Edwards Aquifer (Loaiciga, 2008). A study of global warming impacts on the San Antonio segment of the Edwards Aquifer by Chen et al (2000) predicts that annual temperatures will rise (~3F) and annual rainfall will decrease (~4 in) by 2030 resulting in a 20% decrease in recharge during droughts. Hunt et al. (2012) show increasing temperatures and hydrologic (stream and springflow) variability increasing over the past 40 years. Increasing demand due to population growth and rising temperatures will be the dominant factors affecting springs and groundwater availability (Mace, 2008; Loaiciga, 2008). Climate change will likely exacerbate these impacts.

Governmental agencies and other organizations that participate in water resource planning are either currently planning for the potential changes due to climate change, or they intend to incorporate that into future planning. Hirsch (2008) recommended the following approach to water management: 1) collect more data; 2) consider paleoclimate records; 3) keep an eye on climate science and change; and 4) don't lose sight of other stresses (e.g. population & demand, urbanization, return flows, etc).

Other Sources of Recharge

There is now evidence that intra-aquifer flow from the San Antonio segment and urban leakage are two additional sources of recharge to the Barton Springs aquifer. None of the current models or water budgets explicitly incorporates these sources, although they are indirectly incorporated into the overall budgets. Additional (increasing) sources of recharge could have significant implications for estimating and managing extreme low flow and drought conditions at Barton Springs.

The southern groundwater divide is now known to be dynamic, fluctuating between Onion Creek under wet conditions, and the Blanco River under drought conditions (Smith et al., 2012). Casteel et al. (2013) demonstrates that increases in recharge along the Blanco River can result in measureable responses of discharge of 1-2 cfs at Barton Springs. In addition, other recent studies have shown the potential for a portion of the Edwards Aquifer groundwater to bypass San Marcos Springs and flow toward Barton Springs under drought conditions (Land et al. 2010; Smith et al., 2012). Recharge arising from this "leaky divide" may serve to sustain the springflow at Barton Springs during extreme drought events, meaning that springflows at Barton Springs remain at higher levels for a longer period of time than otherwise simulated for severe drought conditions in a closed system. It could also mean that Barton Springs flow is impacted by changes to flows in the Blanco River.

Another source of recharge is anthropogenic in nature and generally countervails the assumption that groundwater quantity and springflow will decline as a result of urbanization and increased impervious cover in the recharge and contributing zones of the Barton Springs watershed. Investigators have determined that there is a substantial "indirect recharge," or leakage from utility networks (water mains, wastewater and storm sewers, and on-site sanitation systems), irrigation return flow, and stormwater management infiltration devices constructed in the Barton Springs watershed. Leakage from pressurized water mains, for example, is typically known to result in utility-scale, unaccounted-for water losses on the order of 10-30% (Foster et al. 1994); they have been measured on the order of 12% in the service area of the City of Austin (Sharp and Garcia-Fresca 2004). Irrigation return flow, or overwatering of lawns, parks and other turfs and pervious landscapes, is especially common in summer months, when the impacts of drought and low flow on the Barton Springs complex may be severe (Garcia-Fresca and Sharp 2005).

These indirect sources of recharge, and the permeability of what is often called "impervious cover" appear to generally compensate for the decrease of direct recharge arising from increased urbanization (Wiles and Sharp 2008; Sharp and Garcia-Fresca 2004; and Garcia-Fresca and Sharp 2005). Total urban recharge to the Barton Springs aquifer from anthropogenic recharge accounts for 4% of the total recharge (between 1999 and 2000). On a monthly basis anthropogenic recharge can vary from <1 to 59% of total recharge. Irrigation return flows are the most significant contributor during peak anthropogenic recharge, while leakage from utility lines is volumetrically most significant over the study period (Passarello, 2011).

Endangered Species Habitat Requirements

As more information regarding the endangered Barton Springs salamander emerges, certain springflow requirements may oblige the BSEACD to modify the DTM. The Habitat Conservation Plan developed by the BSEACD as part of its Incidental Take Permit from the U.S. Fish and Wildlife Service (BSEACD, in preparation) is based on the latest scientific studies of the physiological requirements of the endangered Barton Springs salamander and the quantitative relationship between dissolved oxygen and low springflows. However, there are substantial uncertainties in both of these elements. Further, the necessary reliance on laboratory studies to examine salamander behavior in the wild introduces additional uncertainties. No study has established a measured springflow level below which the salamander population would not recover or survive; however future studies may provide such a threshold. Despite these uncertainties, it is also more likely the BSEACD would modify its mandatory drought management requirements during ERP, than modify the DTM if and when a "jeopardy" situation for the salamander is approached.

Barton Springs Flow Data

The springflow data reported by the U.S. Geological Survey (USGS) for Barton Springs can be of poor quality for periods of time. This may be especially true during low flow periods. Reported daily springflow at Barton Springs is based upon a stage-to-discharge relationship with a nearby well (58-42-903) that is operated by the USGS. However, the stage in the well is influenced by the operation and human-induced fluctuations in water levels within Barton Springs Pool and the reported flow data are frequently being corrected and revised. Further errors are introduced at the stream cross section below the pool where manual flow measurements are made and the cross section is not a stable, uniform site, and often is busy with swimmers and waders. As flow decreases, the cross section deteriorates in quality and results in some measurements rated from fair to poor (5-10% error). In addition, even the slight fluctuations in lake levels of Lady Bird Lake influence both manual and gage data (Hunt et al., 2012).

Owing to the nature of the stage-to-discharge relationship at Barton Springs and other uncertainties in the data, the USGS, City of Austin, and the BSEACD collaborate to collect frequent manual measurements to verity the reported discharge.

Trinity Aquifer

Although the DTM as presented in this report appears to function well for the Middle Trinity Aquifer, future evaluations of a DTM related to the Middle Trinity Aquifer will be necessary. Over time, the BSEACD will have more data over the entire hydrologic cycle from the Trinity Aquifer system and will be able to evaluate the effectiveness of this DTM.

CONCLUSIONS

- There are two primary components of flow in the aquifer: conduit flow and diffuse flow into or out of storage. The two components of flow are well-represented by Barton Springs and Lovelady, respectively.
- The DTM uses flow from Barton Springs and water levels in the Lovelady monitor well to determine drought status of the aquifer. The two indices have very good correlations and complementary hydrologic responses to drought and recharge for a DTM.
- The DTM satisfies the three guiding principles: 1) drought declarations must be made with sufficient time to achieve benefits of curtailment and education measures; 2) representative of aquifer-wide conditions; and 3) simple to implement.
- The Middle Trinity Aquifer reflects the same hydrologic trends in the Edwards, including drought periods.
- The DTM is an effective tool for aquifer management of the Edwards and Middle Trinity Aquifers.

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APPENDICES

A-1: Summary of drought declared by District since 1991

A-2: Multivariate Analyses (Guyton, October 2005)

A-3: Recharge, Storage, and Discharge Evaluations

A-4: Drought Rules Adopted October 11, 2012

A-1: Summary of drought declared by BSEACD since 1991

Official Declaration Date	Drought Status	Duration (Months)	Comments
25-Aug-93	Stage I - Alert	11.1	Late August "localized drought" declaration, First drought ever declared by the Board
25-Jul-94	Stage II - Alarm	2.7	
15-Oct-94	Stage I - Alert	2.0	Estimated day of declaration; flooding October 8-9, 2004
15-Dec-94	No Drought	13.2	
15-Jan-96	Stage I - Alert	3.0	Estimated day; record high heat in February near 100.
15-Apr-96	Stage II - Alarm	12.0	Buda and San Leanna dropped below Stage III - Critical
10-Apr-97	No Drought	14.9	May and June 1997 flooding; 10th wettest year on record.
2-Jul-98	Stage I - Alert	3.7	
22-Oct-98	No Drought	9.8	Widespread Flooding, one rain event brought the Aquifer to No Drought Status
12-Aug-99	Stage I - Alert	2.7	
1-Nov-99	Stage II - Alarm	13.6	
14-Dec-00	Stage I - Alert	1.9	
8-Feb-01	No Drought	30.6	Major flooding: November 15-16, 2001; July 2002
14-Aug-03	Stage I -Alert	2.6	2003 is 10th driest on record
30-Oct-03	Stage II - Alarm	2.6	
15-Jan-04	Stage I - Alert	5.3	
21-Jun-04	No Drought	19.8	Third wettest year on record.
27-Oct-05	Stage I	3.4	
6-Feb-06	Alarm	7.3	New drought trigger methodology adopted by Board on 1/26/06. Alarm drought declared 10-days later when 10-day average was below trigger; Declaration based upon 2006 DTM; Very dry 2005

14-Sep-06	Critical	4.4	Barton Springs 19 cfs (Sept-06); Very dry and hot 2006; 2006 DTM
24-Jan-07	Alarm	1.9	Very wet January (>8 inches rainfall); 2006 DTM
22-Mar-07	No Drought	15.3	Third wettest year on record
23-Jun-08	Alarm	5.7	
11-Dec-08	Critical	10.5	Barton Springs daily mean low of 13 cfs (Sept-09)
22-Oct-09	Alarm	1.9	
17-Dec-09	No Drought	16.6	Hurricane Alex and Tropical Storm Hermine
28-Apr-11	Alarm	4.4	
8-Sep-11	Critical	5.6	Driest and hottest year on record; Barton Springs daily mean low of 16 cfs (Nov-11)
23-Feb-12	Alarm	0.9	
22-Mar-12	No Drought	7.9	
15-Nov-12	Alarm	5.1	
17-Apr-13	Critical	6.3	
October 24, 2013	Alarm	0.9	Wet September and wettest October on record
November 19, 2013	No Drought		

A-2: Multivariate Analyses

A multivariate analysis was performed by LBG-Guyton (2005) on drought indicators for the Barton Springs aquifer and is summarized below. The analysis presented to the BSEACD by LBG-Guyton is attached. Data included in the principal components analysis included: springflow, water levels, precipitation, streamflow, and Palmer Hydrologic Drought Index (PHDI). Key findings of the study include:

- Precipitation is uncorrelated with the other variables.
- The Buda, Dowell, and Porter wells represent a similar grouping of water-level observations, and the Lovelady well represents a separate group of observations.
- Three variables gave the best fit with no redundancy: Porter well level, Lovelady well level, log of Blanco River at Wimberley.
- Other variables such as Dowell and Buda well levels, PHDI, and other streamflows were either redundant or degraded the fit of the multiple linear regression.
- Under the 1990 DTM, the Dowell and Buda wells appear to provide the same information. Both are highly correlated to the Porter well, but neither provides as good a correlation to springflow as the Porter well.
- An Aquifer Index (excluding springflow) was developed including terms for 3 hydrologic components in the system: a quick-response component (Porter), a slower long-term storage component (Lovelady), and a regional precipitation component (Blanco River at Wimberley).

The analysis performed a best fit of variables to springflow that eliminated redundant variables and those that add little to the fit of the regression. The study concluded with a proposed regression equation or "Aquifer Index." An "Aquifer Index" of the Porter water level, Lovelady water level, and streamflow at the Blanco River (Wimberley) gauge site corresponds well (R^2=0.92) to Barton Springs flow. The Index has a muted response when compared to temporary spikes in springflow (as in June 2000). The equation (using weekly average values) is as follows:

Aquifer Index = 0.420P + 0.474L + 14.2logBW – 445

Where:

P = Porter Well Level, ft AMSL
L = Lovelady well Level, ft AMSL
logBW = base 10 logarithm of flow (cfs), Blanco at Wimberley

Multivariate Analysis for Barton Springs Drought Triggering Methodology

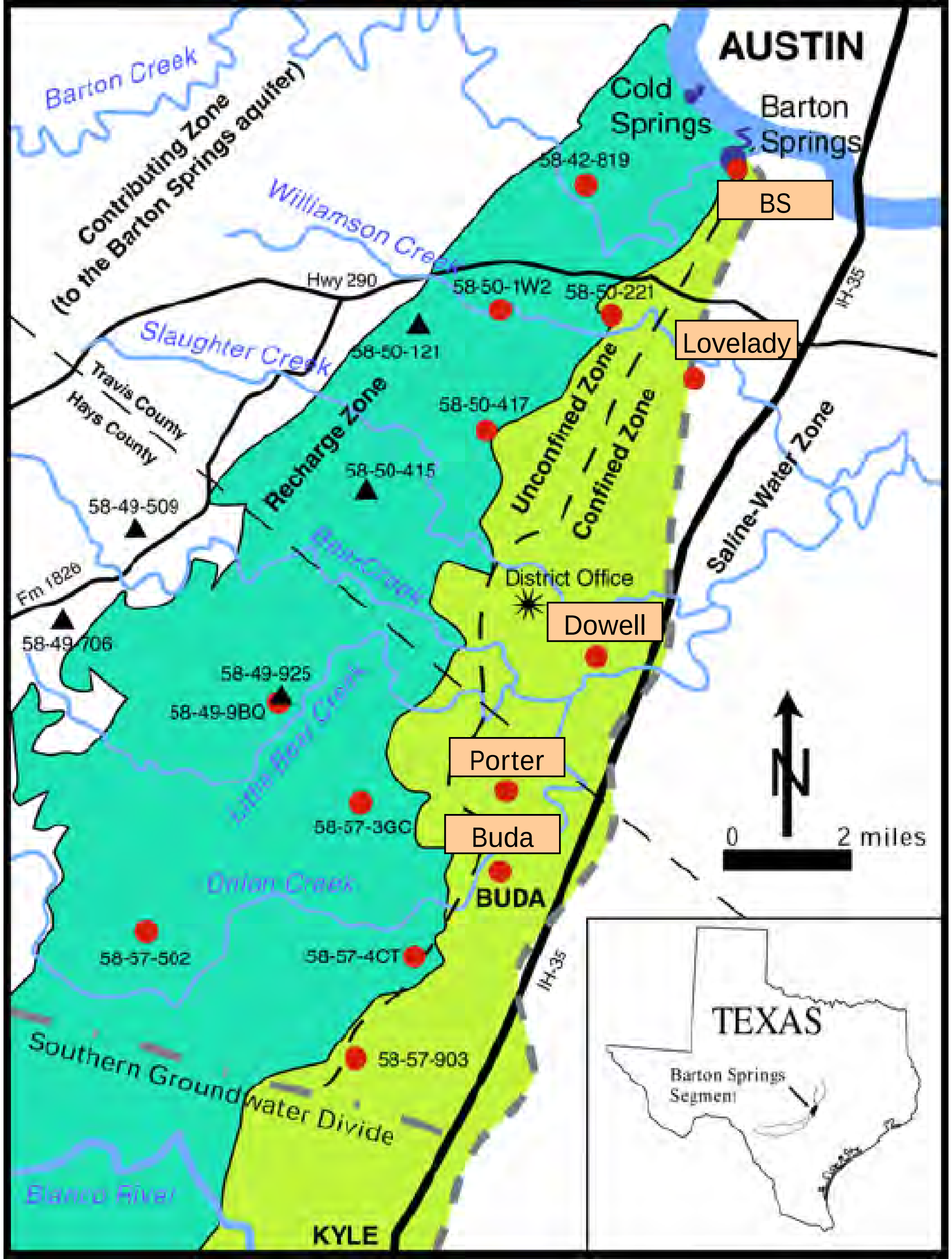
October 2005

LBG-GUYTON ASSOCIATES

Scope for Multivariate Analysis

1. Select and prepare data sets for the multivariate analysis: springflow, water levels, precipitation, streamflow, and Palmer Hydrologic drought index.
2. Perform principal components analysis on the data set.
3. Evaluate the results of the analysis in light of current drought triggering methods, suggest any potential alternative drought triggering formulations.

LBG GUYTON

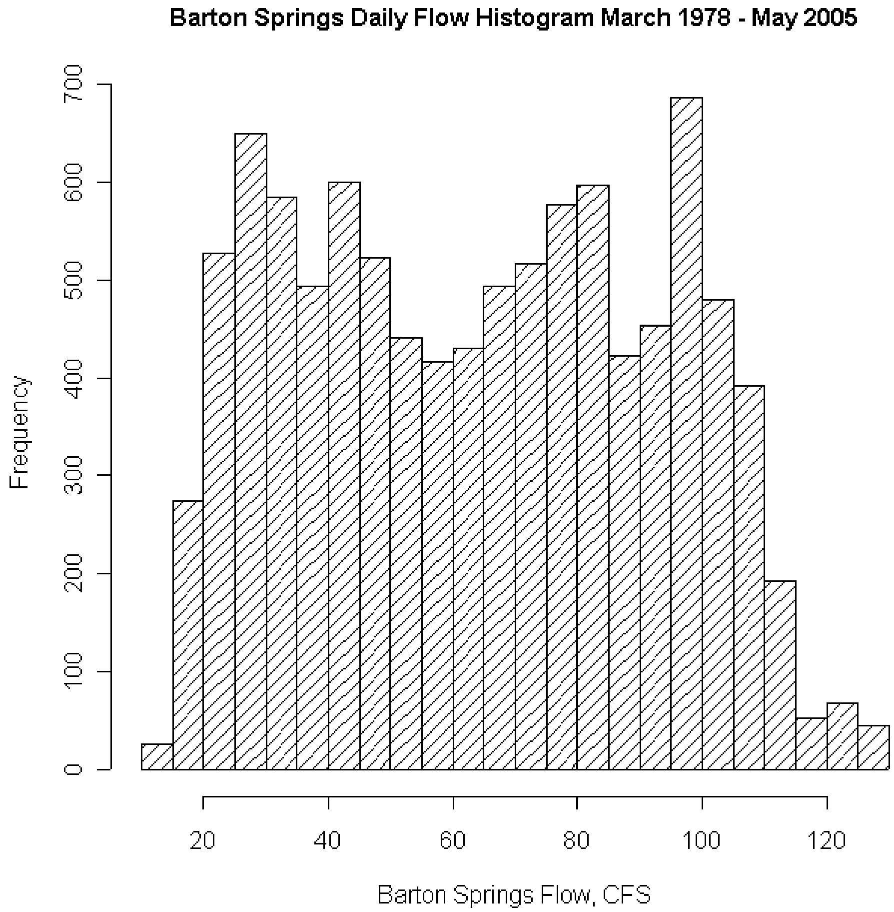


Map Source: BSEACD

Multivariate Analysis Methodology

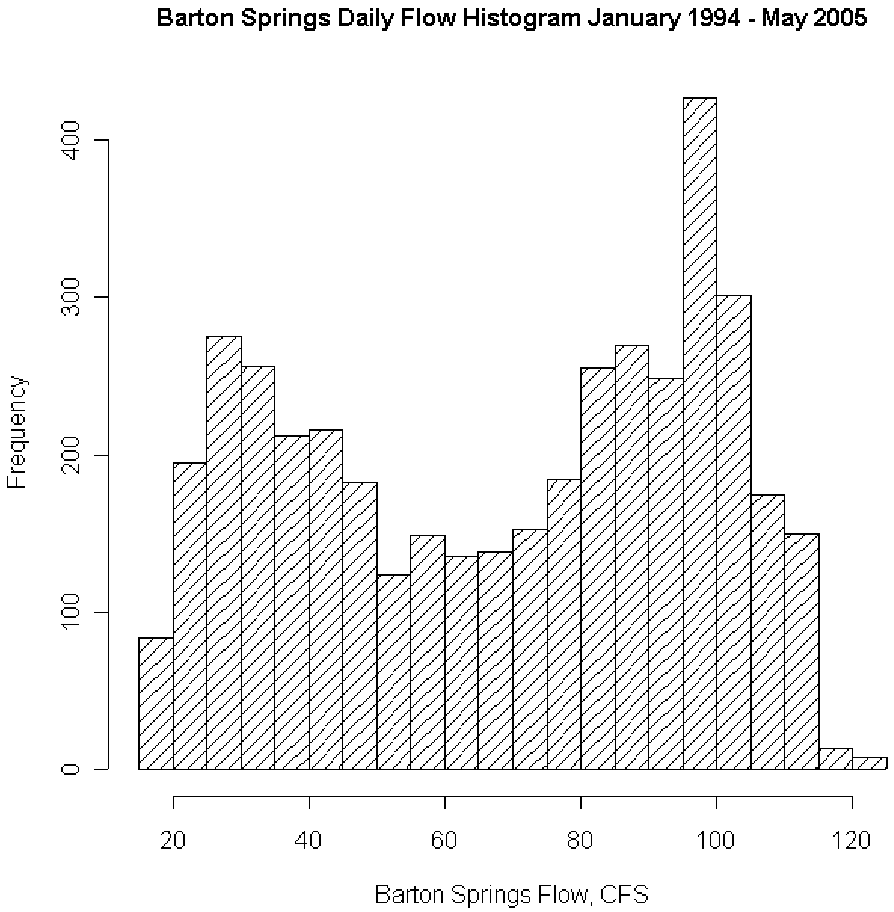
1. Review dataset and select well, precipitation, drought index, pumpage, and streamflow measurement points with records through the 1990s and at least weekly observation frequency
2. Well data that matched selection criteria: Buda, Dowell, Lovelady, and Porter
3. Precipitation and drought index data that matched selection criteria: Camp Mabry, Dripping Springs, Wimberley, San Marcos, Palmer Hydrological Drought Index
4. Streamflow data that matched selection criteria: Barton Creek at 360, Barton Creek at Lost Creek Blvd., Bear Creek at FM1826, Slaughter Creek at FM1826, Blanco River at Wimberley, Blanco River at Kyle, Onion Creek at Driftwood
5. Only monthly pumpage data was available. Like precipitation events, pumping did not correlate with any other variable on a monthly dataset because pumping and precipitation events do not scale in the same way as other variables.
6. Perform principal components analysis on correlation matrix of these data to identify similarities and differences of variables
7. Perform stepwise multiple linear regression to determine the best fit of variables to springflow, eliminating redundant variables and those that add little to the fit of the regression
8. Evaluate the regression equation as “Aquifer Index” over the time period

Barton Springs Daily Flow Histograms: Bi-modal Distribution



Barton Springs Daily Flow Histogram March 1978 - May 2005

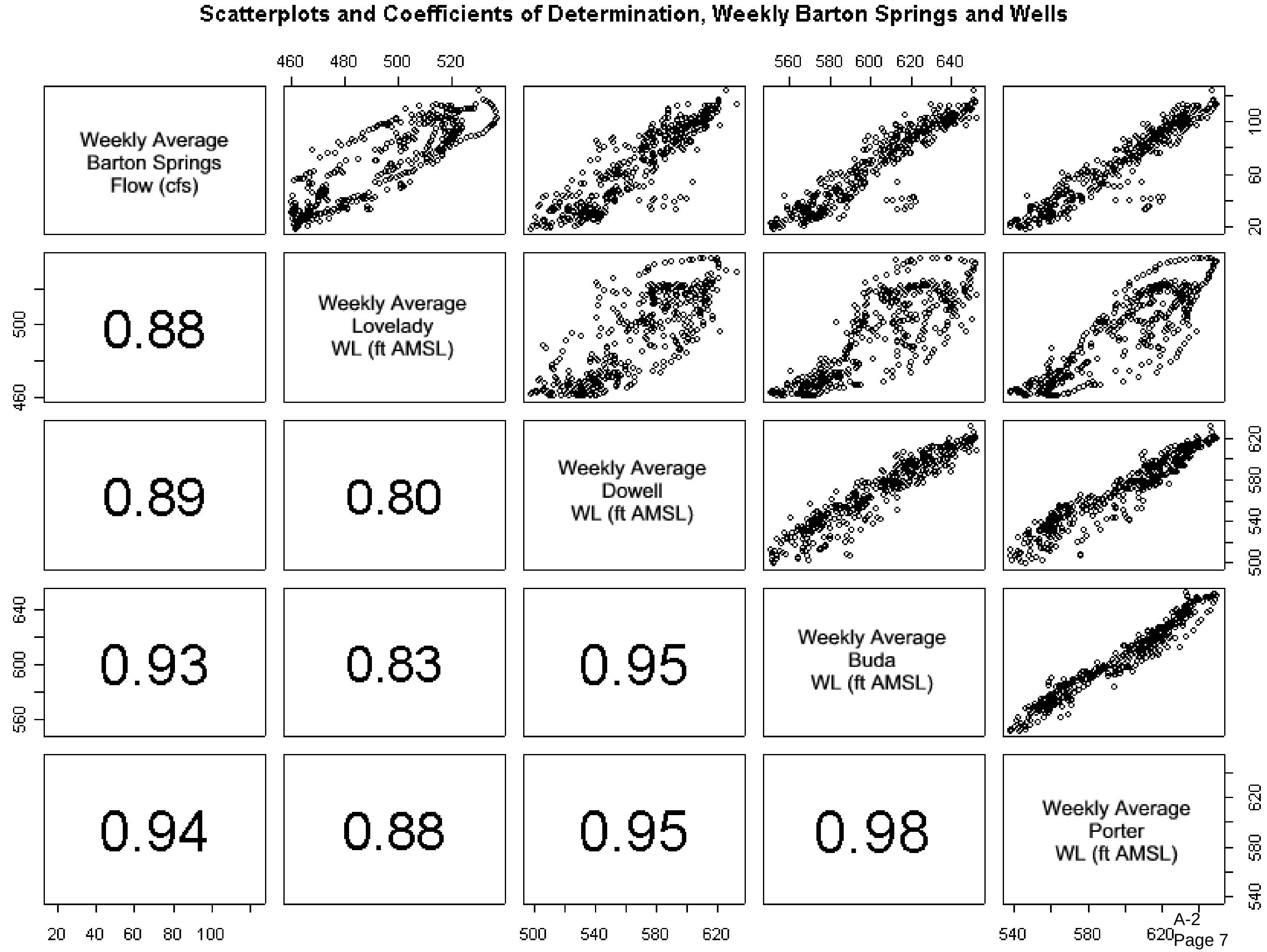
Min.	1st Quar.	Median	Mean	3rd Quar.	Max.
14	40	66	64.93	89	130



Barton Springs Daily Flow Histogram January 1994 - May 2005

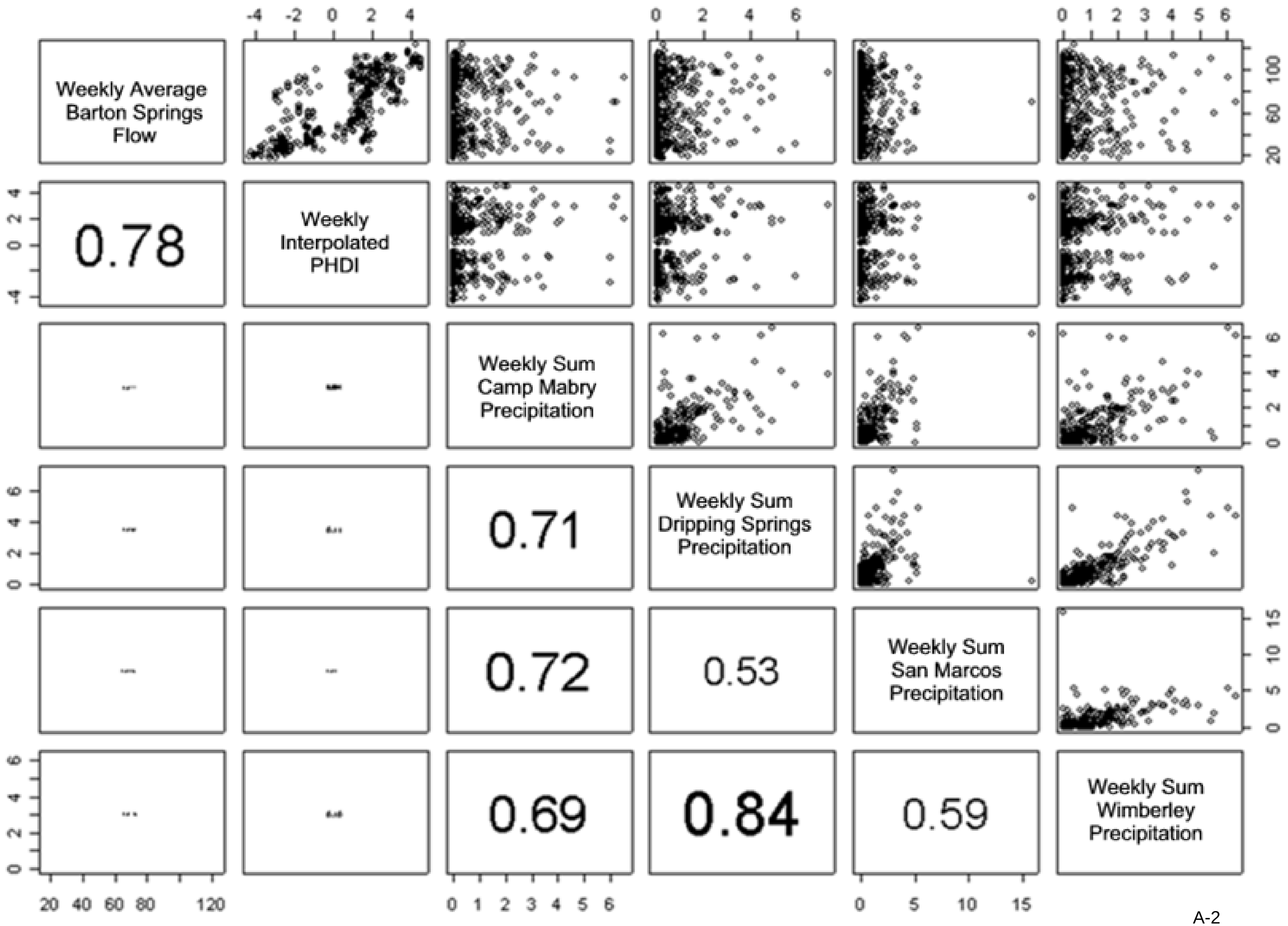
Min.	1st Quar.	Median	Mean	3rd Quar.	Max.
16	41	74	68.97	96	125

Scatterplot of Springs and Wells



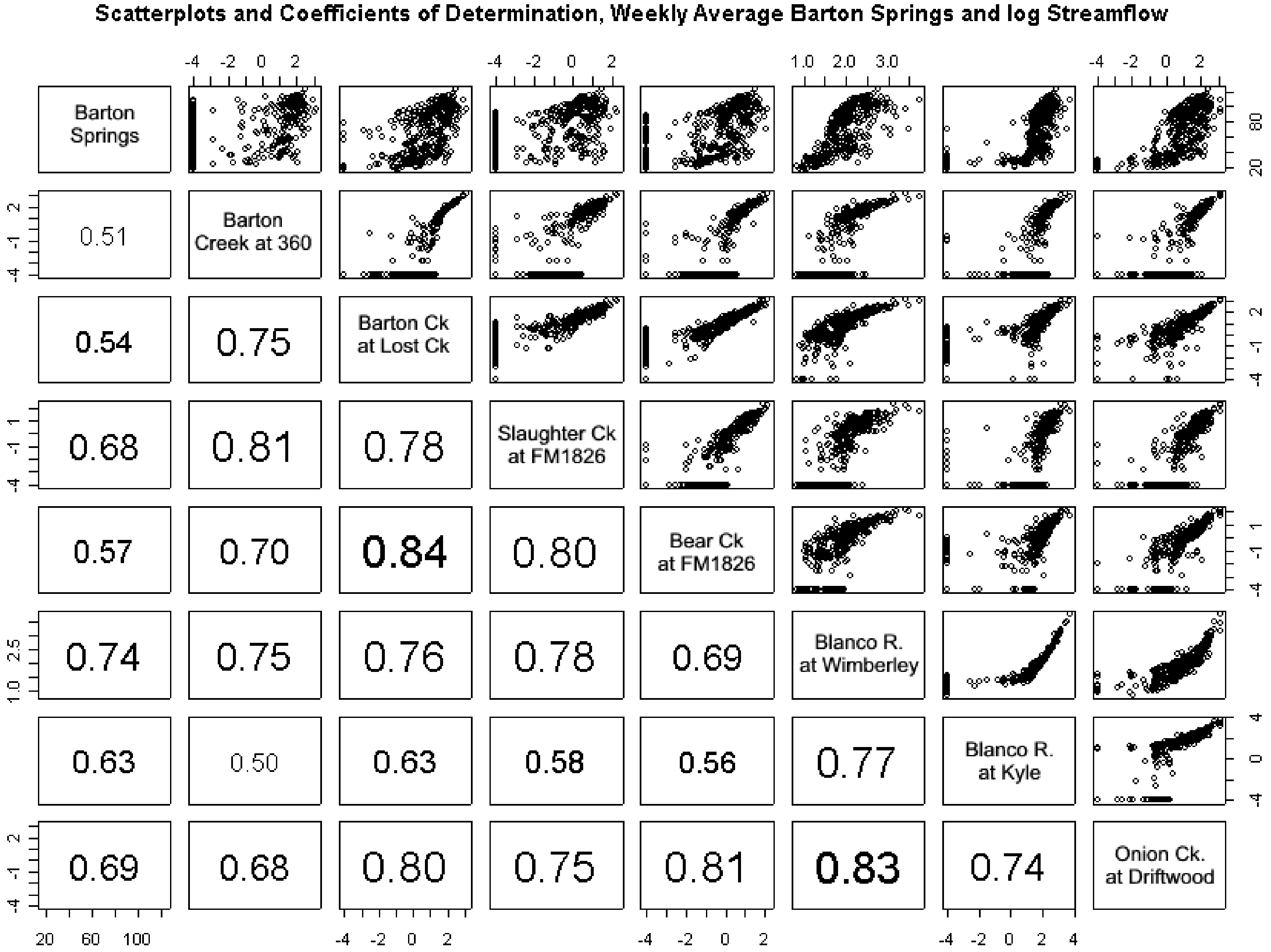
Scatterplots and Coefficients of Determination, Weekly Barton Springs and Wells

Scatterplot of Springs and Precipitation



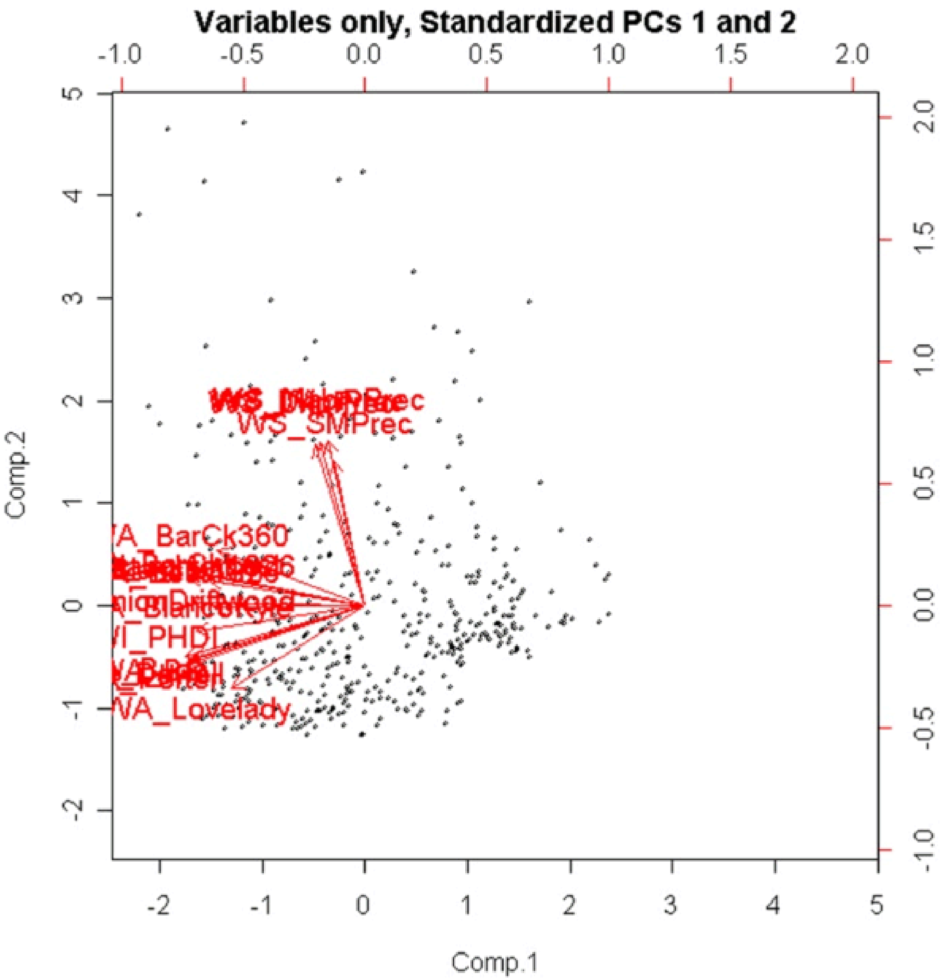
Scatterplots and Coefficients of Determination, Weekly Barton Springs and Precipitation

Scatterplot of Springs and log Streamflow



Scatterplots and Coefficients of Determination, Weekly Average Barton Springs and log Streamflow

Principal Components Analysis Summary



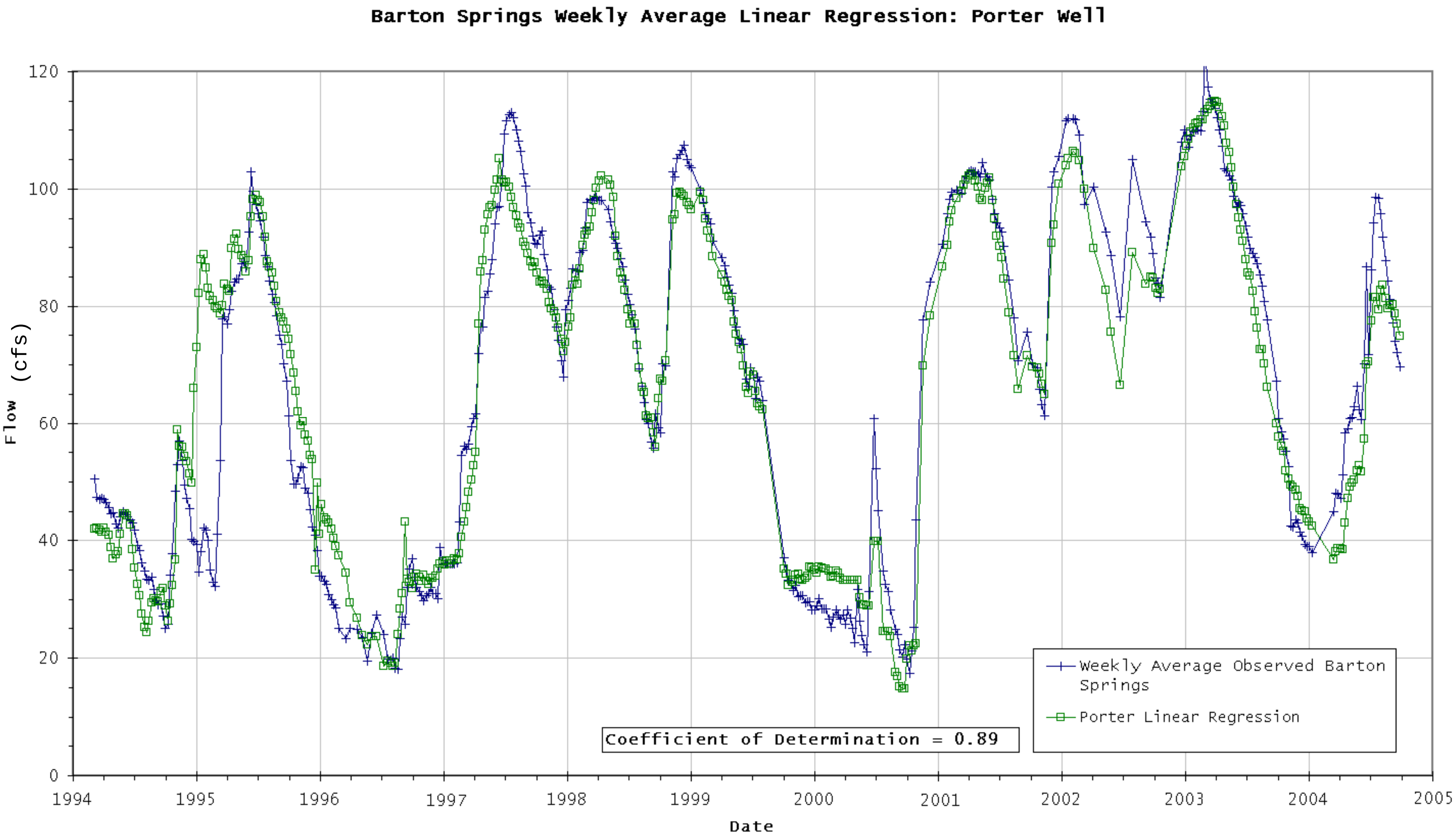
Variables only, Standardized PCs 1 and 2

- Springflow, water levels, log streamflow, and PHDI are loaded on the first component, and account for about 56% of system variance.
- The second component is a precipitation component, and is uncorrelated with the other variables. It accounts for about 19% of system variance.
- The Buda, Dowell, and Porter wells represent a similar grouping of water level observations, and the Lovelady well represents a separate group of observations.
- A stepwise multiple linear regression on Barton Springs flow can be performed for all these variables. The most important variables are likely to be those loaded on the first component. Only one of a highly correlated grouping of variables is likely to be important to the regression.

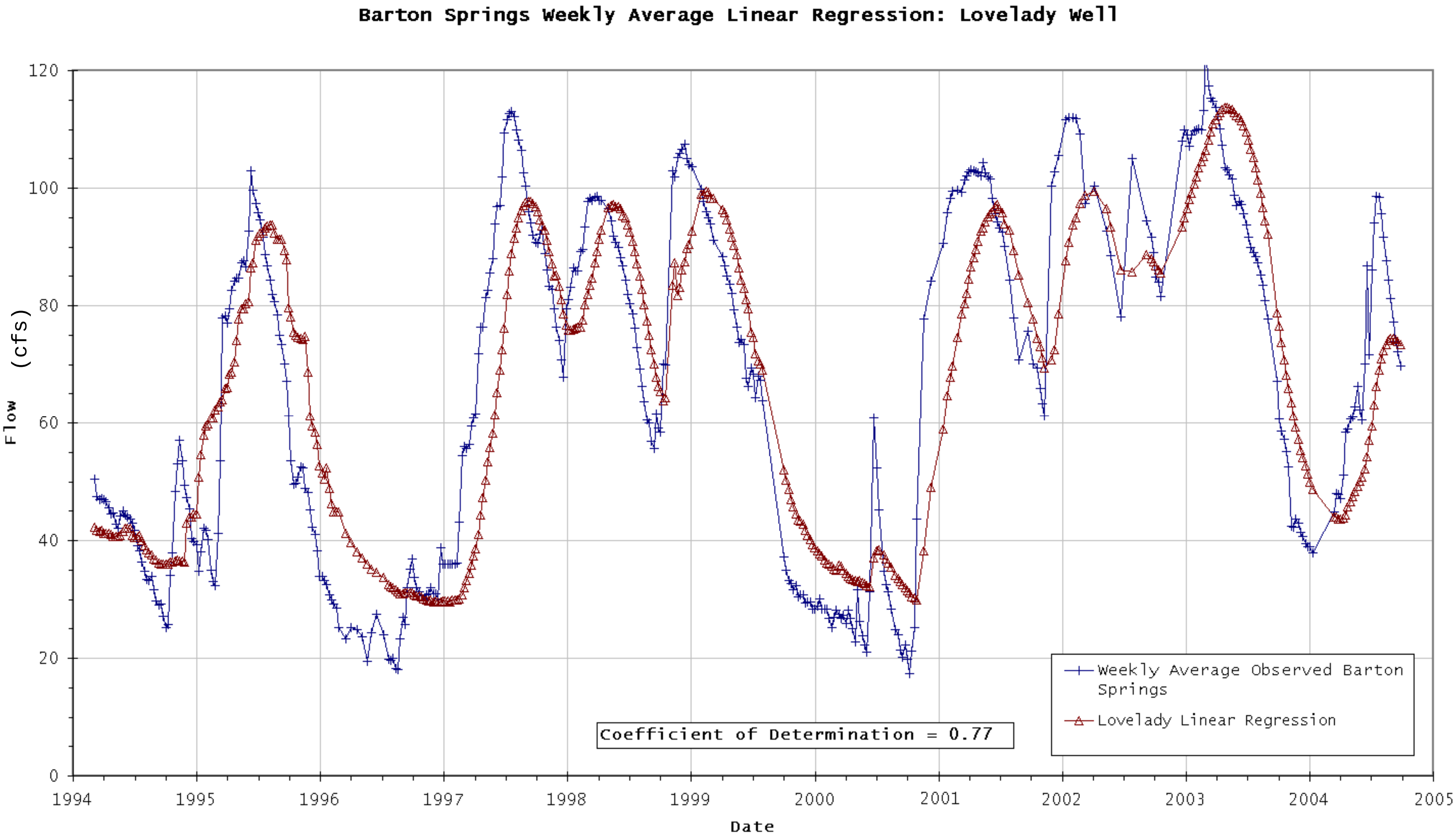
Multiple Linear Regression

- Stepwise Multiple Linear Regression on all the variables in the dataset identified 3 variables that gave the best fit with no redundancy: Porter well level, Lovelady well level, log of Blanco at Wimberley streamflow.
- Other variables such as Dowell and Buda well levels, PHDI, and other streamflows were either redundant or degraded the fit of the multiple linear regression.
- Under the current triggering methodology, the Dowell and Buda wells appear to provide the same information. Both are highly correlated to the Porter well, but neither provide as good a correlation to springflow as the Porter well.
- An “Aquifer Index” of the Porter-Lovelady-BlancoWimberley Multiple Linear Regression corresponds well to springflow, while avoiding temporary spikes.

Linear Regression on Porter Well

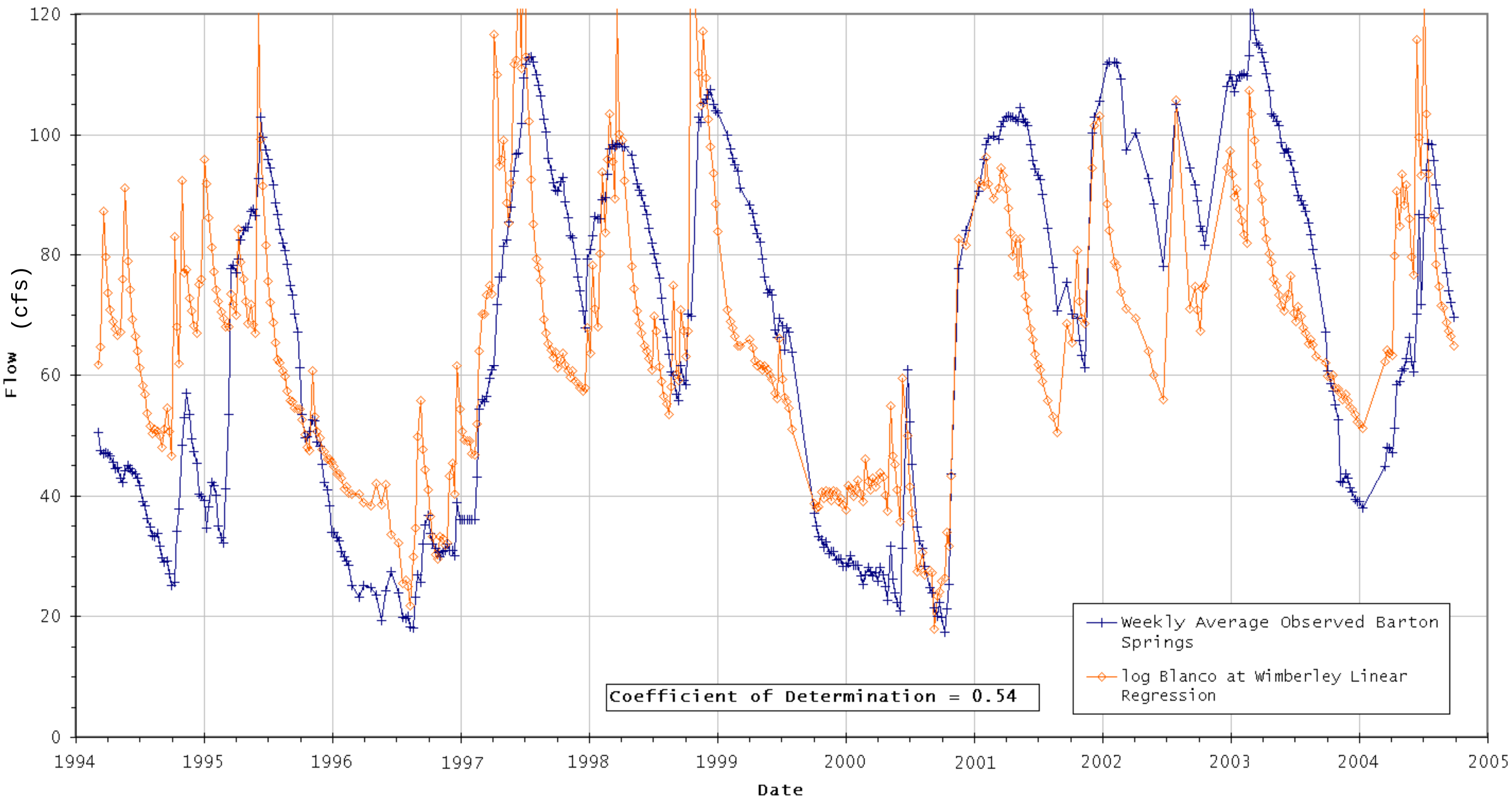


Linear Regression on Lovelady Well

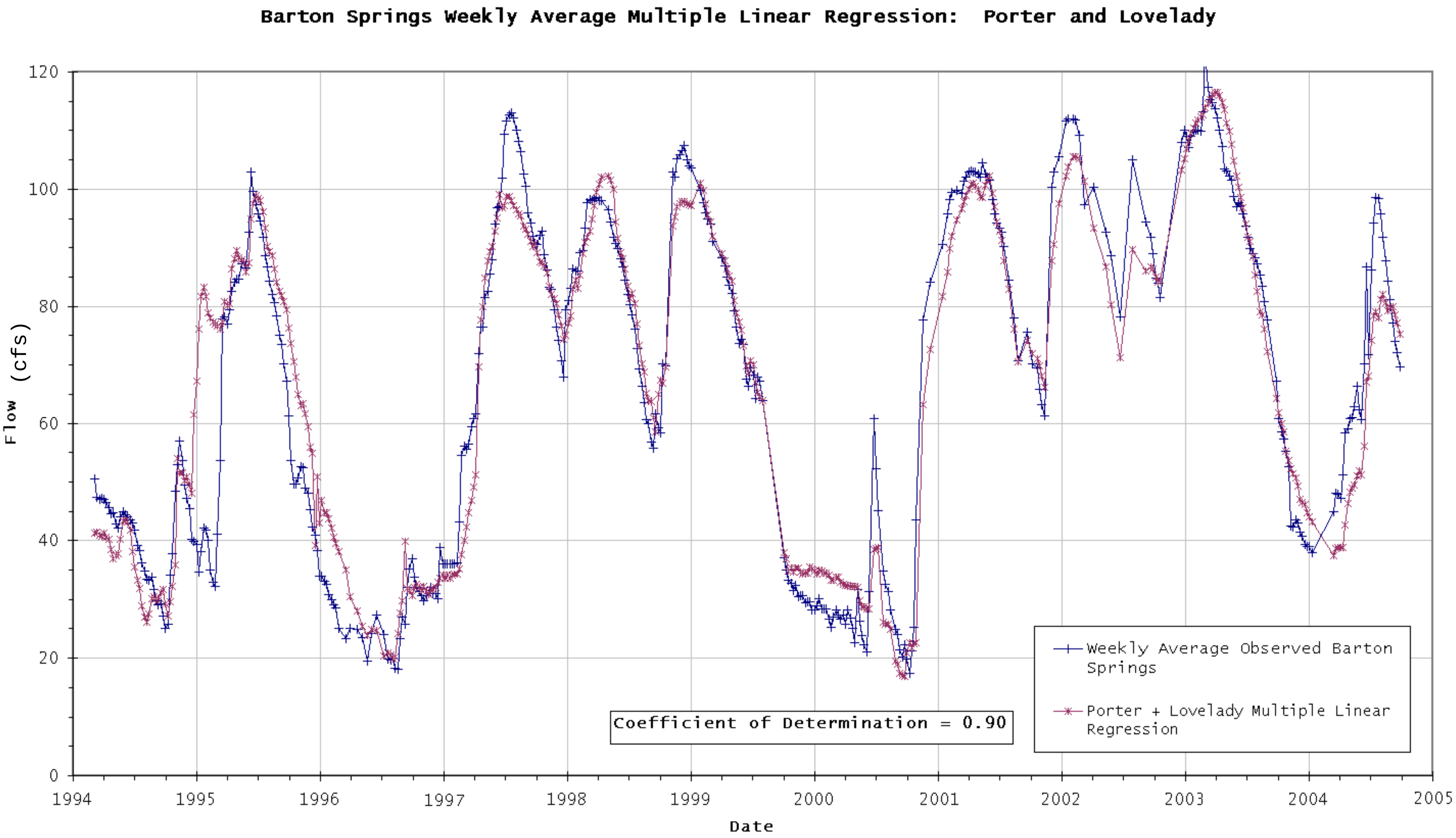


Linear Regression on log Blanco River at Wimberley

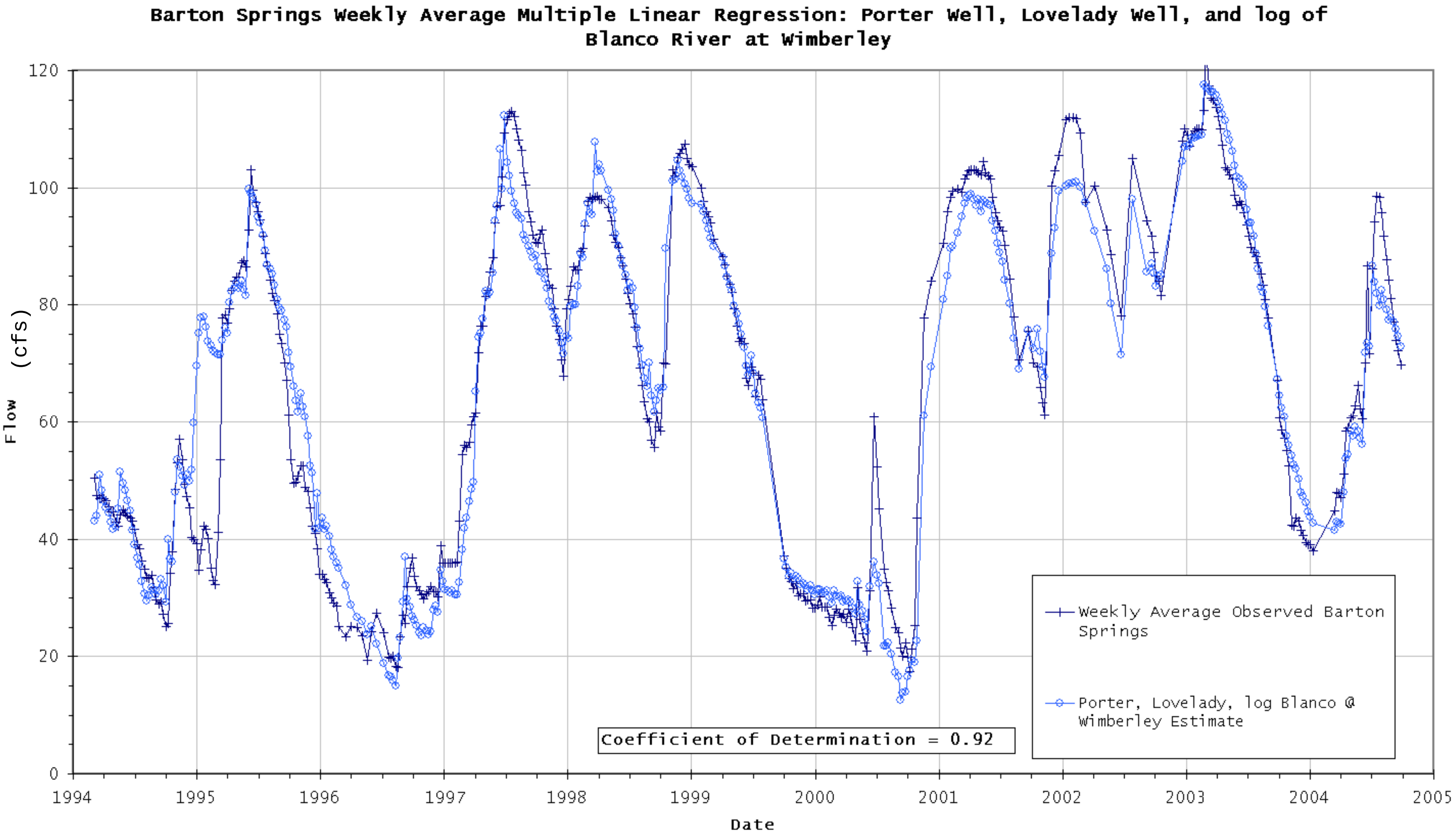
Barton Springs Weekly Average Linear Regression: log Blanco River at Wimberley



Multiple Linear Regression on Porter and Lovelady Wells



Multiple Linear Regression on Porter, Lovelady, and log Blanco at Wimberley



Regression Equation: Porter, Lovelady, and log Blanco at Wimberley

Using Weekly Average Values:

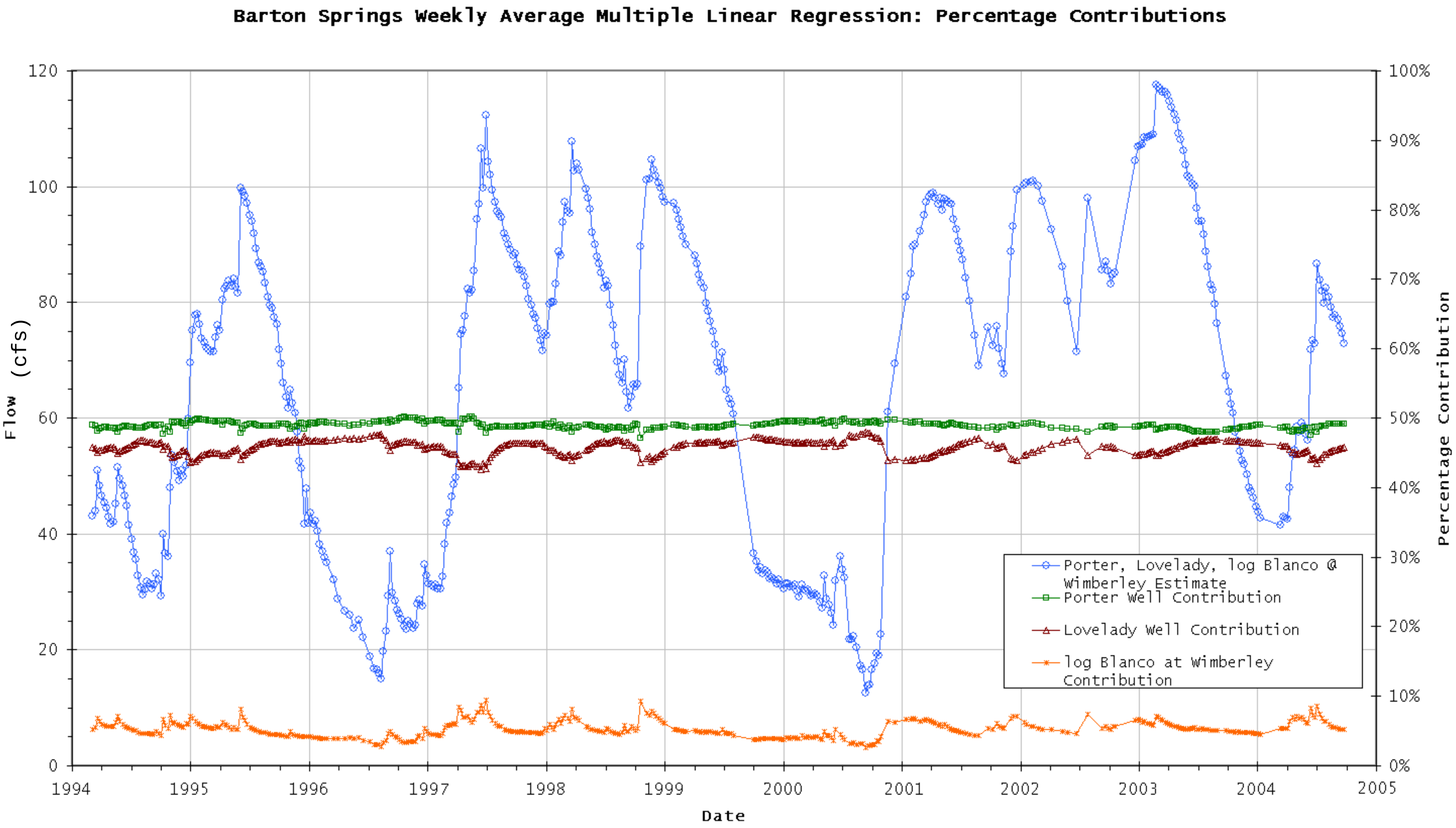
Aquifer Index = 0.420P + 0.474L + 14.2logBW – 445

P = Porter Well Level, ft AMSL
L = Lovelady Well Level, ft AMSL
logBW = base 10 logarithm of flow (cfs), Blanco at Wimberley

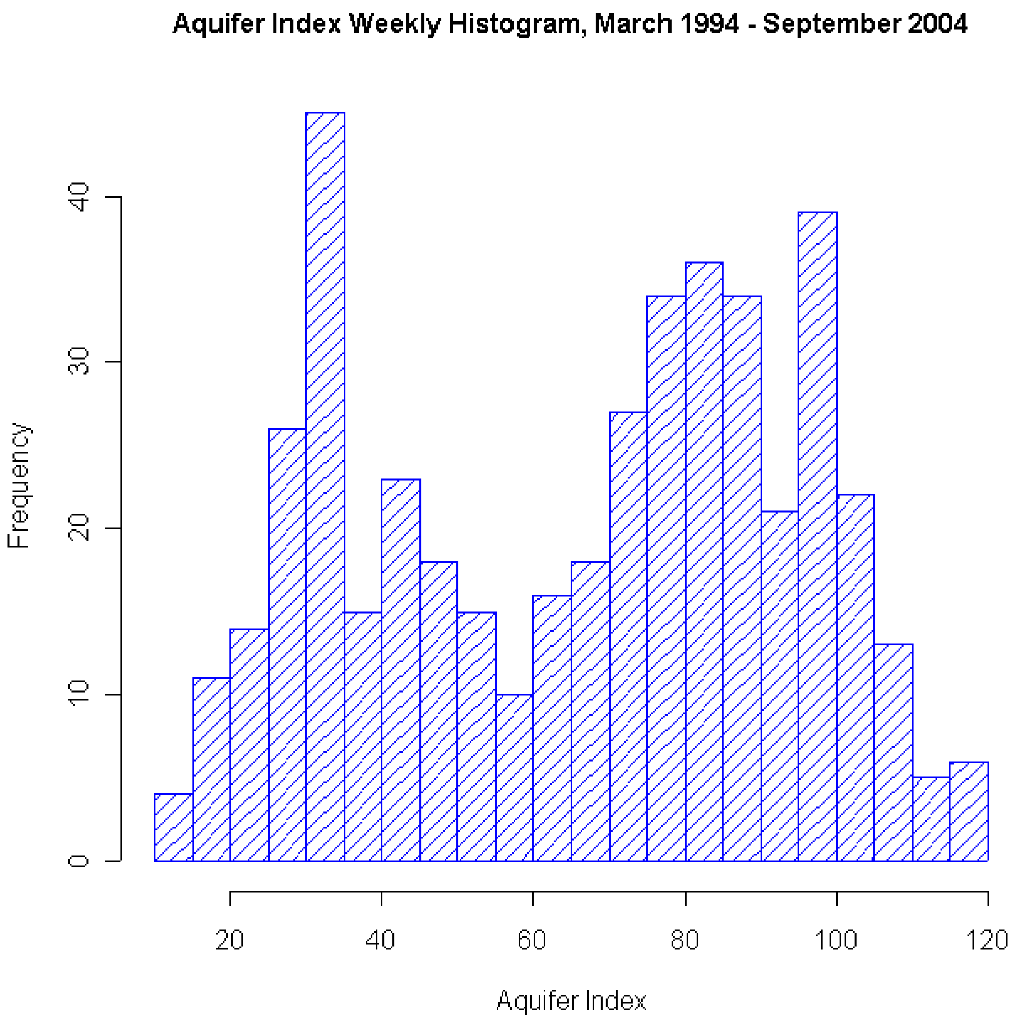
Comments:

1. The Aquifer Index includes terms for 3 hydrologic components: a quick-response component (Porter), a slower long-term storage component (Lovelady), and a regional precipitation component (Blanco at Wimberley). Perhaps after a longer period of data collection, the Onion Creek gage at Twin Creeks Road will be useful as a statistical indicator of regional precipitation that is correlative to Barton Springs flow.
2. This Aquifer Index regression has an R^2 value of 0.92 when compared to springflow.
3. This regression follows the “recessing limb” of springflow in most cases very well (such as in September 1999 – June 2000).
4. The Aquifer Index typically has a muted response when compared to temporary spikes in springflow (as in June 2000).

Multiple Linear Regression - Percentage Contributions



Aquifer Index Histogram



Min.	1st Quar.	Median	Mean	3rd Quar.	Max.
12.53	38.86	72.3	66.19	88.96	117.5

A-3: Evaluation of Potential Monitor Wells for a Drought Trigger Methodology

Recharge

Gauging recharge to an aquifer system would give the first indication of incipient drought conditions. However, recharge to this karst aquifer system is difficult to quantify directly owing to the many potential recharge sources, variables, and its dynamic nature.

Surrogate recharge data (e.g. rainfall, creekflow, etc.) are general indicators of drought, but have poor correlations to water levels and springflow. Although a lack of rainfall leads directly to drought conditions, rainfall data are only broadly correlated to aquifer conditions. This is due to the fact that a number of variables determine if rainfall is converted into runoff and then recharge. Those factors include evapotranspiration, antecedent moisture conditions, time of year, rate, and location of rainfall. Other recharge surrogates such as drought indices like the Palmer Hydrologic Drought Index have a low correlation ($R^2= 0.59$) with Barton Springs and aquifer conditions. For example, the PHDI index has historically spanned from +3 to -5 (extreme drought) for 20 cfs discharge at Barton Springs. The PHDI is a long-term index that reflects numerous factors such as reservoirs and groundwater levels and therefore may be slower to develop and may not be representative of conditions in the Barton Springs aquifer. Although streamflow provides the source of the majority of recharge to the aquifer, it provides only a general predictor of aquifer conditions. Streamflow data have a poor correlation to Barton Springs. For aquifer conditions to approach drought stage, the Onion Creek flow station upstream of the recharge zone (at Driftwood gaging station) must be below 10 cfs for 1-7 months (average of 4 months). For aquifer conditions to approach Critical Stage drought, Onion Creek flow at the Driftwood station must be below 10 cfs for 3-12 months (average of 8 months). This indicates that recharge is very dynamic in terms of its impact on storage and discharge. In order to exit a drought, Onion Creek flow needs to exceed 30 cfs for longer than 1 month to provide temporary relief to drought, and for longer than about 3 to 4 months to completely exit a drought cycle.

Storage and Discharge Correlations

Water levels in wells uninfluenced by pumping represent storage in the aquifer; therefore an evaluation of water levels in wells was a large part of this evaluation. The primary source of water-level and well data for this evaluation is a report by Hunt and Smith (2006). All of the wells and water-level data in Hunt and Smith (2006) were evaluated for selection as a drought indicator on the basis of the following criteria:

- Edwards Aquifer completion
- Sufficiently long and continuous period of record through drought periods (especially the DOR)
- Hydrodynamics: confined versus unconfined, response to recharge events, influence of local pumping, and influence of triple porosity (especially conduit flow) system
- Positive correlation to Barton Springs and other Edwards Aquifer wells
- Located within the BSEACD boundaries
- Well site and water level are accessible
- Perception as a representative monitor well

Most wells in the study area correlate closely with Barton Springs and could be candidates for drought indicators. However, on the basis of the criteria above, only a few wells were selected for final consideration as a drought indicator and are presented in **Table A3-1** and shown on **Figures A3-1 and A3-2**. The following discussion is the result of evaluating wells as drought indicators, and reasons for their exclusion from consideration for the purposes of this DTM.

The best monitor wells to correlate to historic droughts are wells with a long period of record. All wells evaluated had a good correlation to Barton Springs for the period of record and also during most drought periods. Only a few wells have very good correlation to springflow at less than 40 cfs of springflow (**Table A3-2; Figure A3-1**), and these include the Lovelady well. From this evaluation and others, as previously noted, it is apparent that the Buda and Dowell wells do not correlate well as they are influenced by local pumping. The Lovelady, Porter, and Negley wells appear very similar to Barton Springs and correlate very well to each other, although the dataset from the Negley well is limited to the 2000 drought only. During the 1996 drought, the Lovelady well is the only well that appears to be in a recession after August 1996.

Wells that had a long period of record, including the DOR, but were excluded from the final evaluations due to access and other issues include: United Gas (5858301), Armbruster (5858104), Bee Caves (5842911), and Rutherford (5857201). The last two wells also have very minor fluctuations of water levels under drought conditions, making them undesirable as drought indicators.

Wells intersect the combined matrix, fracture, and conduit porosity of this aquifer and water levels within each well can vary according to the influence of this triple porosity system. Some wells appear to be heavily influenced by the conduit-flow system and would not be desirable drought indicators as they respond rapidly to ephemeral recharge events and less to long-term changes in storage (within the matrix). These wells include 5850411 and 5850417. Additionally, the Ruby Ranch (5857602, 5857509) wells appear nearly flat under drought conditions and appear to be influenced by conduit-flow (Hunt and Smith, 2006). Some wells are less-influenced by conduit flow and appear muted in their water-level response to recharge when compared to other wells and Barton Springs. The Lovelady (5850301) and United Gas (5858301) wells appear to respond like this. Although the Lovelady well is located near the saline-zone boundary, the United Gas (5858301) well is located more than a mile into the "saline-water zone," making it less desirable as a drought indicator due to its perception as a non-representative well of the fresh-water Edwards.

Many of the wells reported in Hunt and Smith (2006) have a relatively long period of record and include more recent droughts (1990, 1996, 2000, and 2006). Some of these wells were excluded on the basis of the influence of the operation of Barton Springs pool on water levels. These wells include the Target well (5850216) and Barton well (5842903). Although the changes in water level in the Target well are relatively minor, they could be considered significant if changes in level due to pool operation occurred near a drought trigger level.

Water levels with relatively large fluctuations in water levels due to natural climatic variability would be the most desirable as a drought indicator. Many confined wells with long periods of record show water level fluctuations of 70 to 100 feet, making uncertainties in manual and instrumentation measurements very small and threshold crossing easily discerned. However, some wells are undesirable as drought indicators because they only have minor fluctuations between wet and dry periods. These well are generally located in the western portion of the unconfined zone or near the springs. The Barton well (5842903) and Bee Caves (5842911) wells are located near the springs and have very minor fluctuations. The Ruby Ranch (5857602) and Rutherford (5857201) wells are located along the western side of the recharge zone. The Callon/Thames wells have a good correlation to Barton Springs and are unconfined wells. However, the Callon well is very shallow and is dry during the lowest levels of drought periods. On the basis of the limited data (2000 drought) the Ruby Composite and Callon/Thames water levels also have a good correlation to Barton Springs except during drought conditions when water levels are nearly constant. That lack of sensitivity during drought is not desirable for a drought indicator well.

Table A3-1. Final list of wells evaluated for DTM

Well Name	SWN	Period of Record (POR)	Data Count**	Hydrodynamics	Access
Lovelady	5850301	1949	5,000+	Confined (brackish), matrix dominated flow	Yes, easement
Porter	5858123	1994	3,100+	Confined, minor influence by pumping	Yes
Buda	5858101	1937	5,300+	Confined, significant influence from local pumping	Yes
Dowell	5850801	1941	4,900+	Confined, significant influence from local pumping	Yes
Negley	5857903	1949	2,300+	Confined	Yes
Ruby Ranch composite	5857204, 5857602 (plg), 5857509+	1950	823	Unconfined	Uncertain, well in use
Callon+Thames	5857301, 58573GC	1937	1,400+	Unconfined, Callon well too shallow and goes dry during droughts	Uncertain

*well not within the Hunt and Smith (2006) report

**a plus (+) indicates currently monitored by the BSEACD

Table A3-2. Correlation (R^2) of water levels to springflow at Barton Springs for drought periods

Drought Period	Lovelady	Dowell	Buda	Negley	Porter	Ruby Composite	Callon + Thames
all data	0.76	0.77	0.81	0.90	0.88	0.80	0.76
2000*	0.95	0.51	0.83	0.96	0.96	0.82	0.82
1996*	0.93	0.84	0.84		0.95		
1988-90	0.31	0.95	0.85				0.59
1983-85	0.79	0.75	0.87	0.42			
1981-83	0.77	0.80	0.79	0.88			
1977-79	0.97	0.89					
1970-71			0.61				
1966-67			0.81				
1963-65			0.67	0.81			
1954-57	0.75	0.65	0.93	0.65			

Blanks indicate insufficient data

*daily data available, correlation made to lowest springflow value

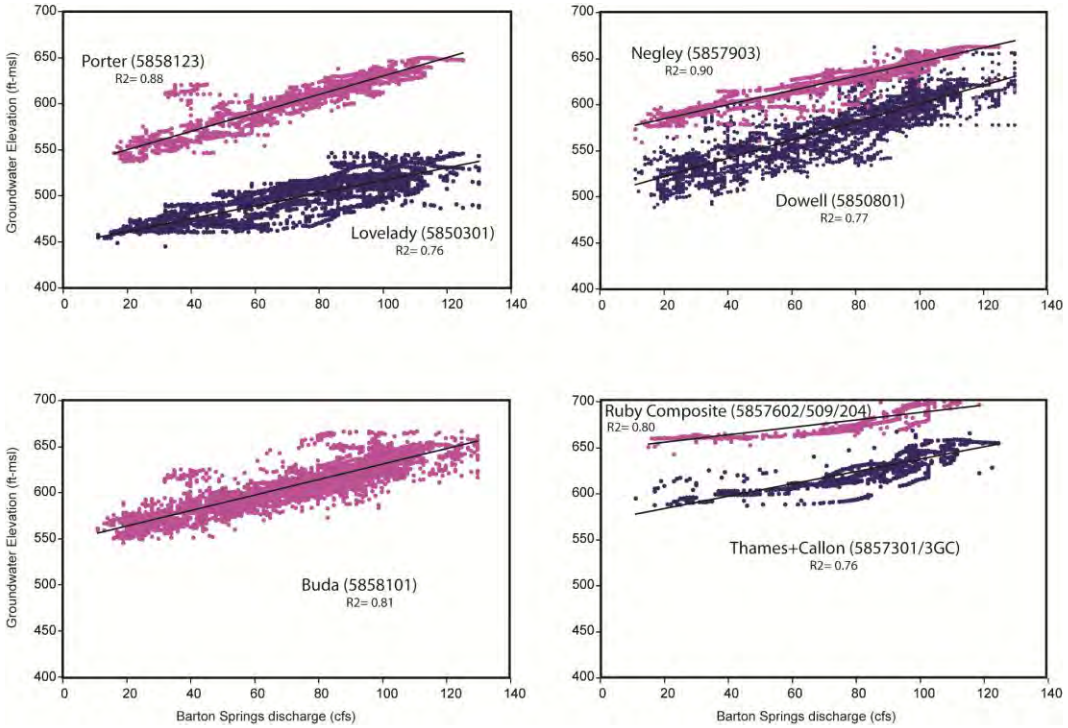


Figure A3-1. Water level and springflow correlations from selected wells. These correlations reflect the entire data set for each well (**Table 8**). There is a good correlation between water levels and springflow in most wells.

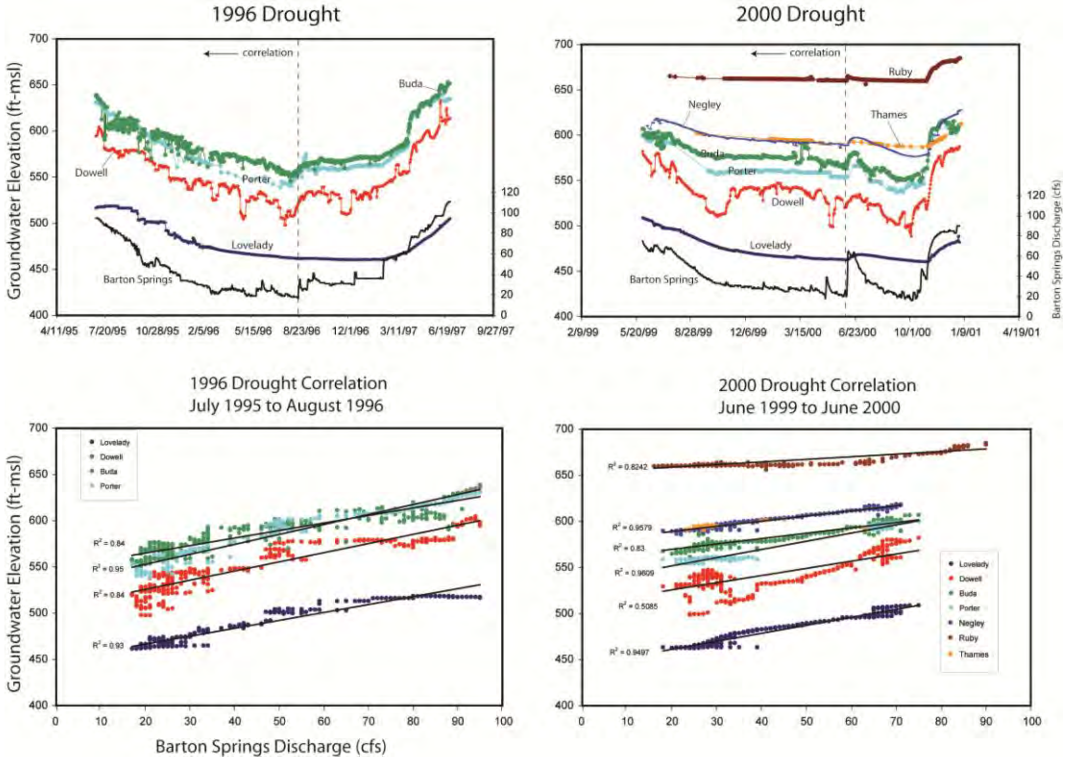


Figure A3-2. The top two figures are hydrographs from the 1996 and 2000 droughts with water levels and Barton Springs discharge. The bottom two figures are correlations of water levels to Barton Springs during each drought period for the time indicated.

A-4 Drought Rules Adopted October 11, 2012.

3-7.3. DROUGHT STAGES AND TRIGGERS.

Drought severity stages for all management zones are triggered by declines in the rate of discharge at Barton Springs and/or increases in depth to water in the District's Drought Indicator Well. Drought stages may have different applicability and requirements among the management zones. A decision to change the drought status of the aquifer may consider other factors that influence or reflect aquifer conditions (Section 3-7.3(G)).

There is a "No-Drought" condition, the Stage I Water Conservation Period, and three drought severity stages: Stage II Alarm, Stage III Critical, and Stage IV Exceptional. A Stage I Water Conservation Period will be in place between May 1 and September 30 of each year when not in a declared drought stage, during which voluntary reductions in water use are requested and expected of all groundwater users. The implementation of required demand reduction measures will begin with the requirements of Stage II Alarm Drought. More stringent reduction measures will be required in Stage III Critical Drought, and even more stringent measures will be required for certain wells in Stage IV Exceptional Drought.

A. No-Drought Status. The District will be in a "No-Drought" condition when, for a period of ten (10) or more days, the rate of discharge at Barton Springs is above the Stage II Alarm Drought flow rate of 38.0 cfs, and the elevation of the water level in the Lovelady Drought Indicator Well (state well number 58-50-301) is above the Stage II Alarm Drought level of 478.4 feet, relative to mean sea level datum (msl), and/or when the Board declares "No Drought" condition. During this condition, the District will maintain and conduct a routine aquifer monitoring program. This stage shall be determined and administered at the discretion of the District's General Manager.

B. Stage I Water Conservation Period. This period will be in effect between May 1 and September 30 every year when not in a declared drought stage. Permittees within the District will be expected to follow the voluntary measures described in their User Drought Contingency Plans (Section 3-7.5) during this period, and all other groundwater users will be asked to reduce their water use voluntarily during this period.

C. Stage II Alarm Drought. A Stage II Alarm Drought commences when a 10-day running average rate of discharge from Barton Springs is equal to or less than 38.0 cfs, <u>or</u> the elevation of the water level in the Lovelady Drought Indicator Well is equal to or less than 478.4.0 feet (msl), <u>and</u> the District's Board of Directors determines that conditions warrant the declaration of this stage.

D. Stage III Critical Drought. A Stage III Critical Drought commences when a 10-day running average rate of discharge from Barton Springs is equal to or less than 20.0 cfs, <u>or</u> the elevation of the water level in the Lovelady Drought Indicator Well is equal to or less than 462.7 feet (msl), <u>and</u> the District's Board of Directors determines that conditions warrant the declaration of this stage.

E. Stage IV Exceptional Drought. A Stage IV Exceptional Drought applies only to the Freshwater Edwards Management Zones and commences when a 10-day running average rate of discharge from Barton Springs is equal to or less than 14.0 cfs, <u>or</u> the 10-day running average elevation of the water level in the Lovelady Drought Indicator Well is equal to or less than 457.1 feet (msl), <u>and</u> the District's Board of Directors determines that conditions warrant the declaration of this stage.

F. Discontinuance of Drought Stages.

(1) Stage II Alarm Drought will be discontinued when the rate of discharge from Barton Springs rises above a 10-day running average of 38.0 cfs and the water level elevation in the Lovelady Drought Indicator Well is above 478.4 feet (msl), and/or when in the judgment of the District's General Manager or Board of Directors a Stage II Alarm Drought situation no longer exists.

(2) Stage III Critical Drought will be discontinued when the rate of discharge from Barton Springs rises above a 10-day running average of 20.0 cfs and the water level elevation in the Lovelady Drought Indicator Well is above 462.7 feet (msl), and/or when in the judgment of the District's General Manager or Board of Directors a Critical drought situation no longer exists.

(3) Stage IV Exceptional Drought will be discontinued when the rate of discharge from Barton Springs rises above a 10-day running average of 14.0 cfs, and the 10-day running average water level elevation in the Lovelady Drought Indicator Well is equal to or above 457.1 feet (msl) and/or when in the judgment of the District's Board of Directors an Exceptional drought situation no longer exists.

G. Emergency Response Period (ERP). The District Board may declare an Emergency Response Period, applicable to the Western and Eastern Freshwater Edwards Management Zones, during Extreme Drought conditions when a 10-day running average rate of discharge from Barton Springs is at or below 10 cfs or the 10-day running average water level elevation in the Lovelady Drought Indicator Well is equal to or above 453.4feet (msl) (this trigger level may be revised as additional scientific information on the low flow characteristics of Barton Springs is developed). In addition to possible measures to be directed or ordered at the Board's discretion during an ERP, as characterized in District Rule 3-7.6 below, the Board may take emergency actions underneath District Rule 2-4.2 and request other governmental agencies to implement structural measures designed to minimize take and prevent jeopardy of endangered species populations (e.g. the Barton Springs Recovery Plan).

h. Drought Factors. In addition to the rate of discharge at Barton Springs and the elevation of the water level in the Lovelady well, the District may consider other factors that may have some relevance to the urgency of declaring a drought or that may indicate that a drought is likely to continue regardless of spring discharge or water levels. These factors may be related to hydrogeologic or climatological conditions that have a bearing on aquifer conditions. Some factors that may be considered include:

- Water levels in the Buda (58-58-101), Porter (58-58-123), and Negley (58-57-903) monitor wells,
- Number of consecutive prior months with below average rainfall and related climatological outlook,
- Rainfall deficit for previous 12-month period,
- Palmer Drought Severity Index,
- Flow in Blanco River at Wimberley,
- Number of months since last creek flow in major contributing creeks,
- Recent pumping rates, and
- Saturated thickness of the aquifer.

APPENDIX G

Definition of the District's Groundwater Drought Stages and Related Triggers

District Rules & Bylaws, Section 3-7.4, Board-Adopted October 11, 2012

Appendix G
Definition of District Drought Stages and Triggers
(District Rule 3-7.3, Adopted October 11, 2012)

3-7.3. DROUGHT STAGES AND TRIGGERS.

Drought severity stages for all management zones are triggered by declines in the rate of discharge at Barton Springs and/or increases in depth to water in the District's Drought Indicator Well. Drought stages may have different applicability and requirements among the management zones. A decision to change the drought status of the aquifer may consider other factors that influence or reflect aquifer conditions (Section 3-7.3(G)).

There is a "No-Drought" condition, the Stage I Water Conservation Period, and three drought severity stages: Stage II Alarm, Stage III Critical, and Stage IV Exceptional. A Stage I Water Conservation Period will be in place between May 1 and September 30 of each year when not in a declared drought stage, during which voluntary reductions in water use are requested and expected of all groundwater users. The implementation of required demand reduction measures will begin with the requirements of Stage II Alarm Drought. More stringent reduction measures will be required in Stage III Critical Drought, and even more stringent measures will be required for certain wells in Stage IV Exceptional Drought.

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B. Stage I Water Conservation Period. This period will be in effect between May 1 and September 30 every year when not in a declared drought stage. Permittees within the District will be expected to follow the voluntary measures described in their User Drought Contingency Plans (Section 3-7.5) during this period, and all other groundwater users will be asked to reduce their water use voluntarily during this period.

C. Stage II Alarm Drought. A Stage II Alarm Drought commences when a 10-day running average rate of discharge from Barton Springs is equal to or less than 38.0 cfs, <u>or</u> the elevation of the water level in the Lovelady Drought Indicator Well is equal to or less than 478.4.0 feet (msl), <u>and</u> the District's Board of Directors determines that conditions warrant the declaration of this stage.

D. Stage III Critical Drought. A Stage III Critical Drought commences when a 10-day running average rate of discharge from Barton Springs is equal to or less than 20.0 cfs, <u>or</u> the elevation of the water level in the Lovelady Drought Indicator Well is equal to or less than 462.7 feet (msl), <u>and</u> the District's Board of Directors determines that conditions warrant the declaration of this stage.

E. Stage IV Exceptional Drought. A Stage IV Exceptional Drought applies only to the Freshwater Edwards Management Zones and commences when a 10-day running average rate of discharge from Barton Springs is equal to or less than 14.0 cfs, <u>or</u> the 10-day running average elevation of the water level in the Lovelady Drought Indicator Well is equal to or less than 457.1 feet (msl), <u>and</u> the District's Board of Directors determines that conditions warrant the declaration of this stage.

F. Discontinuance of Drought Stages.

(1) Stage II Alarm Drought will be discontinued when the rate of discharge from Barton Springs rises above a 10-day running average of 38.0 cfs <u>and</u> the water level elevation in the Lovelady Drought Indicator Well is above 478.4 feet (msl), <u>and/or</u> when in the judgment of the District's General Manager or Board of Directors a Stage II Alarm Drought situation no longer exists.

(2) Stage III Critical Drought will be discontinued when the rate of discharge from Barton Springs rises above a 10-day running average of 20.0 cfs <u>and</u> the water level elevation in the Lovelady Drought Indicator Well is above 462.7 feet (msl), <u>and/or</u> when in the judgment of the District's General Manager or Board of Directors a Critical drought situation no longer exists.

(3) Stage IV Exceptional Drought will be discontinued when the rate of discharge from Barton Springs rises above a 10-day running average of 14.0 cfs, <u>and</u> the 10-day running average water level elevation in the Lovelady Drought Indicator Well is equal to or above 457.1 feet (msl) <u>and/or</u> when in the judgment of the District's Board of Directors an Exceptional drought situation no longer exists.

G. Emergency Response Period (ERP). The District Board may declare an Emergency Response Period, applicable to the Western and Eastern Freshwater Edwards Management Zones, during Extreme Drought conditions when a 10-day running average rate of discharge from Barton Springs is at or below 10 cfs <u>or</u> the 10-day running average water level elevation in the Lovelady Drought Indicator Well is equal to or above 453.4feet (msl) (this trigger level may be revised as additional scientific information on the low flow characteristics of Barton Springs is developed). In addition to possible measures to be directed or ordered at the Board's discretion during an ERP, as characterized in District Rule 3-7.6 below, the Board may take emergency actions underneath District Rule 2-4.2 and request other governmental agencies to implement structural measures designed to minimize take and prevent jeopardy of endangered species populations (e.g. the Barton Springs Recovery Plan).

H. Drought Factors. In addition to the rate of discharge at Barton Springs and the elevation of the water level in the Lovelady well, the District may consider other factors that may have some relevance to the urgency of declaring a drought or that may indicate that a drought is likely to continue regardless of spring discharge or water levels. These factors may be related to hydrogeologic or climatological conditions that have a bearing on aquifer conditions. Some factors that may be considered include:

(1) Water levels in the Buda (58-58-101), Porter (58-58-123), and Negley (58-57-903) monitor wells,

(2) Number of consecutive prior months with below average rainfall and related climatological outlook,

(3) Rainfall deficit for previous 12-month period,

(4) Palmer Drought Severity Index,

(5) Flow in Blanco River at Wimberley,

(6) Number of months since last creek flow in major contributing creeks,

(7) Recent pumping rates, and

(8) Saturated thickness of the aquifer.

APPENDIX H

Entities and Programs for Groundwater Quality Protection in the HCP Planning Area

Appendix H
Groundwater Quality Management and Planning Efforts in the HCP Planning Area

E.1 Edwards Aquifer Protection Program

The Edwards Aquifer was designated as a sole source aquifer, and TCEQ promulgated rules regulating development activity in the Edwards Aquifer recharge, transition, and contributing zones (30 TAC Chapter 213). Subchapter A applies to all regulated activities (defined as construction-related or post-construction activity) within the recharge zone, to certain activities within the surrounding transition zone that stretches along the eastern and southern boundary of the recharge zone, and to other activities that may potentially contaminate the aquifer and hydrologically connected surface streams. Persons or entities subject to the rules must submit an Edwards Aquifer protection plan to the TCEQ prior to certain types of construction in the recharge or transition zones of the Edwards Aquifer. The plan must include a geological assessment report identifying pathways for movement of contaminants to the aquifer and a report on BMPs and measures to prevent and abate pollution of the aquifer. After the plan is approved, notice must also be filed in the county deed records that the property is subject to an approved Edwards Aquifer protection plan. Certain facilities are also prohibited from being built in the recharge or transition zones, such as Type 1 municipal solid waste landfills and waste disposal wells; direct discharge of wastewater to streams in the recharge (but not contributing) zone is also prohibited.

30 TAC Chapter 213 Subchapter B applies to regulated activities in the Edwards Aquifer contributing zone. All activities that disturb the ground or alter a site's topographic, geologic, or existing recharge characteristics are subject to regulation, which would require either sediment and erosion controls or a Contributing Zone Plan to protect water quality during and after construction. Exemptions include construction of single-family residences on lots larger than five acres where no more than one single-family residence is located on each lot; agricultural activities; oil and gas exploration, development, and

production; clearing of vegetation without soil disturbance; and maintenance of existing structures not involving additional site disturbance.

E.2 U.S. Fish and Wildlife Service Concurrence on Optional Enhanced Measures for the Protection of Water Quality in the Edwards Aquifer

In February, 2005, the USFWS and the TCEQ entered into a joint agreement (TCEQ 2005e) with regard to a set of development guidelines for the Edwards Aquifer Protection Program. In a letter to Governor Rick Perry, the USFWS notified the State of Texas that the federal government will recognize that new, optional water quality measures serve to protect certain federally listed endangered species, including the Barton Springs salamander, if voluntarily implemented in developments over the Edwards Aquifer (USFWS 2005c). The letter further stated that non-federal landowners using these practices would have the USFWS support that no “take” under the ESA would occur provided certain conditions are met (USFWS 2005c).

E.3 U.S. Fish and Wildlife Service Recovery Plan for the Barton Springs Salamander (*Eurycea sosorum*)

The Final Rule listing the Barton Springs Salamander as endangered (62 FR 23377-23392) identified the primary threats or reasons for listing as “the degradation of the quality and quantity of water that feeds Barton Springs” as a result of urban expansion over the watershed. The restricted range of this species makes it vulnerable to both acute and chronic groundwater contamination. These threats could result in the “destruction, modification, or curtailment of the species habitat or range” through “chronic degradation, catastrophic hazardous materials spills, increased water withdrawals from the aquifer, and impacts to the surface habitat.” The USFWS has completed a Recovery Plan for the Barton Springs salamander (USFWS 2005) that addresses water quality and quantity concerns for the species.

The Final Rule listing the salamander identifies a comprehensive regional plan as a means to protect the Barton Springs salamander from the above-mentioned threats. Although such a plan had not been developed at the time the Recovery Plan was completed, certain state and local entities, including the City of Austin (COA), have taken actions to protect the salamander and its habitat, such as adopting water quality protection ordinances and acquiring thousands of acres of open space in the Barton Springs watershed.

The goal of the Recovery Plan is to ensure the long-term viability of the Barton Springs salamander in the wild, allowing initially for reclassification to threatened status and, ultimately, recovery of the species to a point where it is a secure, self-sustaining component of its ecosystem, so that the protections of the ESA of 1973, as amended, are no longer necessary.

According to the Recovery Plan, the Barton Springs salamander should be considered for reclassification when:

(1) the Barton Springs watershed is sufficiently protected to maintain adequate water quality (including sediment quality) and ensure the long-term survival of the Barton Springs salamander in its natural environment;

(2) a plan is implemented to avoid, respond to, and remediate hazardous material spills within the Barton Springs watershed such that the risk of harm to the Barton Springs salamander is insignificant;

(3) an aquifer management plan is implemented to ensure adequate water quantity in the Barton Springs watershed and natural springflow at the four spring outlets that comprise Barton Springs;

(4) a healthy, self-sustaining natural population of Barton Springs salamanders is maintained;

(5) surface management measures to remove local threats to the Barton Springs ecosystem have been implemented; and

(6) genetically representative captive breeding populations have been established, and a contingency plan is in place to ensure the survival of the species should a catastrophic event destroy the wild population.

The Recovery Plan identified five recovery strategies for the species:

(1) Protect water quality (including sediment quality) within the Barton Springs watershed;

(2) Sustain adequate water quantity at Barton Springs;

(3) Manage surface habitat at Barton Springs;

(4) Maintain a captive population of Barton Springs salamanders for research and restoration purposes; and

(5) Develop and implement an education and outreach plan.

With a concerted effort to meet all of the recovery criteria, including full cooperation of all partners needed to achieve recovery, the Recovery Plan envisions that reclassifying the status of the species from endangered to threatened could be met within ten years, and delisting could be accomplished within ten years following reclassification.

The Recovery Plan identifies the District as the relevant entity to establish pumping limits that should be an integral part of an aquifer management plan. The Recovery Plan concludes that groundwater pumping from the Barton Springs segment of the Edwards Aquifer should be limited, particularly during drought, when pumping should be reduced by aquifer management such that springflow at Barton Springs does not drop below that level which would support the long term survival of the Barton Springs salamander in its natural environment. According to this plan, aquifer management should ensure that natural springflows are continuous at Main Springs, Eliza Springs, and Sunken Gardens Springs even in the most severe drought, and that flows should not fall below the historic low flow of 10 cfs, as measured by the USGS for all four sites combined. However, the Recovery Plan does not address the statutory, legal, and institutional constraints on reducing pumping for such purposes.

The Recovery Plan also recommends that the District develop a Proposed Habitat Conservation Plan that would identify the effects of groundwater pumping on the Barton Springs and Austin blind salamanders and would include measures to avoid, minimize, and mitigate for those impacts resulting from permitted groundwater pumping. The Recovery Plan noted that the District staff would collaborate with experts and various agencies to develop an HCP that addresses the needs of the salamanders, groundwater demands and sustainability, and includes appropriate planning and aquifer management strategies needed to protect the Barton Springs and Austin blind salamanders from degradation of water quantity.

E.4 Local Groundwater Quality Programs

Local municipalities, especially the COA, have also imposed aquifer protection requirements. The COA has imposed watershed ordinances to require development standards for erosion and sedimentation control, impervious cover limits, stream or creek setback requirements and water quality control within its boundaries and extraterritorial jurisdiction (COA, 2005a; Land development restrictions instituted by the COA are codified in the Austin City Code, Title 25, “Land Development”).

The COA is a home-rule city that derives its land use control and development authority from the Texas Constitution. That authority is articulated in the City Charter that stipulates that development must conform to a comprehensive plan (COA 2005a, 2005b).

Comprehensive plans integrate social, economic and environmental planning into a framework to which zoning and subdivision ordinances must conform. The COA's current comprehensive plan, known as the Austin Tomorrow Plan (1979), articulated many of the city's watershed protection goals. The COA protects water quality through the Land Development Code (LDC) that governs zoning, subdivision and the site plan process. The city's watershed protection ordinances are codified, particularly in those sections of the LDC that address subdivision and site plan (COA 2005a).

Although the COA does not use zoning expressly for water quality purposes, the reduced density or impervious cover percentage requirements for various zoning districts may in fact provide water quality benefits. Subdivision regulations have become one of the most important regulatory tools that cities possess and have historically governed the division of land into two or more separate parcels for future sale or use. Projects that require subdivision or site plan approvals must comply with the COA's watershed ordinances. These ordinances have evolved over time to: 1) reflect current understanding of water quality and stormwater hydrology and 2) cover all 45 watersheds within the city's planning area, either wholly or in part.

The COA has adopted fewer than 10 watershed ordinances since 1980. These include: Lake Austin, Lake Austin Peninsula, Barton Creek, Williamson Creek, Lower Watersheds, Comprehensive, Interim, Composite, and Save Our Springs Ordinance. Several of those ordinances have been amended on more than one occasion. The following descriptions are intended only to highlight the major watershed ordinances and may include discussions of: impervious cover, density, transfer of impervious cover or development rights, stormwater treatment and detention requirements, construction site management and stream setbacks or buffer zones.

The Lake Austin Watershed Ordinance (LAWO) was adopted permanently in January 1980 and represents the COA's first major attempt to address water quality degradation in the face of increasing urbanization. Key features of the ordinance included: slope based impervious cover limits of up to 30 percent that were eventually raised to a maximum of 80 percent with transfers, a provision for water quality and quantity structural controls when minimum ordinance standards were not met and a requirement for an erosion/sedimentation control plan prior to subdivision application approval. It should be noted that all of the city's watershed ordinances include provisions for an erosion/sedimentation control plan. The LAWO did not require stream setbacks or buffer zones. The ordinance did, however, prohibit building sites within the 100-year floodplain of any creek or tributary in the watershed. The District HCP Planning Area is not subject to LAWO.

The Barton Creek Watershed Ordinance (BCWO) was passed in 1980 and represented a significant departure from the LAWO. Key features of the ordinance included: impervious cover limits capped at 35 percent for commercial and multi-family development, and the use of density limits that varied with the location of the development. The BCWO did not require water control structures, nor did it provide a mechanism whereby an applicant could increase impervious cover using alternate methods. This ordinance relied entirely on non-structural water quality controls and introduced stream set-back requirements that created five water quality zones with enumerated development restrictions for each one. The ordinance also provided incentives (increased density) for the transfer of development rights that included the conveyance of land in the critical water quality zone, for water quality protection, to the city as parkland.

The Williamson Creek Watershed Ordinance (WCWO) applied to that part of Williamson Creek crossing the recharge zone and was passed in December 1980. The WCWO included a requirement for stormwater treatment, a departure from previous ordinances. Key features of the ordinance included: impervious cover limits for single- and two-family homes of 40 percent and limits of up to 65 percent for commercial and multi-family developments, the use of stream setbacks based on the present concept of major, intermediate and minor waterways and the inclusion of a critical water quality zone that was to remain free of all but certain types of development.

The Lower Watersheds Ordinance (LWO) was adopted in 1981 and extended water quality protection into the Slaughter, Bear, Little Bear, and Onion Creek watersheds. The LWO resembles the WCWO in many ways, except that it reduces impervious cover allowances for commercial development to 40 percent and 55 percent with transfers, and for residential development, reduces it to 30 percent and 40 percent with transfers. The LWO introduced a water quality buffer zone, and set impervious cover limits of up to 18 percent and 15 percent, respectively, for single-family and commercial development in this zone.

The Comprehensive Watersheds Ordinance (CWO) was adopted in 1986, superceded previous watershed ordinances, and extended water quality protection throughout the COA's planning area to all but the urban watersheds. While similar in some respects to its predecessors, the CWO contained a number of significant innovations. For the first time, watersheds that do not provide a portion of our drinking water received significant water quality protection. The CWO was also the first ordinance to use net site area (NSA) impervious cover calculations instead of calculations based on gross site area (GSA). GSA includes the entire site, while NSA requirements include only a site's buildable areas and can reduce overall impervious cover. The ordinance included other firsts too, such as the designation of critical environmental features and provisions for their protection. The CWO also began to organize watersheds into groups based on their relationship to 1) the city's water supply, in particular Lake Austin, 2) the Barton Springs Edwards Aquifer recharge zone and to some extent the Northern Edwards Aquifer, and 3) the degree of urbanization within a watershed, i.e. urban, suburban, or rural.

The SOS Ordinance was adopted in 1992 and differed from its predecessors because it became law by citizen initiative. Two ordinances worth noting preceded the SOS Ordinance: the Interim and Composite Ordinance. These ordinances addressed development in the Barton Springs Zone, which includes Barton Creek and the other creeks draining to, or crossing, the Edwards Aquifer recharge zone. Highlights of these ordinances included: the first requirements for non-degradation (based on stormwater discharge concentrations) and provisions that excluded variances, unless a demonstrable improvement in water quality was shown. Variances, which made departures from an ordinance permissible, were a general feature of watershed ordinances up until this time.

The SOS Ordinance, applied throughout the Barton Springs Zone, required: non-degradation (based on total average annual loading), reduced impervious cover to 15-percent NSA for all development in the recharge zone, 20-percent NSA for development in the Barton Creek portion of the contributing zone, and 25-percent NSA for development in the remaining portions of the contributing zone in Williamson, Slaughter, Bear, Little Bear, and Onion Creeks.

The SOS Ordinance has withstood a number of legal challenges. Efforts to protect water quality in Austin and throughout Texas are still beset by a State law that provides "grandfathering" of some developments from current regulations. The most recent enactment of this state law was as House Bill 1704 by the 76th legislature. H.B. 1704 is the culmination of previous legislation that essentially freezes regulations on the date the first permit application is filed until the project is complete.

While no major watershed ordinances have been passed since the SOS ordinance, other efforts that may result in new ordinances or ordinance amendments include the city's Smart Growth initiative, an effort to reshape urban and suburban growth so that it will enhance our communities, strengthen the economy, and protect the environment. Akin to earlier comprehensive planning efforts, Smart Growth concepts were originally described by the Citizen's Planning Committee beginning in late 1994. An important Smart Growth principle is the city's division into Drinking Water Protection and Desired Development Zones. This division is a reflection of the sensitivity of watersheds that are located over, or adjacent to, the Barton Springs Edwards Aquifer recharge zone or that supply water to Lake Austin. Smart Growth initiatives seek to direct growth away from these areas into less environmentally sensitive areas, while at the same time seeking LDC amendments and policy changes that will protect or enhance watershed water quality throughout Austin.

The *Environmental Criteria Manual* (COA 2005a) is the fifth volume in Series One of the City of Austin’s Development Criteria Manuals. The rules contained in the manual apply to tracts of land within the corporate limits of the COA and its extraterritorial jurisdictional areas as defined in the Austin City Code. The rules are designed, intended and are to be administered in a manner to not contravene the provisions of the Austin

City Code and to promote uniformity, clarity and stability in the application of development regulations.

The rules have been promulgated to administer and implement the technical criteria necessary to accomplish the environmental protection and management goals of the Austin City Code. The guidelines and design criteria presented in this manual address the issues of water quality management, landscaping, preservation of trees and natural areas, the underground storage of hazardous materials and construction activity in city parks.

The City of Austin Watershed Protection and Development Review Department collects water, sediment and other samples throughout the Austin area, including Barton Springs Pool. City of Austin staff has collected water quality information from Barton Springs Pool since 1986 for a variety of different parameters. The Water Resource Evaluation (WRE) Section of the City of Austin collects and stores environmental quality data from throughout the local area. More than 42,000 samples of water, sediment, and biological data collected by City Staff at over 1,100 sites in the Austin area are currently stored in the Water Resource Information System (WRIS) database (COA 2005b).

The LCRA also has existing water quality protection ordinances applicable to portions of Travis County. The LCRA's regulatory authority derives from the state of Texas. Its responsibility to control pollution of groundwater and surface water extends through 10 counties. LCRA divides its regulatory programs into two general categories: those that deal with land-based activities and those that address the water surface. The land-based activities include the installation and upkeep of septic systems and construction that can result in increased runoff, or nonpoint-source pollution. LCRA oversees the installation and operation of on-site sewage treatment and disposal systems within, in general, 2,200 feet of the Highland Lakes. The OSSF staff reviews plans, issues permits and licenses, and inspects new construction and septic system repairs.

In 1986, LCRA actively supported the state's ban on all pollutant discharges, or point-source pollution, into the Highland Lakes. A construction boom around the Highland Lakes drew attention to nonpoint-source pollution (NPS) issues. LCRA's response was the NPS Program that consists of two ordinances. These ordinances do not limit impervious cover; instead, the program is performance-based. Landowners and developers must show that standards are met before moving forward with projects (LCRA 2005).

On July 25, 2005 the Travis County Commissioners Court adopted interim subdivision rules (Travis County 2005) for the areas outside of municipalities’ extra territorial jurisdictions. A small area of the HCP Planning Area along Hamilton Pool Road and Crumley Ranch Road in the southwestern portion of Travis County would be affected by these interim subdivision regulations (if the Barton Creek watershed were to be considered part of the Town Lake watershed). These interim regulations provide for construction and post-construction water quality measures for residential subdivisions exceeding 20 acres and all commercial developments. These provisions include best management practices for stormwater control, stream bank erosion control, buffer zones for environmentally valuable features, protection for recharge features, and permanent water quality control measures to remove variable percentages (based upon three slope categories) of total suspended solids, total phosphorus, oil and grease.

E.5 Regional Water Quality Plan

Rapid growth and development in northern Hays County and southwest Travis County have created concerns about an increasing potential for pollution of groundwater and surface waters. These concerns included not only the impacts to drinking water supplies but to the threatened or endangered species that reside in the area (Naismith Engineering 2005).

In December, 2002, officials of Hays County and the City of Austin convened a Regional Summit to begin discussions on the impacts development was having on the region and particularly to water quality in the Barton Creek Watershed. From this initial effort a Regional Group was established to address the water quality issues facing the area of the Barton Springs segment of the Edwards Aquifer and its contributing zone and the desire to preserve water quality in this area. The Regional Group was comprised of an Executive Committee and Core Committee whose members were made up of representatives from the cities of Dripping Springs, Austin, Buda, Kyle, Rollingwood, Sunset Valley, the Village of Bee Cave; Hays and Travis counties; and the Barton Springs/Edwards Aquifer Conservation District and the Hays Trinity Groundwater Conservation District.

It was determined by the group that there was a need to develop a regional approach to water quality protection within the Barton Creek watershed in order to protect the quality of drinking water and the endangered species in the aquifer and springs ecosystem, particularly the Barton Springs salamander. The group believed that the completion of a regional water quality protection plan would provide the basis for political subdivisions, to the extent allowed by law, to implement local water quality protection plans and ordinances and provide best management practices that could be adopted by local stakeholders for water quality protection.

The planning process used to develop the regional plan was a very public, stakeholder-driven process involving public input in every aspect of the development of the plan. Building consensus as the plan was developed was seen as critical to producing a plan that could be adopted and implemented by local governments and stakeholders. Elements of the planning process included:

- Stakeholder involvement in all phases of development of the Water Quality Protection Plan;

- Identification of the best management practices for the protection of water quality in the area;

- Identification of entities that can implement water quality protection measures within the planning area;

- Development of model ordinances to implement and enforce water quality protection plans for the area; and,

- Development of a consensus-based Water Quality Protection Plan including best management practices, water quality protection strategies and regional planning tools to protect both surface and groundwater quality.

The planning effort was funded by grants from the Lower Colorado River Authority and the TWDB and through in-kind services from many other entities. The planning area is the Barton Springs segment of the Edwards Aquifer and its contributing zone. The area covers northern Hays County, southwest Travis County and a small section of Blanco County. The area includes the cities of Dripping Springs, Austin, West Lake Hills, Buda, Hays City, Kyle, Mountain City, Rollingwood, Sunset Valley, the Villages of Bee Cave and Bear Creek and the areas of the Barton Springs/Edwards Aquifer and Hays Trinity Conservation Districts. This study area comprises a large part of the District HCP Planning Area.

At a meeting of the Executive and Core Committees on June 13, 2005, the following resolution was adopted:

> "The Core Committee of the Regional Water Quality Planning Project for the Barton Springs Segment of the Edwards Aquifer and its Contributing Zone endorses the final draft of the Regional Water Quality Protection Plan, including the amendments dated June 3, 2005, as a framework for adoption of water quality standards by the local governments represented on the Core Committee, recognizing that each has a unique role to play in achieving the regional solution and that it will take more time and a continuing strenuous effort by government and the public to reach the level of water quality protection described in the Plan."

The 2005 document is considered the final version of the plan.

E.6 Barton Springs/Edwards Aquifer Conservation District

The Barton Springs/Edwards Aquifer Conservation District strongly supports a collaborative, cooperative approach to ensuring the availability of aquifer water in sufficient quantity and quality to meet all uses (Kirk Holland, General Manager, BS/EACD, personal communication). These uses include high-quality drinking water supply (including the sole source for several tens of thousands of citizens), critical ecological habitat of many plant and animal species (including some that are threatened or endangered), and an iconic recreational and aesthetic resource. The District believes that it is vital to the protection and enhancement of the uses of the Barton Springs Segment that a regional, multi-agency approach be used for planning, studying and evaluating effects, impacts, and mitigation strategies, and also for coordinating among regulatory programs.

As noted above, a consensus plan, the “Regional Water Quality Protection Plan for the Barton Springs Segment of the Edwards Aquifer and its Contributing Zone” (Naismith Engineering 2005) has been developed to provide the basis for the implementation of needed measures. The District participated in developing the regional plan and supports not only its consensus-building approach but also its conclusions and recommendations, as a balanced, scientifically sound, and politically acceptable plan to protect uses of the aquifer. The District considers all sponsors and stakeholder groups involved in creating the plan as cooperating entities that will now use the plan as a guide for action.

The District is concerned about all impacts on the Edwards Aquifer water system, whether related to quantity or quality. It fully understands the interest possible impacts evoke in various stakeholder groups and the not unreasonable concerns of interested parties that possible effects might prove to be actual effects, and that postulated impacts (i.e., consequences) of those effects might prove to be not just potential but real, adverse, or even irreversible or irretrievable. These effects are, however, currently uncertain and this ongoing HCP study is designed to better assess the impacts of low aquifer water-level conditions, springflow and corresponding water quality conditions that are unequivocally and directly related to the current flow regime, even apart from other, possible man-made stresses. The District considers the HCP as a necessary and reasonable step in evaluating existing conditions and the efficacy and consequences of structural and non-structural mechanisms that affect flow quantity and quality.

Specific programs that are underway at the District and are intended to improve groundwater management in the long term include: (1) the Drought Management Plan; (2) the well permits program; (3) conservation and education programs; (4) groundwater availability model formulation; and (5) major work elements of the USFWS grant to develop the Draft HCP/PDEIS.

These studies and programs will also establish a scientific baseline for gauging the necessity for, and scope of, other studies, identified in Chapter 6: The District Habitat Conservation Plan, that might be required, either by the District itself or in association with (or by) other entities to further evaluate degradation. The District will continue to provide leadership in a rational, systematic, regionalized initiative to address the use, conservation, protection, and enhancement of the segment’s ground water resource and the uses dependent on it.

E.7 Other Municipalities

The Cities of Buda, Sunset Valley, Dripping Springs and the Village of Bee Caves have water quality protection ordinances. The City of Sunset Valley has very strong aquifer-related regulations, and most importantly, the City of Dripping Springs has subdivision and site development watershed ordinances that cover more than 100 square miles of the HCP Planning Area.

APPENDIX I

Conservation Physiology of the Plethodontid Salamanders *Eurycea nana* and *E.sosorum*: Response to Declining Dissolved Oxygen, Woods et al., 2010

A Report of the Results of Two Research Studies Commissioned by the District for its HCP

Conservation Physiology of the Plethodontid Salamanders *Eurycea nana* and *E. sosorum*: Response to Declining Dissolved Oxygen

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Conservation Physiology of the Plethodontid Salamanders *Eurycea nana* and *E. sosorum*: Response to Declining Dissolved Oxygen

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***Eurycea sosorum* and *E. nana* are plethodontid salamanders endemic to several karst springs in central Texas. Landscapes around these habitats are increasingly urbanized. At the Barton Springs complex, where *E. sosorum* occurs, average dissolved oxygen (DO) in the main flow is approximately 6.5 mg L^{-1}. However, DO is quite variable, ranging between 2.4 and 10 mg O_2 L^{-1}, and recent data suggest a positive relationship between DO and spring discharge in Barton Springs Pool, though this relationship may not be as strong under extreme low-flow conditions. Here we examine sensitivity of a surrogate species, *E. nana*, to experimental variation in oxygen availability (DO); due to limited availability of *E. sosorum*, they were examined in only a subset of experiments. A suite of traits was measured on adults: spontaneous activity, metabolic rate, and mortality during 28 days of exposure. A separate experiment examined growth of juveniles across levels of DO during 60 days of exposure. Levels of DO below 3.4 mg O_2 L^{-1} appeared to pose a grave threat to salamander survival over a 28-day study, whereas DO above 4.5 mg O_2 L^{-1} gave no observable effects in any experiment. Between these values is a critical range in which salamanders became progressively compromised. An ambient water quality criterion for DO in lentic systems (5 mg O_2 L^{-1}, 24 hour minimum) appears adequate to protect *Eurycea*.**

GLOBAL amphibian declines over the past half century (Houlahan et al., 2000) appear to have stemmed from factors associated with climate change, including increased UV-B exposure, changes in precipitation patterns, and outbreaks of pathogens (Kiesecker et al., 2001). At local scales, declines also stem from habitat degradation or destruction (Blaustein et al., 1994) related to watershed urbanization (Wang et al., 2001; Price et al., 2006; Miller et al., 2007). Because urban land use influences many aspects of streams—flow regime, channel morphology, water quality, and biological community composition (Wang et al., 2001)—it is difficult to identify specific factors, or interactions of factors, that adversely affect populations. But doing so is important: although urbanization may be inevitable, understanding relative risk associated with various stressors will support better conservation decision-making.

Here we focus on dissolved oxygen (DO), which is known to vary spatially and temporally in aquatic systems (Wetzel and Likens, 2000). The U.S. Environmental Protection Agency has established national ambient water quality criteria for DO that are intended to protect aquatic life in surface waters. In the central Texas karst system at the Barton Springs complex, DO in the main spring has been measured irregularly since 1969. Since then, mean DO has been approximately 6.5 mg L^{-1} (Turner, 2004), with individual measurements ranging between 2.4 and 10 mg L^{-1} (for comparison, air-saturated DO at spring temperature, 20°C, is about 8.5 mg L^{-1}). Moreover, data since 2003 indicate a positive relationship between DO and spring discharge (Turner, 2004). These data suggest that low spring flows, which could stem from either droughts or higher levels of pumping from the aquifer, may subject salamanders to lower DO. Whether the current water quality criteria for DO in surface waters are appropriate for protecting salamanders in spring-fed ecosystems is unknown.

For salamanders, adequate DO is important for all life stages (Hillman and Withers, 1979). Hypoxia can retard embryonic development (Mills and Barnhart, 1999), slow or arrest juvenile growth (Werner and Glennemeier, 1999; Stevens et al., 2006), and depress adult oxygen consumption (Booth and Feder, 1991; Crowder et al., 1998; Sheafor et al., 2000). Identifying problematic levels of DO is difficult, however, because effects vary by species, stage, and physiological circumstance. For example, Withers (1980) showed that O_2 consumption (in air) by resting *Plethodon* spp. was unaffected by ambient PO_2 down to approximately 5 kPa. By contrast, exercised salamanders, forced to escape repeatedly, were much more sensitive to ambient PO_2, with rapid declines in O_2 consumption below 14 kPa. In some circumstances, negative effects of hypoxia may be mitigated by physiology and behavior. Known responses include increases in egg capsule conductance (Mills et al., 2001), precocious hatching (Petranka et al., 1982), increases in heart rate and buccal pumping (Sheafor et al., 2000), behavioral hypothermia (Tattersall and Boutilier, 1997), gill hypertrophy and increases in gill perfusion (Bond, 1960), and frequent excursions to the water–air interface for air or 'bobbing' (Wassersug and Seibert, 1975; Crowder et al., 1998).

Eurycea nana and *E. sosorum* are obligately aquatic neotenes, with gills retained throughout adulthood (perennibranchiate). Oxygen uptake must therefore occur across the skin or the gills; the dominant route is unknown. Booth and Feder (1991) showed that amphibians using cutaneous respiration in water, including *E. bislineata*, can develop steep oxygen gradients across boundary layers adjacent to the skin; even when ambient DO was high (>8 mg L^{-1}), DO at the skin surface usually was 1–2 mg L^{-1}. In *E. sosorum* and *E. nana*, boundary layers near the skin may be minimized by other factors, including small body size (<1 g) and association with rapidly flowing, well-oxygenated spring flows (Sweet, 1982).

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Here we examine sensitivity of juvenile and adult *E. nana* and *E. sosorum* to experimental variation in oxygen availability (DO). Using adult salamanders, we imposed short- to long-term variation in ambient DO and quantified spontaneous activity, metabolic rates, and mortality. For juvenile salamanders, we measured growth rates during 60 days of exposure to different levels of oxygen. This data set provides the most complete multi-stage description of oxygen's effects for any salamander and suggests levels of DO below which physiology, and likely fitness, is compromised. We subsequently performed a probabilistic ecological hazard assessment (PEHA) to relate salamander response thresholds to DO measurements in spring habitats.

MATERIALS AND METHODS

Animals.—Experiments were carried out between November of 2005 to December of 2006. Adult *Eurycea nana* (SVL 22.1–35.1 mm, mean 27.9 mm; Tupa and Davis, 1976) were collected by hand from rocky substrates below the Spring Lake dam (San Marcos, Texas), placed in aerated coolers, returned to Austin, and separated into four ten-gallon holding aquaria. We collected 20 adult *Eurycea sosorum* (SVL 22.9–30.2 mm, mean 26.1 mm) from Eliza Spring during a single collecting trip. Salamanders were collected with the cooperation and supervision of the City of Austin using the same techniques as those described for *E. nana*.

Salamanders were held in ten-gallon aquaria filled with Eliza Spring water. Each aquarium had multiple pieces of pre-soaked PVC tubing for cover, gravel collected from below the Spring Lake dam, an air stone delivering room air, and a filter unit (AquaClear, with mechanical, chemical, and biological filtering capability, 400 liters h^{-1}). We also controlled water pH using a pH-stat system (Milwaukee Instruments model SMS122, Rocky Mount, NC), which measured pH continuously and, whenever it rose above 7.6, injected CO_2 until pH fell below the set point. pH regulated in this way was quite stable, varying between 7.3–7.8 over the course of 15–20 min. Salamanders were kept on a 13L:11D light cycle and fed bloodworms every day (Hikari, with multivitamins added, approximately two bloodworms per salamander). *Eurycea nana* were used in all experiments; *E. sosorum* were used only in measurements of short-term metabolic rates.

Water collection.—Water was collected from Eliza Spring, part of the Barton Springs complex (includes also Eliza Spring, Upper Barton, and Old Mill) that supports the highest density of *E. sosorum* in the wild (pH 7.1–7.5, conductivity about 600 μS cm^{-1}, temperature = 20°C). Water was pumped into food-grade trashcans, transported to the University of Texas campus, and filtered through 0.45-μm PTFE membranes (Pall Life Sciences, TF-450) into two 1,136-liter food-grade polyethylene holding tanks. All holding containers were presoaked with tap water for one week and allowed to air dry before use. Stored Eliza water was aerated continuously with room air.

Spontaneous activity.—Spontaneous activity of *E. nana* (n = 8) was recorded using a modification of the infrared method of Sheafor et al. (2000). Salamanders were confined individually to custom-built, flow-through glass chambers (1.5 × 9 cm), with water driven through the chambers by small gear pumps (Micropump, Vancouver, WA) at 1 cm s^{-1}. Water was recirculated past salamanders from a reservoir, a design that facilitated easy modification of water characteristics (see below). The entire apparatus, including the reservoir, was held underwater in a temperature-controlled water bath (maintained at 20°C). Salamander activity was measured using AD-1 infrared activity detectors (Sable Systems, Las Vegas, NV) with LED emitters and detectors on 70-cm long wires, so that they could be placed directly into the water around the glass chambers. Output voltages from the detectors were sampled once per second onto a computer running Expedata software (Sable Systems, version 2.33).

Individual salamanders were put into chambers, allowed to acclimate for four hours in Eliza Spring water (approximately 660 μS cm^{-1}), then subjected to DO ramp from 8.9 mg O_2 L^{-1} down to 1.3 mg O_2 L^{-1} over 2.5 hours and back up to 8.9 mg O_2 L^{-1} over the subsequent 2.5 hours. Desired levels of DO were obtained by mixing pure O_2, N_2, and CO_2 and bubbling the resulting stream directly into the water reservoir. Gas flow rates were controlled by mass flow controllers (all by Unit Instruments, Milpitas, CA, models UFC-1100 or 1101A; O_2: 0–1 slm or 0–500 sccm; N_2: 0–1 slm or 0–500 sccm; CO_2: 0–10 sccm), which were themselves controlled by a separate electronics package (MFC-4, Sable Systems, Las Vegas, NV). Total flows were approximately 500 ml min^{-1}, and CO_2 flows were adjusted to give a pH of approximately 7.5. Conductivity, pH, and DO were measured continuously with a YSI 556 handheld multiparameter instrument, which was calibrated regularly against standards.

Activity data were analyzed using log survivorship analysis (Slater and Lester, 1982) implemented in S-Plus (v. 6.1). First, raw voltage traces were filtered so that each logged value was classified either as 'no activity' (0) or 'activity' (1). We did this, rather than using raw voltages directly, because there is no linear relationship between magnitude of voltage spike and instantaneous degree of activity (advice from Sable Systems). Individual voltage measurements were considered 'no activity' if they were less than five standard deviations from the mean background noise and 'activity' otherwise. Second, we calculated intervals (N) between every sequential activity event, which were then plotted (as log N) on a histogram. In data traces containing distinct bouts of activity, the log plots show a characteristic concave shape, arising from two different event timings. Within bouts, there is a high probability of subsequent activity (short intervals), and thus at the left side of the graph the slope is steep (corresponding to a high probability of subsequent activity). The shallower part of the trace, to the right, corresponds to between-bout times—i.e., the slope is shallow because the probability of a subsequent event is low.

Historically, the 'bout criterion'—the time distinguishing within bout from between bout intervals—has been identified by eye as the point at which the slope changes most rapidly. However, several authors argue for more quantitative methods of estimation. We used the method of Slater and Lester (1982), which they show minimizes the total number of misclassified intervals. They define the optimal bout criterion as

$$t' = \left(\frac{1}{\lambda_W - \lambda_B}\right) \log\left(\frac{\lambda_W N_W}{\lambda_B N_B}\right),$$

where λ_W and λ_B are slopes of the within- and between-bout parts of the log survivorship graph, N_w is number of intervals in the within-bout section, and N_B is number of intervals in the between-bout section. The four parameters were estimated for each individual salamander by fitting a double exponential equation to the log survivorship plot, using a non-linear least squares fitting function in S-Plus. Once the bout criterion was identified for each salamander, its activity vector was filtered again to identify regions that were either within activity bouts or between activity bouts.

Responses were modeled with logistic regression, which is appropriate with binary response variables (e.g., active vs. not active). We used both probit and logit links. Fitted coefficients were used to calculate IC_{50}, the level of DO giving activity half the time, as

$$IC_{50} = -a/b,$$

where a is the fitted intercept and b the coefficient for DO. The eight separate estimates of IC_{50} (one per salamander) were then used to calculate mean IC_{50} with 95% CI.

Salamander metabolic rates.—To estimate critical levels of oxygen that cause changes in metabolic rate (Booth and Feder, 1991), we measured metabolic rates of *E. nana* (n = 15) and *E. sosorum* (n = 14) over ramped levels of DO. Oxygen consumption was measured using a semi-closed system. In each metabolic chamber, a perforated nylon insert protected the salamander from a stir bar. A second nylon insert was milled with three ports, one for a mini Clark-style oxygen electrode (model 730, Diamond General, Ann Arbor, MI), and one each for water inlet and outlet (1/8 inch stainless steel). Fits on the stainless steel tubing were tight enough that no additional sealants were used; electrodes were sealed with silicone. The three-port insert was sealed to the glass beaker (100 ml volume) by an o-ring (Buna-N).

Accurate measures of metabolic rate in aquatic systems depends on controlling or measuring several characteristics of the water, including volume, mixing, and biological activity. Water volumes in chambers were measured gravimetrically (47–64 ml). Stir bar rotation was set to mix chamber water thoroughly within 10 s (measured in preliminary experiments using dye dispersal), and the ports allowed us to flush chambers gently while salamanders were in place. When chambers were closed (no flushing), changes in oxygen were due only to biological activity. Extensive testing showed, first, that chambers were essentially leak-free; and, second, biological oxygen consumption by non-salamander sources (e.g., bacteria) were minimal, as introduction of air-saturated water gave stable, air-saturated electrode readings for several hours. To ensure that this was so in every experiment, we always included one or more blank chambers.

The mini electrodes were connected to a picoammeter (Microsensor, Diamond General) via a 10-channel electrode multiplexer (Diamond General, model 1090A), which allowed us to run up to eight salamander and two blank chambers during a single run. Signals from the picoammeter were logged onto a computer via an A/D converter (Sable Systems, UI2, Las Vegas, NV). Electrode membranes (polyethylene, 1 mil thick) were replaced regularly.

To reduce bacterial growth, all chamber parts were washed thoroughly. Electrodes were calibrated at temperature using N_2-purged and air-saturated water. Salamanders were weighed (Mettler Toledo analytical balance, ± 1 mg) and photographed through a stereo-zoom microscope (Nikon SMZ1500 with DS-5M camera) for later analysis of SVL, then placed one to a chamber (up to eight salamanders with two blank chambers) filled with Eliza Spring water (conductivity approximately 680 $\mu S\ cm^{-1}$). Chambers were submerged in a temperature-controlled water bath set to 20°C. Salamanders were given 45 minutes to acclimate, and then each chamber was flushed with five volumes (250 ml) of air-bubbled Eliza Spring water. Using the electrode multiplexer, we then manually stepped through electrodes, measuring O_2 levels in each chamber for 1–2 min. Each chamber was sampled generally five times in 45–60 min, during which time oxygen content fell from air-saturated to a minimum of 80% of air saturation (approximately 7.4 mg O_2 L^{-1}). Subsequently, each chamber was flushed with five volumes of water at a lower level of DO (equilibrated to gas streams generated by mass-flow controllers, as described above).

We used non-linear mixed-effects models, implemented in S-Plus v. 6.1 (Insightful Corporation, Seattle, WA), to examine relationships between DO and metabolic rate. Visual inspection of the data suggested that metabolic rates fell at lower levels of DO. We therefore chose to fit the 'Biochemical Oxygen Demand' model in Bates and Watts (1988),

$$y(x) = \phi_1[1 - \exp(-\exp(\phi_2)x],$$

where y is metabolic rate, x is level of DO, ϕ_1 is the asymptote (in our case, the asymptotic metabolic rate, units mg O_2 hr^{-1}), and ϕ_2 describes how sharply the curve transitions from zero to the asymptote. From fitted values of ϕ_2, the $metIC_{50}$ (the DO giving a 50% reduction in metabolic rate, units mg O_2 hr^{-1}) can be calculated as

$$metIC_{50} = \log 2/\exp(\phi_2).$$

We followed the iterative strategy of Pinheiro and Bates (2000:appendix C.3) for fitting such models in S-Plus, using the function SSasympOrig.

28-day oxygen-toxicity test.—To assess long-term lethal levels of DO, we measured mortality of 60 adult *E. nana* in a 28-d oxygen toxicity test (where low oxygen was the stressor). Salamanders were housed individually in 2-L aquaria, each equipped with an air stone inside a hydraulic lift tube to drive water circulation. Oxygen levels were maintained by bubbling air from the box head spaces into salamander-containing aquaria. Head spaces in the upper chambers were regulated by a multichannel oxygen regulator (ROXY-8, Sable Systems, Las Vegas, NV). To maintain aquarium temperature, the lower halves of the chambers were plumbed for continual recirculation of chilled water (20°C). Aquarium pH was controlled between 7.0 and 8.0 using the pH-stat system described above.

Individual aquaria were arranged three to a Plexiglas chamber (Fig. 1). Plexiglas chambers in the same oxygen treatment were connected via gas lines, with gas flow between them driven by small fans. Twelve salamanders (pseudo-replicates) were randomly assigned to one of five nominal DO exposure treatments, 1.3, 2.4, 3.6, 4.6, and 7.5 mg/L (see Table 1 for measured values), in individual aquaria. Three aquaria were randomly assigned to a given Plexiglas chamber (replicate) providing an experimental design with five treatments and four replicates (Plexiglas chambers) with three pseudo-replicates per replicate (aquaria). Pseudo-replicates were averaged per replicate to provide four values per treatment. During the course of the experiment, there was some mortality from salamander

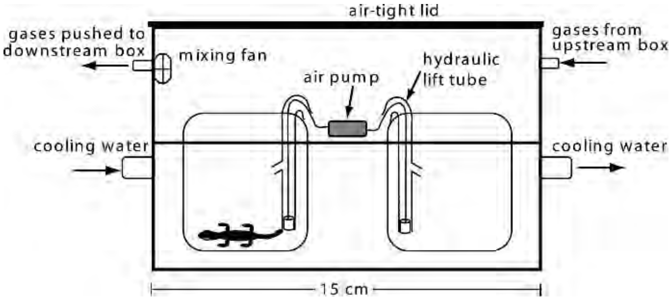

Fig. 1. Experimental set-up for the 28-day oxygen toxicity experiments. Each of 20 controlled atmosphere boxes held three aquaria (one salamander per aquarium); only two aquaria are shown in the figure.

escapes not related to DO level. A total of six escapes and one fungal contaminated salamander resulted in an unbalanced design, with $n = 10$ salamanders in treatments with DO = 3.6 and 4.6 mg/L and $n = 9$ in the DO = 7.5 mg/L.

60-day juvenile growth experiment.—Juvenile salamanders were obtained from the captive breeding program for *Eurycea nana* at the San Marcos (TX) National Fish Hatchery. Juveniles were placed in the same set up as described in the 28-d oxygen toxicity experiment, but DO treatments were set to be non-lethal (see Table 1 for measured values). Juveniles were maintained under these conditions for 60 d. During that time, we weighed and measured snout to vent length (SVL) of each salamander approximately every five days. Juveniles were weighed to the nearest 0.01 mg on a Sartorius MC-5 microbalance. To minimize errors from adherent water and evaporation, salamanders were gently blotted with a dry tissue before being transferred to a weigh boat. Snout–vent length was measured from calibrated digital images. Due to limited availability of juveniles from the captive breeding program, we were able to place only five salamanders into each treatment at the beginning of the experiment.

Toxicity data analysis.—For the 60 d juvenile growth study specific growth rate (G_W), defined as the rate of change of the logarithm of weight through time, was calculated as

$$G_W = 100 \cdot (\ln (W_{final}/W_{initial})/t),$$

where $W_{initial}$ is salamander weight at the beginning of the experiment, W_{final} is weight at the end, and t is time (days). Lowest observable adverse effect level (LOAEL) and no observed adverse effect level (NOAEL) thresholds were determined using Bonferroni's *post hoc* test (USEPA, 2002).

Data for both the 28 d lethality study and the 60 d juvenile growth study were modeled using the linear and non-linear equations outlined in Table 2 (Brain and Solomon, 2007). Model fit was based on the coefficient of determination and the *P*-value for each associated ANOVA. Each model employs an iterative process by fitting parameters simultaneously. If the convergence criteria (approach to stable parameter values) are not met in a specified number of iterations, the model cannot be fit. Based on the variability and distribution of the data, tolerance criteria may not be met for a given model; thus, multiple models were tested. To optimize the fitting process, we adjusted number of iterations, step sizes, and thresholds of tolerance. Effective (60 d juvenile growth study) or lethal (28 d lethality study) concentrations required to inhibit or kill x percent of the organisms (EC_x or LC_x) were calculated, with x set to 5, 10, 25, and 50.

Table 1. Measured Oxygen Levels in the 28-d (Adult Toxicity) and 60-d (Juvenile Growth) Experiments.

	28-day		60-day	
Treatment	mean DO (mg L^{-1})	Std. err.	mean DO (mg L^{-1})	Std. err.
1	1.7	0.32	4.4	0.28
2	2.8	0.34	5.0	0.36
3	3.1	0.28	5.3	0.18
4	4.6	0.13	6.0	0.31
5	7.3	0.10	8.0	0.52

Dissolved oxygen distribution.—Data for Barton Springs DO were acquired from the City of Austin, which was originally obtained from the U.S. Geological Survey (Chris Herrington, pers. comm.). This dataset, containing 517 DO observations taken between November 1969 and April 2009, was plotted according to published methods (Solomon and Takacs, 2002) as a cumulative frequency distribution, with probability on the y-axis and $\log_{10}$ DO on the x-axis (Solomon et al., 2000). Plotting positions (*j*) were expressed as percentages and calculated from the Weibull formula

$$j = 100 \cdot i/(n+1),$$

where i is the rank and n is the total number of data points in the data set. Linear regressions were performed on the transformed data using SigmaPlot 2000 (SPSS, Chicago, IL. http://www.sigmaplot.com). This approach is conceptually similar to an approach recently proposed for anoxia thresholds of benthic marine invertebrates (Vaquer-Sunyer and Duarte, 2008).

Toxicity threshold calculations.—Low centiles of 1% and 5% from the DO distribution were considered potentially appropriate thresholds of exposure and used as Toxicological Benchmark Concentrations (TBCs; Hanson and Solomon, 2002) for this initial assessment. The first centile represents a conservative lower bound of the probabilistic distribution, whereas the fifth centile is analogous to the HC_5 (5th centile hazardous concentration; concentration affecting 5% of species and therefore protective of 95% of species) derived from a species sensitivity distribution of toxicity values (Wagner and Lokke, 1991; Aldenberg and Slob, 1993; Sijm et al., 2002). Hence, based on the DO exposure distribution(s), 99 and 95% of DO concentrations are expected to fall above these thresholds, respectively.

Probabilistic ecological hazard assessment (PEHA).—We performed a PEHA that used the observed DO distribution from Barton Springs, and the LC_5, LC_{10}, LC_{25}, LC_{50}, and 60 d NOAEL and LOAEL thresholds calculated for the 60-d chronic study. A PEHA indicates the likelihood that a DO value will be encountered in Barton Springs that is below the indicated threshold for *Eurycea nana*. This calculation was done by modifying equations from Solomon et al. (2000) as outlined in Brain et al. (2006). We substituted a single threshold value for percentage-based exposure values using Microsoft Excel 2003 (Microsoft Corporation, Redmond, WA) as

$$P_x = NORMDIST(m_{tox} \cdot \log_{10}(x) + b_{tox}),$$

Table 2. Equations Used to Fit the Concentration–Responses of *Eurycea nana* Exposed to Varying Dissolved Oxygen Levels. The variable LC_x is the calculated effective concentration at which proportion p of the endpoint is affected, and x is the actual concentration (mg L^{-1}), y is the response or change from control of the endpoint modeled, and a, b, and y_0 are constants.

Regression	Equation	Modeling type
Linear	$y = a+((ap)/LC_x)x)$	Increase
Four parameter logistic	$y = y_0+a/(1+(x/LC_x)^b)((a/(1-p)(y_0+a)-y_0)-1)$	Decrease
Four parameter logistic	$y = y_0+a/(1+(x/LC_x)^b)((a/(1+p)(y_0+a)-y_0)-1)$	Increase
Three parameter logistic	$y = a\ (1+(p/(1-p)(x/LC_x)^b))$	Decrease

where x is the threshold exposure value, P_x is the probability of encountering a DO value below the designated threshold (x), NORMDIST returns the standard normal cumulative distribution function, and m_{tox} and b_{tox} are the slope and intercept, respectively, of the probit/log transformed regression line of the exposure data.

RESULTS

Spontaneous activity.—All eight *E. nana* in the DO ramp had discernable breakpoints that identified activity bouts (see Fig. 2). Mean bout criterion was 1.60 minutes (range 0.82–2.56).

Salamanders had a clear onset of activity as DO dropped to between 2.7 and 5.5 mg O_2 L^{-1} (Fig. 3A). During the ramp back up, activity ceased at a lower level of DO, approximately 1.8–4.1 mg O_2 L^{-1}. Figure 3B summarizes salamander activity during the experiment. For each salamander, we fitted a logistic regression model separately to rising and falling parts of its activity curve, estimated each IC_{50}, then calculated means and 95% CI across the eight salamanders. Probit and logit links gave virtually identical results, so we present averages of the two techniques. For the rising part of the activity curve (declining DO), the DO at which 50% of salamanders became active was 4.54 mg O_2 L^{-1} (95% CI 4.02–5.06). For the falling part of the activity curve (increasing DO), the DO at which 50% of salamanders became inactive was 3.12 mg O_2 L^{-1} (95% CI 2.39–3.86). Changes in activity thus exhibited some hysteresis.

Salamander metabolic rates.—Metabolic data were quite variable, both within and between salamanders. Nevertheless, the two species had similar average metabolic rates, and the metabolic rates clearly declined at low levels of DO (Fig. 4A, B), especially below 3 mg O_2 L^{-1}.

Estimates of $metIC_{50}$ were obtained using Eq. 4. For *E. nana* we estimate $metIC_{50}$ = 1.31 mg O_2 L^{-1} and for *E. sosorum* $metIC_{50}$ = 1.62 mg O_2 L^{-1} (Table 3). The confidence intervals for both parameters, ϕ_1 and ϕ_2, were broadly overlapping, so we consider species' responses to DO to be statistically indistinguishable. Estimated values for ϕ_1 (metabolic rate under non-limiting oxygen conditions) were 0.052 and 0.043 mg O_2 hr^{-1} for *E. nana* and *E. sosorum*, respectively.

28-day oxygen-toxicity test.—There was a clear logistic relationship between DO and percent mortality (Fig. 5), with mortality falling from high to low between approximately 2 and 4 mg O_2 L^{-1}. Salamander mortality related to DO occurred in the lowest three treatments (1.3, 2.4, and 3.6 mg/L), and all mortality that occurred in the two lowest DO treatments happened within 48 hours of initiating the experiment. No DO related mortalities were observed in either of the two highest treatments (4.6 and 7.5 mg/L). $LC_{5,}$ LC_{10}, LC_{25}, and LC_{50} estimates were calculated for adult mortality data (Table 4) using a three parameter logistic model (r^2 of 0.93; Fig. 5) these values were considered thresholds of response for *E. nana* exposed to varying DO concentrations.

60-day juvenile growth experiment.—Although juveniles in the lowest DO (4.4 mg O_2 L^{-1}) had growth rates that were approximately 30% lower than control salamanders (Table 5), the differences were not significant when analyzed by linear mixed-effects models, perhaps because both the sample sizes and the DO range were small ($n = 4$ or 5 per treatment). Using a toxicological approach, we determined that the specific growth rate NOAEL was 4.4 mg O_2 L^{-1} ($P >$ 0.05; Table 4), the lowest DO examined. Therefore, a lowest observable adverse effect level (LOAEL) was not determined. However, had growth rates in 4.4 mg O_2 L^{-1} been just slightly lower, they would have been significantly different from controls ($P < 0.05$) based on minimum significant difference values. This indicates that the growth NOAEL of 4.4 mg O_2 L^{-1} closely approached a LOAEL for juvenile *E. nana* over a 60-d period. A similar analysis using absolute growth rate for each salamander—calculated as the slope of its mass over time—gave similar results (no significant effect of DO at $P < 0.05$).

Probabilistic ecological hazard assessment.—The linear regression equations generated from the probability and $\log_{10}$ transformed DO data for Barton Springs, Eliza Spring, and Old Mill sampling locations (Fig. 6) were $y = 12.5x-9.8$, $y = 13.2x-10.1$, and $y = 6.1x-4.5$, respectively. The probabilities of exceedance (the probability of encountering a DO value below the specified biological threshold; LC_x or NOAEL), based on these DO distributions at the three sampling locations, and calculated using the LC_x estimates generated from the 28-d study with adult *E. nana* thresholds (mortality) and a 60-day NOAEL (specific growth rate), are summarized in Table 4. The exceedance values for Barton Springs and Eliza Spring were similar; however, Old Mill had substantially higher exceedance estimates owing to a flatter slope and lower measured DO values. However, the correlation coefficient (r^2) for the regression line fitted to the Old Mill data was also lower (0.65) than those for Barton Springs and Eliza Spring (0.97 and 0.96, respectively). In addition, inspection of the data (Fig. 6) indicates that the flow–DO relationship at Old Mill was not log-linear. Nonetheless, there were many low DO values, potentially related to low spring flows, compared to the other two sites, causing a shift in the curve and resulting in loss of linearity. Consequently, greater confidence is placed on estimates generated from Barton Springs and Eliza Spring data.

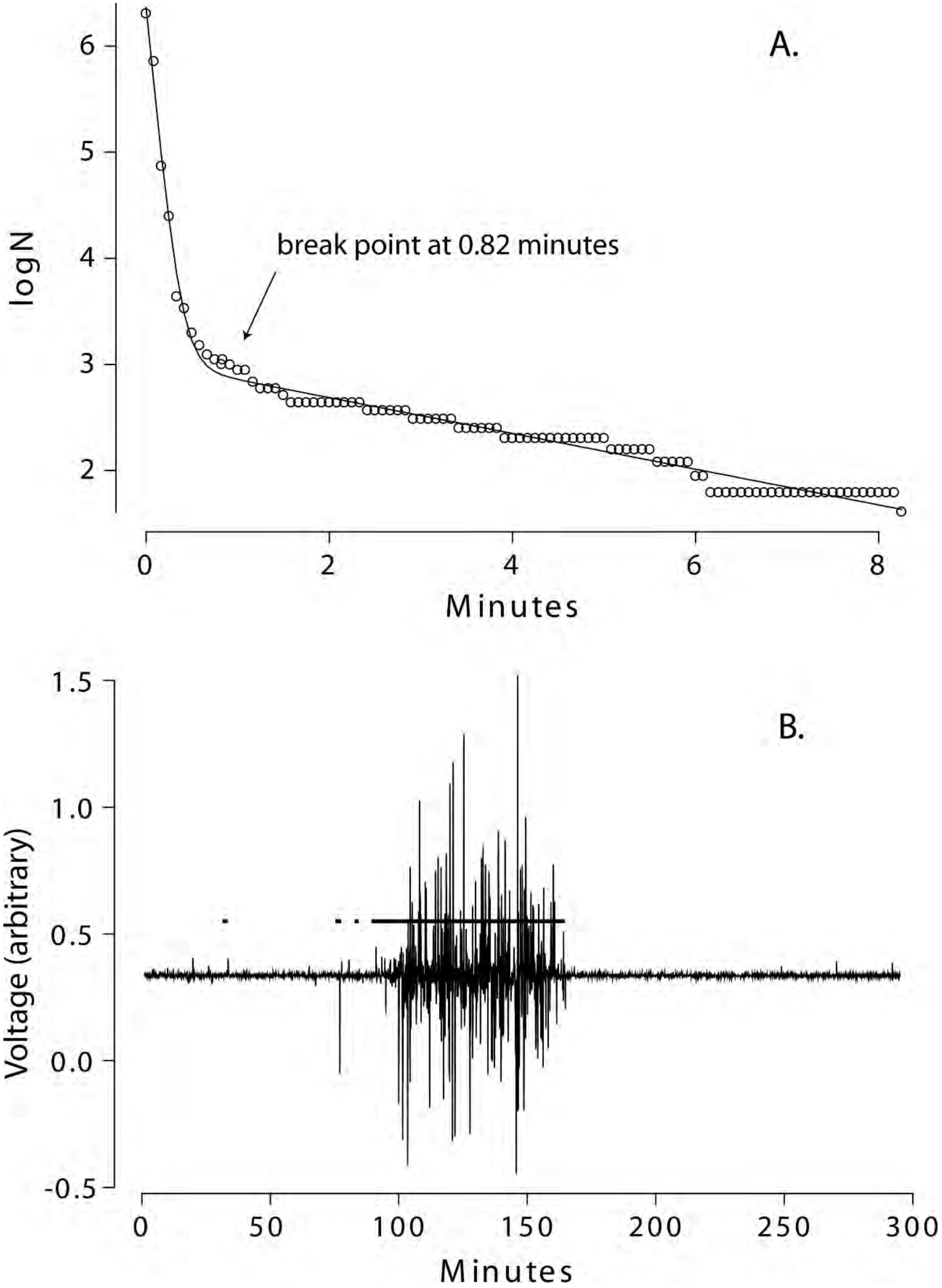

Fig. 2. Example of the log survivorship analysis of activity for one of the salamanders showing (A) the location of the breakpoint at 0.82 min between activity bouts and (B) raw voltage trace from infrared activity meter with activity bouts drawn above according to the breakpoint identified in (A).

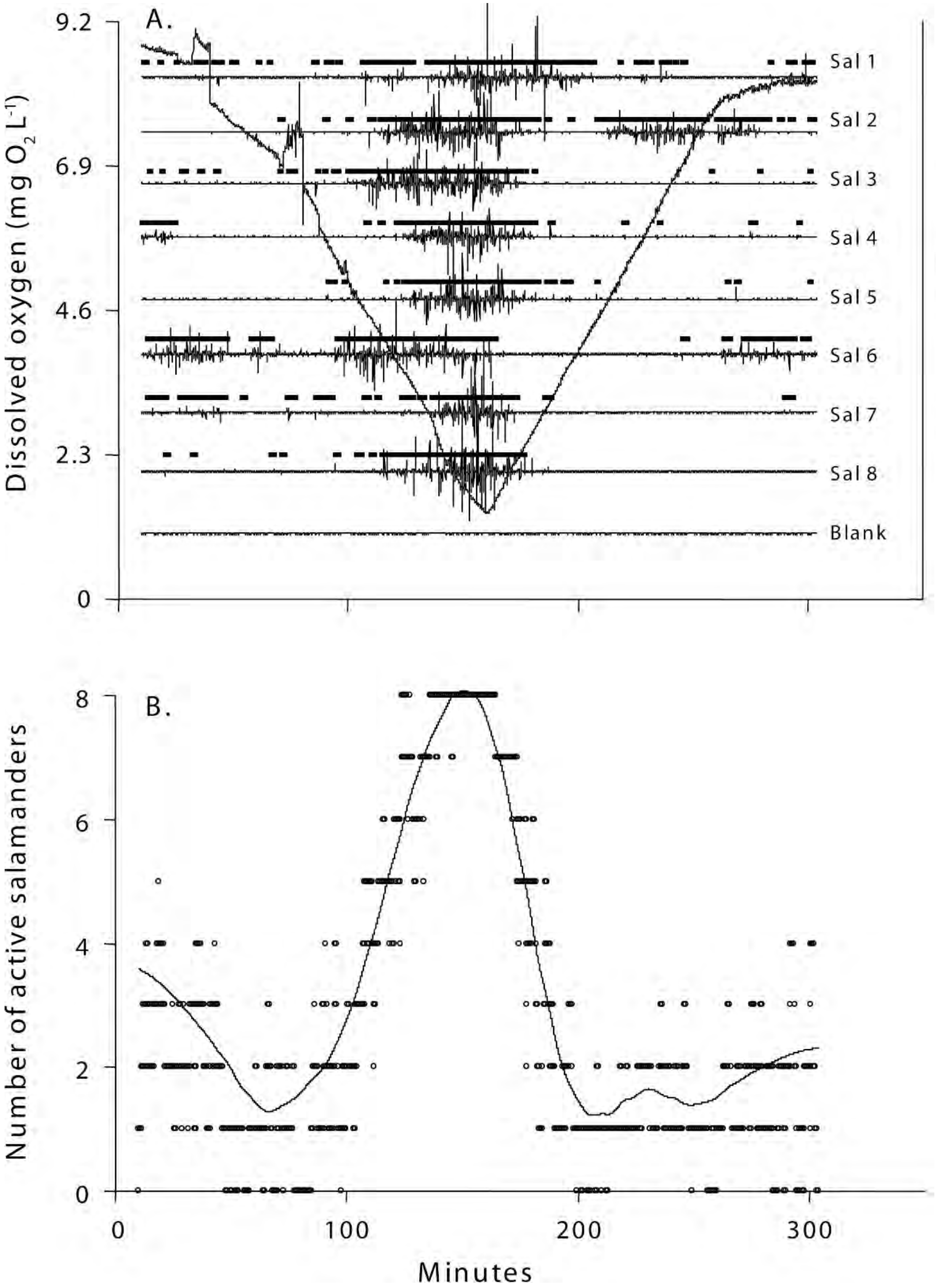

Fig. 3. Spontaneous activity of *Eurycea nana* in response to ramped dissolved oxygen. (A) Raw voltage traces and fitted bouts for each of eight salamanders and a blank chamber superimposed on the trace of dissolved oxygen. (B) Dots are total number of salamanders active (out of eight), and the line is a fitted loess curve (local regression, with smoothing, smoothing parameter = 0.3).

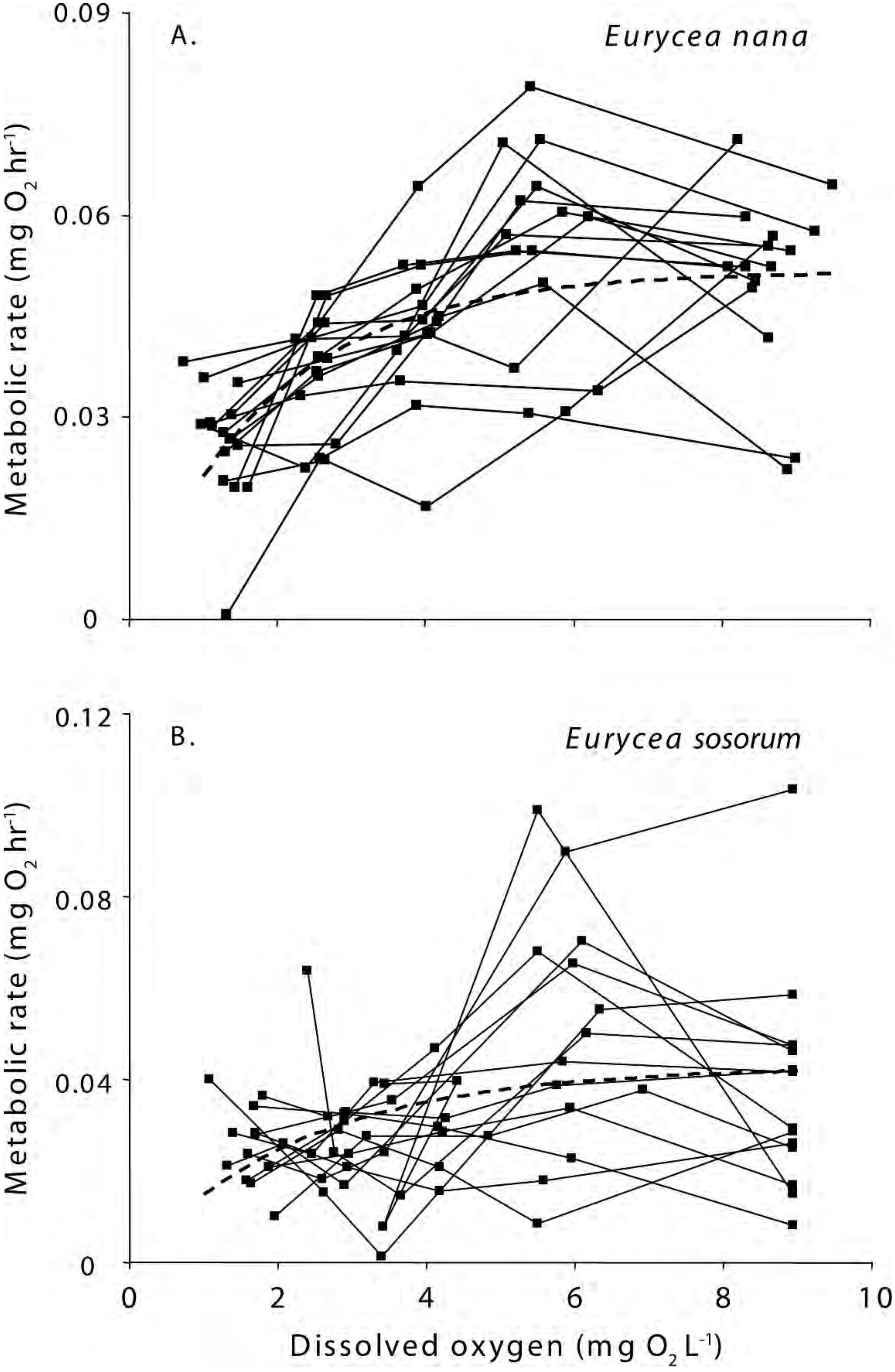

Fig. 4. Metabolic rates of *Eurycea nana* (A) and *E. sosorum* (B) across ramped levels of dissolved oxygen (DO). Lines represent best fits of the Biological Oxygen Demand model (Eq. 3). See Table 3 for summaries of parameter values and statistical significance.

Table 3. Summary of Parameter Values and Statistical Significance from Fitting the Biological Oxygen Demand Model (Eq. 3) to Data on Metabolic Rates as a Function of Dissolved Oxygen Levels (see Fig. 5). $metIC_{50}$ was calculated from Eq. 4.

Species	Parameter	Value	95% CI	num df	den df	*F*	*P*
E. nana	ϕ_1	0.052	0.045 to 0.058	1	59	251.6	<0.0001
	ϕ_2	−0.64	−0.37 to −0.90	1	59	23.5	<0.0001
	$metIC_{50}$	1.31	1.01 to 1.70				
E. sosorum	ϕ_1	0.043	0.032 to 0.053	1	55	85.7	<0.0001
	ϕ_2	−0.85	−1.48 to −0.22	1	55	7.03	0.01
	$metIC_{50}$	1.62	0.86 to 3.04				

As summarized in Table 4, the probability of toxicological threshold exceedances (proportion of DO values below thresholds) for Old Mill ranged from 11% to 38%. For Barton Springs and Eliza Spring the exceedance estimates were similar, ranging from 0.08 to 5.2% and 0.1 to 6.8%, respectively. Based on the DO data from Barton Springs and Eliza Spring there is a 4.5% and 5.8% chance, respectively, that daily DO concentrations will drop below 4.4 mg O_2 L^{-1} (the 60 d NOAEL) that would adversely affect juvenile *E. nana* specific growth rate, a widely accepted parameter linked to population level stress (Suter, 2007). In Old Mill, there is a 28% chance that DO will drop below 4.4 mg O_2 L^{-1} during daily observations

Toxicological Benchmark Concentrations were calculated for low centiles of 1% and 5% based on the DO distributions for Barton Springs at 4 and 4.5 mg O_2 L^{-1}, for Eliza Spring at 3.9 and 4.4 mg O_2 L^{-1}, and for Old Mill at 2.3 and 2.9 mg L^{-1}, respectively. In the absence of more complete data, these values may represent reasonable thresholds of response and indicate that there is ≤1% chance that the DO values will fall below 4, 3.9, and 2.3 mg O_2 L^{-1}, respectively, at Barton Springs, Eliza Spring, and Old Mill, and ≤5% chance that DO will fall below 4.5, 4.4, and 2.9 mg O_2 L^{-1} at the same locations, respectively. It is important to note that this PEHA is driven by probability of discrete and daily average DO values exceeding toxicity thresholds determined from 28-d adult mortality and 60-d juvenile growth studies. Future efforts are needed to determine probabilities of encountering DO exceedances of such thresholds over sustained time periods corresponding to laboratory DO experiments (e.g., 28, 60 d).

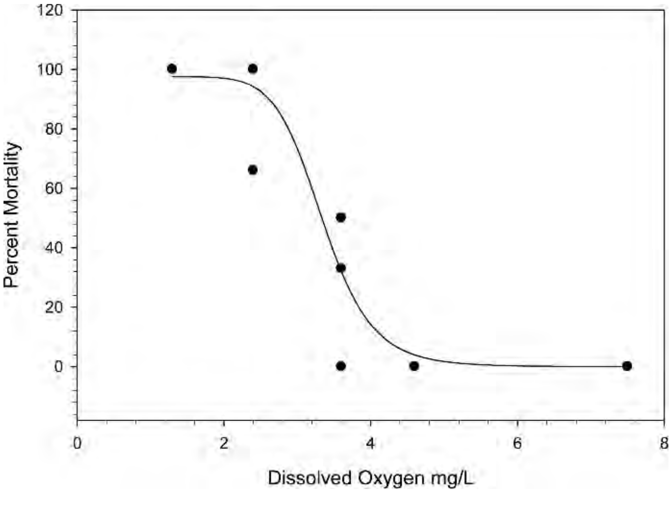

Fig. 5. Percent mortality of *Eurycea nana* exposed to varying dissolved oxygen content.

DISCUSSION

Although species declines stem from multiple factors, more than 70% of endangered organisms are adversely affected by habitat destruction (Pattee et al., 2003). For these species, management decisions often are supported by analyses of ecological hazard or risk (Suter, 2007), with risk assessed in relation to populations. For threatened and endangered species, however, risk may also be assessed in relation to individuals (Suter, 2007), as we have done here. Furthermore, some populations may be imperiled enough that detailed physiological or ecological studies simply cannot be done. Historically, this situation has been approached by studying surrogate species, and sophisticated models are available for analyzing correlations between the responses of surrogates and threatened or endangered species (Raimondo et al., 2007). In this study, we selected *E. nana* as a surrogate because its genetics and life history are similar to those of *E. sosorum* (Chippindale et al., 2000), it occupies similar karst-fed springs in central Texas, and the two species have similar physiologies. Although a lack of even minimal data on *E. sosorum* prevented us from applying formal correlation analyses (Raimondo et al., 2007), our data on *E. nana* provide important, novel insights into how *E. sosorum* is likely to respond to different levels of DO.

Physiology has much to offer conservation, by providing mechanistic insight into links between environmental factors and animal performance (Feder, 1983; Ricklefs and Wikelski, 2002; Helmuth et al., 2005). In turn, understanding performance should allow us to develop prospective views of how animal populations will change in response to stressors and degradation of habitat quality. In practice, establishing strong links between select physiological measures and population processes can be difficult, for two reasons. First, environmental change may affect multiple aspects of performance (e.g., behavior and physiology), and it may be difficult to identify *a priori* which aspects are most important, though the relationship of sensitivities among endpoints is understood for many chemical and physical stressors (Suter, 2007). Second, most animals have complex life cycles (Werner, 1988), and distinct stages can respond to changing environments in different ways.

We analyzed effects on *Eurycea* of an environmental factor, DO, that varies substantially in the habitat of interest (the Barton Springs complex) and that affects other aquatic organisms in profound ways. To assess links between variable DO and salamander population-level processes, we analyzed the effects of DO on fitness-related physiological and behavioral characters (spontaneous activity levels, metabolic rates, survival probabilities, and growth rates) across more than one life stage (juveniles and adults). This approach provides data-rich views of salamander biology,

Table 4. Lethal Concentrations (LC_x) of Oxygen Required to Cause Mortality in 5, 10, 25, and 50% of *Eurycea nana* during 28 Days of Exposure[a] and No Observable Adverse Effect Level (NOAEL) for a 60-Day Exposure. The probability of exceedance for each of the threshold values is provided based on calculations using a probabilistic hazard assessment model (Equation 2) for dissolved oxygen data from Barton Springs, Eliza Springs, and Old Mill sites.

					Probability of exceedance (% of values below threshold)		
Effect	Type	Regression model	Value (mg L^{-1})	*P*	Barton Springs	Eliza Spring	Old Mill
LC_5	28 d	3-parameter logistic	4.5 ± 0.5	<0.0001	5.2	6.8	30
LC_{10}	28 d	3-parameter logistic	4.2 ± 0.3	<0.0001	2.3	3.024	
LC_{25}	28 d	3-parameter logistic	3.7 ± 0.1	<0.0001	0.4	0.4	15
LC_{50}	28 d	3-parameter logistic	3.4 ± 0.2	<0.0001	0.08	0.1	11
NOAEL	60 d	Bonferroni	4.4	>0.05	4.5	5.8	28

while also highlighting further gaps that would have been useful to examine but were not within the scope of the project, for example, how DO affects reproduction, egg development, and hatching.

Effects of DO on salamander activity.—A potentially important response to low DO is mitigation. In most habitats, salamanders will occur across mosaics of high and low DO (or of other factors, such as water flow rate, that affect O_2 availability). Although sensing and responding to such mosaics may be irrelevant at high average DO levels, it surely becomes more important at low DO. In our experiments, salamanders clearly perceived and responded to low (or falling) DO, as the infrared detection system measured onset of activity during falling DO and cessation of activity during subsequent rising DO (Fig. 3).

We interpret activity as having either of two mitigation functions. The more likely is escape from low DO into higher DO areas (though this was not possible for salamanders in our experiments). In the wild, salamanders in local pockets of low-DO water may find higher-DO water nearby (Nolan and Ultsch, 1981). Rigorously assessing this possibility would require measuring the spatial scale of DO variation in natural habitats (Revsbech and Jorgensen, 1986; Dodds, 1991; Kemp and Dodds, 2001). This interpretation is consistent with patterns of salamander presence and absence in the Barton Springs complex. Counts of *E. sosorum* decline in Barton Springs when DO falls below 5 mg O_2 L^{-1} (Turner, 2004). It is likely that salamanders move into the karst system during periods of low DO; however, it is not known whether recolonizing salamanders are the same individuals as those leaving.

A second function of increased activity may be to minimize boundary layers adjacent to skin and gills. Water flow rates in our experiments were, for technical reasons, fairly low (1 cm s^{-1}), likely giving substantial boundary layers. Salamanders may increase oxygen flux to sites of respiratory exchange by disrupting those boundary layers, for example, by bobbing, flicking their heads, or swimming (Wassersug and Seibert, 1975; Crowder et al., 1998).

Table 5. Summary of Growth Rates of Juvenile *Eurycea nana* over 60 Days in Different Dissolved Oxygen Levels.

Treatment	DO (mg L^{-1})	*n*	Growth rate (mg d^{-1})	Std. err.
1	4.44	5	0.15	0.04
2	5.17	4	0.33	0.07
3	5.31	4	0.26	0.03
4	6.35	5	0.24	0.05
5	8.22	4	0.23	0.06

Effects of DO on salamander physiology, survival, and growth.—The three traits, respiration rate, 28-d adult survival probability, and 60-d juvenile growth rate, were differentially sensitive to DO. In particular, *metIC₅₀* (acute exposure giving 50% depression of oxygen consumption rate) was low. For *E. nana* it was 1.3 mg O_2 L^{-1} and for *E. sosorum* 1.6 mg O_2 L^{-1}. In the 28-d oxygen toxicity test, the LC_{50} (giving 50% reduction in survival) was higher, 3.4 ± 0.2 mg O_2 L^{-1}. This difference may reflect that particular levels of low DO are worse for salamanders the longer their exposure to it. However, in the 60-d juvenile experiment, we observed no significant effects of low DO on growth rate, with the caveat that sample sizes were small and our range of experimental DO levels did not extend below 4.4 mg O_2 L^{-1}. Future studies should assess growth under lower oxygen levels and after acclimation to various DO concentrations.

Linking dissolved oxygen to population persistence.—This study was motivated by a conservation problem: *E. nana* and *E. sosorum* are threatened and endangered, respectively, and exist only in small sets of springs surrounded by urban areas. Water quantity and quality in the springs vary over time, with flow and DO positively correlated for Barton Springs (City of Austin, 1997). Historically, variation in flow has been driven by weather and climate on the Edwards Plateau, the limestone escarpment that is the source of aquifer water feeding the springs. At present, variation in flow likely is influenced also by human water use (Slade et al., 1985; Smith and Hunt, 2004). Pumping appears to increase the likelihood of low water flows and associated low DO. Unfortunately, there are few available observations of DO concentrations at low flows. For example, only 27 observations of flow below 20 c.f.s. were included in the dataset used for a PEHA in this study (Fig. 6), and the mean DO value associated with these low flows is 4.69 (±0.28) mg O_2 L^{-1} for Barton Springs. Further, there were only 35 DO observations for Barton Springs below 4.5 mg O_2 L^{-1} in the available dataset (Fig. 6), and there was no statistically significant ($P > 0.05$) relationship between these low flow and associated DO values. Less information for Eliza Spring and Old Mill precluded similar evaluations here.

Other factors such as nutrients and oxygen-demanding wastes, which are known to influence DO variability and

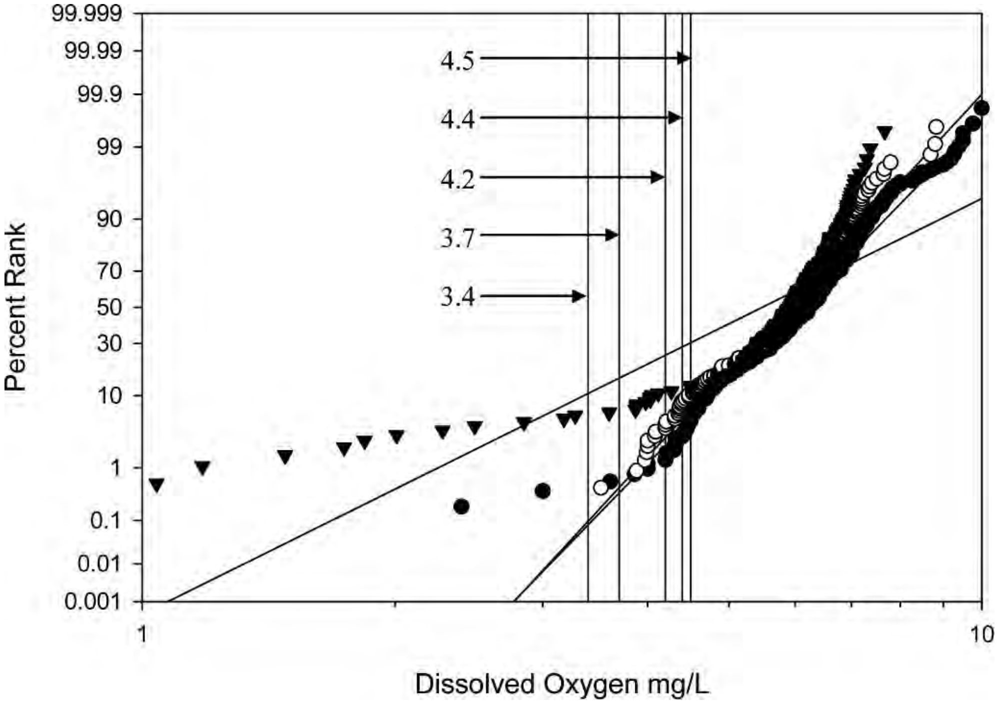

Fig. 6. Percentage rank and log-transformed plot for a distribution of discrete dissolved oxygen measurements for Barton Springs ●, Eliza Spring ○, and Old Mill ▼ locations in central Texas. The corresponding correlation coefficients for the regression lines fitted to each sampling site are 0.97, 0.96, and 0.65, respectively. Vertical reference lines represent the LC_{50} (3.4 mg L^{-1}), LC_{25} (3.7 mg L^{-1}), LC_{10} (4.2 mg L^{-1}), LC_5 (4.5 mg L^{-1}), and NOAEL (4.4 mg L^{-1}), respectively, for 28 d adult mortality and 60 d juvenile specific growth rates of *Eurycea nana* exposed to varying dissolved oxygen concentrations.

daily minima, are targeted by regulatory agencies under the U.S. Clean Water Act to protect aquatic life in inland waters (TCEQ, 2003). A recently developed water quality protection plan for the Barton Springs segment of the Edwards Aquifer identified a number of factors associated with urbanization that may result in water quality stress to endemic salamanders (Naismith Engineering, Inc., 2005). Compared to groundwater withdrawals, the relative contribution of landscape practices and nutrient enrichment on regulation of diel, seasonal, and interannual DO dynamics in habitats of *Eurycea* is not understood, but is likely significant.

A key question is how salamander populations will fare in different levels of DO. The most severe effect would be large-scale mortality of one or more life stages. For example, adult *E. nana* in the 28-d toxicity test had an LC_{50} of 3.4 mg O_2 L^{-1}. Clearly, DO levels $\leq$ 3.4 mg O_2 L^{-1} would constitute a grave threat to populations if conditions persisted for 28 d. The probability of such an event is low (Table 4). However, it is worth also considering less severe conditions, as these have substantially higher probabilities of occurring in the Barton Springs complex: the LC_5 and LC_{10} values are likely to be exceeded with probabilities (percentage of DO values below thresholds) of 5.2% and 2.3%, respectively, over short time intervals (discrete sampling). Certainly, exceedance probabilities will be lower for 28-d periods, but how much lower is unknown. Several additional kinds of data would help resolve this issue: real-time DO diurnal monitoring (e.g., with multiparameter datasondes) in *Eurycea* habitats, more modeling of the probability of long-duration, low-DO events, and the effects on adults of more natural time courses of DO cycling. For the present discussion, an important caveat is that DO toxicity testing was done on adults only. If other stages, eggs or juveniles, are more sensitive (exhibit higher LC_{50}s), higher levels of DO may still constitute a considerable threat. For example, no data are available to evaluate mortality responses of eggs of *Eurycea* to DO. Although eggs are small, which should relieve boundary layer resistance to oxygen flux, they are also immobile and, especially early in development, may have poorly developed systems for coping with oxygen variability.

The converse is to ask: above what level of DO did we observe no statistical change in any of the measured traits? In the growth experiment, there were no observable effects of DO $\geq$ 4.4 mg O_2 L^{-1}, and in the acute experiment there was 10% mortality (LC_{10}; considered equivalent to a NOAEL [TenBrook et al., 2009]) at 4.2 mg O_2 L^{-1}. Metabolic rates appeared only slightly depressed in this range. The spontaneous activity experiment indicated an intermediate sensitivity to DO (IC_{50} of 4.5 mg O_2 L^{-1}).

The DO range between these extremes, of large-scale mortality at 3.4 mg O_2 L^{-1} versus no observable effects above approximately 4.5 mg O_2 L^{-1}, is the location of greatest biological interest. It is likely that populations in the Barton Springs complex would fare increasingly poorly in lower DOs persisting for 28–60 d periods within this range, but how poorly is unknown. Quantitative assessment of these thresholds awaits additional, field-oriented studies.

To relate laboratory stressor–response data to ambient DO values in habitats of *Eurycea*, we performed a PEHA for three spring-fed systems in the Barton Springs Complex: Barton Springs Pool, Eliza Spring, and Old Mill. The PEHA suggests that the fifth centile values of average daily DO (4.5 and 5.8 mg O_2 L^{-1} in Barton Springs Pool and Eliza Spring, respectively) are sufficient to protect juvenile and adult *Eurycea*, as the NOAEL for juvenile growth rates over a 60 d period was 4.4 mg O_2 L^{-1}. However, the likelihood of exceeding ecologically meaningful DO thresholds is much higher in Old Mill (Table 4). These observations suggest that we need a better understanding of the physical, chemical, and biological factors influencing DO below 4.5 mg O_2 L^{-1} in spring-fed habitats of *Eurycea*, particularly given endangered and threatened species concerns and potential Type II errors (Brosi and Biber, 2009).

In Texas, DO water quality criteria for the protection of aquatic life are prescribed for streams/rivers and reservoirs (lakes) as 24 hr average and absolute minimum concentrations, though water quality criteria for other aquatic habitats are not as well defined or understood (Brooks et al., 2008). For example, Barton Springs Pool is considered an unclassified water body with a high aquatic life use and a DO water quality criterion of 5 mg L^{-1} over a 24 hr period (TCEQ, 2003). Thus, DO water quality criteria for lentic systems (5 mg O_2 L^{-1}, 24 hr average) appear to offer adequate protection to *Eurycea*, though future studies are required to define whether *Eurycea* are protected by absolute 24 hr minimum DO water quality criteria applied to high aquatic life use habitats. In addition, Barton Springs Pool, Eliza Spring, and Old Mill are spring-fed surface waters (neither river nor reservoir) with unique physical features known to influence the production–respiration dynamics of ecosystems and, thus, DO (Forbes et al., 2008). Due to data availability and the scope of the present study, we were unable to fully examine whether river DO water quality criteria protect these threatened and endangered salamanders. Further research is needed on how spatial and temporal variation in DO affects the life history and resiliency of *Eurycea*. Future efforts should determine the influence of urbanization and climate variability on water quality and associated ecological thresholds for *Eurycea*.

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APPENDIX J

Integration of Laboratory Data, Field Operations, Regulatory Program, and Statistical Analysis in the HCP

Appendix J

Integration of Laboratory Data, Field Observations, Regulatory Program, and Statistical Analysis in the HCP

The District has integrated the laboratory results described in Section 5.2.1, long-term field observations, its regulatory program requirements, and statistical modeling to assess the effects, particularly the lethal effects of take and their impacts on the Covered Species, both in individual droughts of specified characteristics and cumulatively over the term of the ITP. A step-wise conceptual model implemented by a series of spreadsheets was developed to facilitate the many thousands of calculations on which these estimates are based. This model and its spreadsheets are described in this appendix and provide detailed information on the rationale and basic structure of the methodology and the calculations that are used to inform this HCP. Additionally, the actual spreadsheets are being made available for public download from the District website after the District submits its ITP application and Draft HCP, at http://www.bseacd.org/xxxxx.

A step-wise process was employed for estimating losses and mortality that incorporates:

- the probabilistic estimates of springflows under various scenarios;
- their correlations with water chemistry;
- estimates of harm determined from experimental studies showing the effects of changes in dissolved oxygen (DO) on the physiology and behavior of proxy salamanders (Poteet and Woods, 2007)[1];
- the reduction in number of individuals due to mortality month by month; and
- comparisons of the lethal effects associated with three groundwater management scenarios, including the benefits of proposed or conditional mitigation measures. the apportionment of those reductions to the Covered Activities by subtracting out similarly derived effects of springflows as not affected by pumping.

The model (spreadsheets) used to estimate the cumulative salamander losses during drought and pumping are not population models. They do not consider population dynamics and growth and are likely a very conservative estimate of the adverse impacts on the populations.

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[1] The experimental stressor-response studies were substantiated with further analysis and incorporation of ecological risk assessment methodologies (Woods et al,. 2010) that provided the framework for the more robust assessment of adverse effects on Barton Springs salamander and, by extension, Austin blind salamander that is used in this HCP.

Step One: Developing and Analyzing Hydrographs

The hydrographs described in Section 4.1.2.2 were used to develop a series of monthly frequency curves, one for each of the following three groundwater management scenarios:

1. an approximation of springflow with only the minor amount of exempt, i.e., no non-exempt, pumping included; this Exempt-only Pumping scenario is the take baseline;

2. a pre-HCP springflow, which simulates pumping without HCP measures, for comparison purposes only; and

3. HCP springflow, which is the springflow scenario with the proposed "HCP conservation measures," which refers to measures that avoid, minimize, and/or mitigate take of the Covered Species. These measures are described in detail in Section 6.2 of the main text.

All three scenarios use the period of record from 1917-2013, as shown in Figure 4-2 of the main text. The three hydrographs are based on the following stipulations and assumptions:

1. A natural-flow hydrograph was constructed to reflect what the springflow would have been without any pumping of the Aquifer. It was computed by taking actual monthly-average springflows as measured and/or inferred by USGS techniques and personnel (Slade et al., 1986), and adding the actual and estimated total monthly pumpage from the Aquifer during the period of record. (This synthetic hydrograph for total discharges from the aquifer is shown in Figure 3-5 in the main text.)

2. The pre-HCP and HCP groundwater management scenarios are both based on a total authorized pumpage of 11.6 cfs, which is the currently (2014) authorized pumpage under permit under non-drought conditions. Recall, however, that the pre-HCP scenario had no mechanism to limit total authorized production, so this amount of pumpage is far from a worst-case for the pre-HCP scenario.

3. The 11.6 cfs of total non-exempt pumpage was allocated to individual months of the year on a percentage basis, using the aggregated monthly allowable pumpage during non-drought reported historically by the District's permittees, ranging between 7 cfs for each February and 16 cfs for each August .

4. Since withdrawals for exempt use are not Covered Activities, 5% of the non-exempt use for each month of the 97-year period of record, representing each month's exempt use (Banda, 2010), was "restored' by subtracting it from that month's calculated natural-springflow obtained in the first step above, to establish the "Exempt-only Pumping" scenario, which forms the baseline for take estimates.

5. The pre-HCP scenario corresponds to the curtailments specified in District rules as they existed before 2004, described in more detail in Section 4.1.2.1 of the main text. It is being carried through these mortality estimates primarily to present a “what-if scenario” of what spring flows might have been like without the District’s HCP conservation program, to demonstrate by comparison not only the benefit of those HCP conservation measures but also the District’s ongoing commitment to them even before issuance of the ITP.

6. The HCP scenario corresponds to the full implementation of the HCP conservation measures described in more detail in Section 6.2 below. It is worth noting that in the District’s experience, total actual pumping during non-drought (i.e., un-curtailed) periods is variably but considerably below the authorized amounts of production (see for example, Figure 3-9 in Section 3.2.3 of the main text), so total pumpage included in this scenario tends to be overstated for most months in the later parts of the period of record.

These three hydrographs were then transformed in recurrence curves over the period of record (Figure J-1). Recurrence (non-exceedence)-frequency springflow statistics for the two groundwater management scenarios were generated for flow thresholds of interest to the HCP and compared to analogous baseline statistics for the Exempt-only Pumping springflows (Table J-1).

Table J-1. Comparison of springflow statistics for flows of interest to the HCP. The HCP management scenario protects minimum springflows much better than the pre-HCP scenario during Extreme Drought periods. Source: BSEACD (2014).

Groundwater Management Thresholds		**Percent of Time Springflow Is Less Than Designated Amount in Scenario**		
Aquifer Stage	**Total Springflow**	**Exempt-only Pumping**	**Pre-HCP**	**HCP**
Average Flow	53 cfs	52%	61%	61%
Stage II-Alarm	38-20	37	47	44
Stage III-Critical	20-14	10	24	20
Stage IV-Exceptional	14-10	2	15	8
Emergency Response	<10	<0.01	7	3
Regulated Minimum	6.5	0	3	<1
No Springflow	0	0	<1	0

Step Two: Associating Springflows and Dissolved Oxygen Concentrations

Using the combined-springflow hydrographs produced by each of the three groundwater management scenarios that were based on monthly data from the 1917-2013 period of record (Step One), the District then calculated the DO concentration at each outlet corresponding to the resulting combined springflow for each month. To make this calculation, various regression relationships relating observed DO-springflow pairs (Turner, 2007; Porras, 2014) were assessed for appropriateness on an individual outlet basis, and then selected regression relationships were employed to calculate DO concentrations at each outlet under various low-springflow conditions in the Aquifer (termed “no- storm flows” in Turner (2007), and “no-streambed recharge” in Porras (2014)).

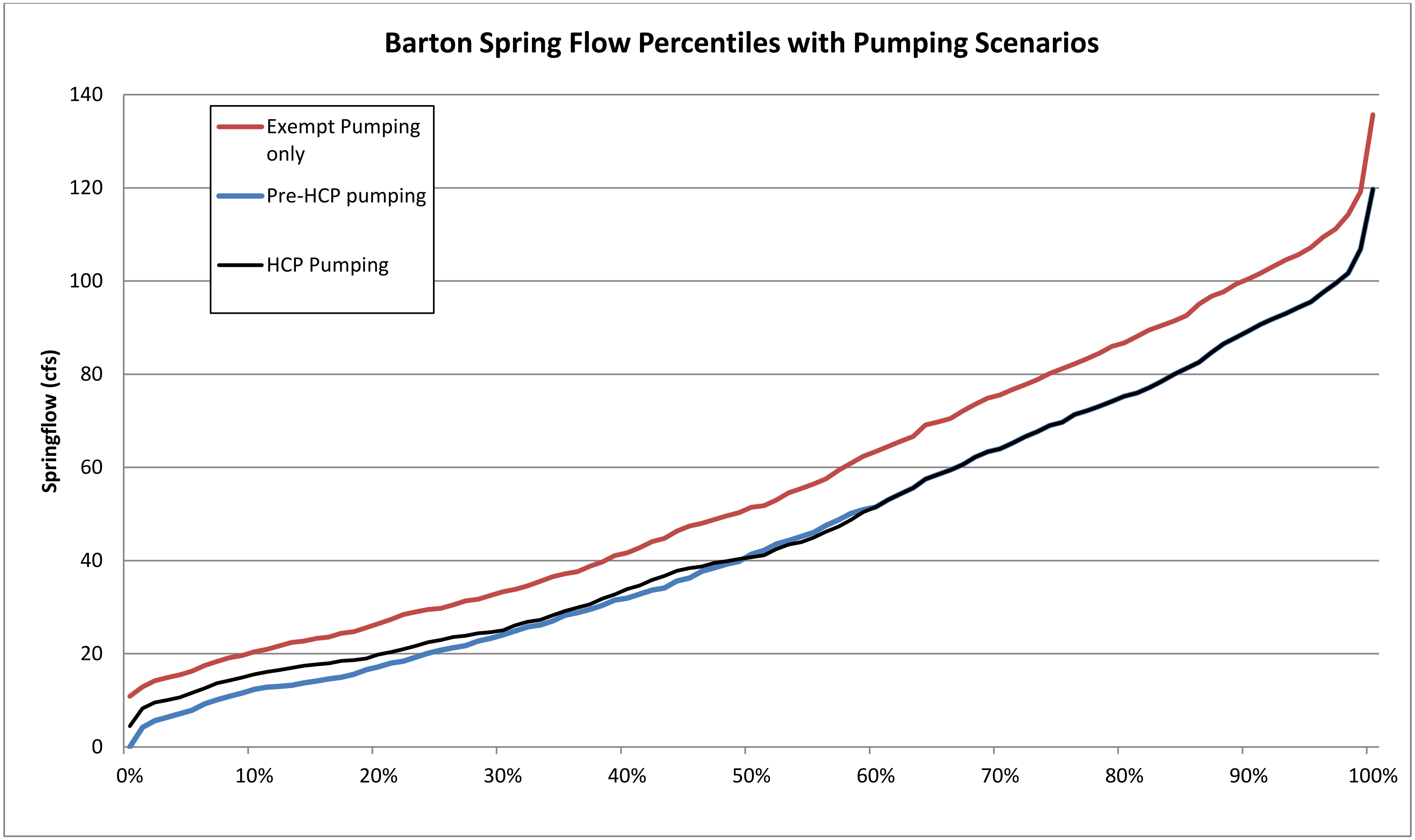


Figure J-1. Recurrence frequency of springflows less than amounts shown under three groundwater management scenarios. The effect of the HCP conservation measures becomes increasingly more beneficial, especially when compared to the pre-HCP scenario, as the lower-than average springflows continue to decrease, where by design the Covered Species are benefited the most.

Turner (2007) surveyed seven or more curve-fitting routines for these data pairs, noting that all of them were very similar in standard errors and correlation coefficients for any one outlet, and concluding that some other criteria should be used to select among them (see Figure 3-7 and its discussion in Section 3.2.2.2.2 of the main text). The District selected the Logarithmic Fit routine as the appropriate regression relationship for Old Mill Spring, and after some trials with the non-linear Exponential Association-3 routine, also selected the Logarithmic Fit routine as the better regression relationship to use for both Eliza and Main Springs as well. It should be noted that the observed DO-flow relationships for Old Mill are not well replicated by any of these models, whereas they are for the other two outlets. It is hypothesized that Old Mill behaves fundamentally differently than Eliza or Main Springs because it has two quite different groundwater flow regimes controlling its water chemistry. (As characterized in Section 3.2.2.2 and elaborated further below, there are hydrogeologic and hydrologic reasons for such a difference.) Moreover, there are some confidence-region limitations associated with the existing data when used with non-linear models in applications like the one needed here that are not present with the (log) linear models. And the issue concerning the requirement of the logarithmic model for the predicted DO at zero flow to be zero (when the data pairs *per se* do not indicate such a trend) proved to be only of material concern at exceedingly low modeled flows (less than 2 cfs combined flow), much lower than those expected to be encountered in the HCP modeling.

The DO dataset of Turner (2007) was recently updated to include data collected from 2007-2014 under no-recharge (i.e., low-flow) conditions and additional statistical analyses were performed (Porras 2014). The logarithmic regression equations developed from these updated data sets are used in this HCP for calculating DO at the perennial outlets corresponding to combined springflow.

The District restricted the data pairs used in these calculations to those collected only under low-flows conditions to avoid the significant confounding influences of (1) highly variable DOs present in rapidly recharging water, and (2) seasonally variable springflow temperatures, both of which accompany various storm events (Mahler and Bourgeais, 2013). For purposes of evaluating the effects of drought on water chemistry in this HCP, censoring the data pairs to include only those during low-flow conditions was judged to produce a more accurate and representative statistical relationship. (However, it should be noted that because data pairs of non-drought flows were excluded from the analysis, those regression relationships are not intended to be used to predict DO under non-drought or even all-flows conditions.)

As noted elsewhere in this HCP, the Aquifer outlet of Old Mill Spring resurges on a different fault and appears to reflect a different water provenance from the other two outlets, with a somewhat higher proportion of older, more saline, and more anoxic groundwater, especially at low flows. Therefore, the relationship of its water chemistry to Aquifer water levels and springflow at Old Mill Spring is reasonably expected to be fundamentally different from either Main or Eliza Springs over a broad range of flows–DO data support that expectation. In severe drought DO of Old Mill Spring declines substantially faster than decreases of DO observed at Eliza or Main Springs. As combined springflows fall below about 15 cfs, the DO decline at Old Mill Spring has accelerated such that it approaches near-anoxic conditions; the Old Mill outlet stops flowing at about 14 cfs of combined springflow. On balance, the Logarithmic Fit option is considered by the District to be a sound choice for Old Mill Spring. However, if and as more data become available during Exceptional and Extreme Drought conditions it may be discovered that there are two distinct linear trends to be fit to Old Mill data, rather than the one currently employed.

Neither Eliza nor Main Springs shows the kind of DO “behavior” exhibited by Old Mill Spring. Their observed DO concentrations decline with springflow, but much more gradually and to a smaller extent, and those outlets continue to flow at lower aquifer water levels than Old Mill. (It is not known if, under natural conditions, either Eliza Springs or Main Springs has stopped flowing in their history.) The data trends do not indicate that declines in DO concentrations at Eliza or Main Springs accelerate toward 0 mg/L at lower flows, although DO data at Extreme Drought flows are lacking. A recent USGS multivariate statistical analysis of a recent part of the period of record including low and high flows suggests that the DO concentration of Barton Springs with no flow would be about 4.0 ±0.3 mg/L at a 95% confidence level (Mahler and Bourgeais, 2013).

The regression formulas used in this HCP are taken from Porras (2014) and are as follows:

Main Springs:	$DO = 0.0687+(1.5133*LN(Q))$	($R^2 = 0.67$)
Eliza Spring:	$DO = 0.3602+(1.38*LN(Q))$	($R^2 = 0.75$)
Old Mill Spring:	$DO = 1.49 + (1.0459*LN(Q))$	($R^2 = 0.32$)

where ‘DO’ is the calculated DO in mg/L, ‘Q’ is total springflow in cfs, and ‘LN’ is the natural logarithm function; and the metric ‘R^2’ is the coefficient of determination, a measure of the proportion of variability accounted for by the equation, which is approximately the square of Pearson’s product-moment sample correlation coefficient, ‘r.’

DO concentrations at each of the three outlets that correspond to springflows of drought management interest and that are derived from the regression equations above are shown in Table J-2. Main Springs and Eliza Spring have similar DO concentrations at all springflows and both have higher DO than Old Mill Spring; in addition, DO at Old Mill decreases much faster than at the other two outlets during severe drought conditions.

Extending the type of calculations in Table J-2 to the entire 97-year period of record produces a set of recurrence frequency curves for DO concentrations at the individual outlets. Results of this step are shown in Figure J-2, with different graphs for each of the three outlets. Similar to the statistical analysis presented for flow, Table J-3 utilizes the information in Figure J-2 to show the recurrence (non-exceedence) frequency by spring outlet for those DO concentrations of physiological and behavioral importance to the Covered Species. This is the final result of Step 2, which then informs the following steps.

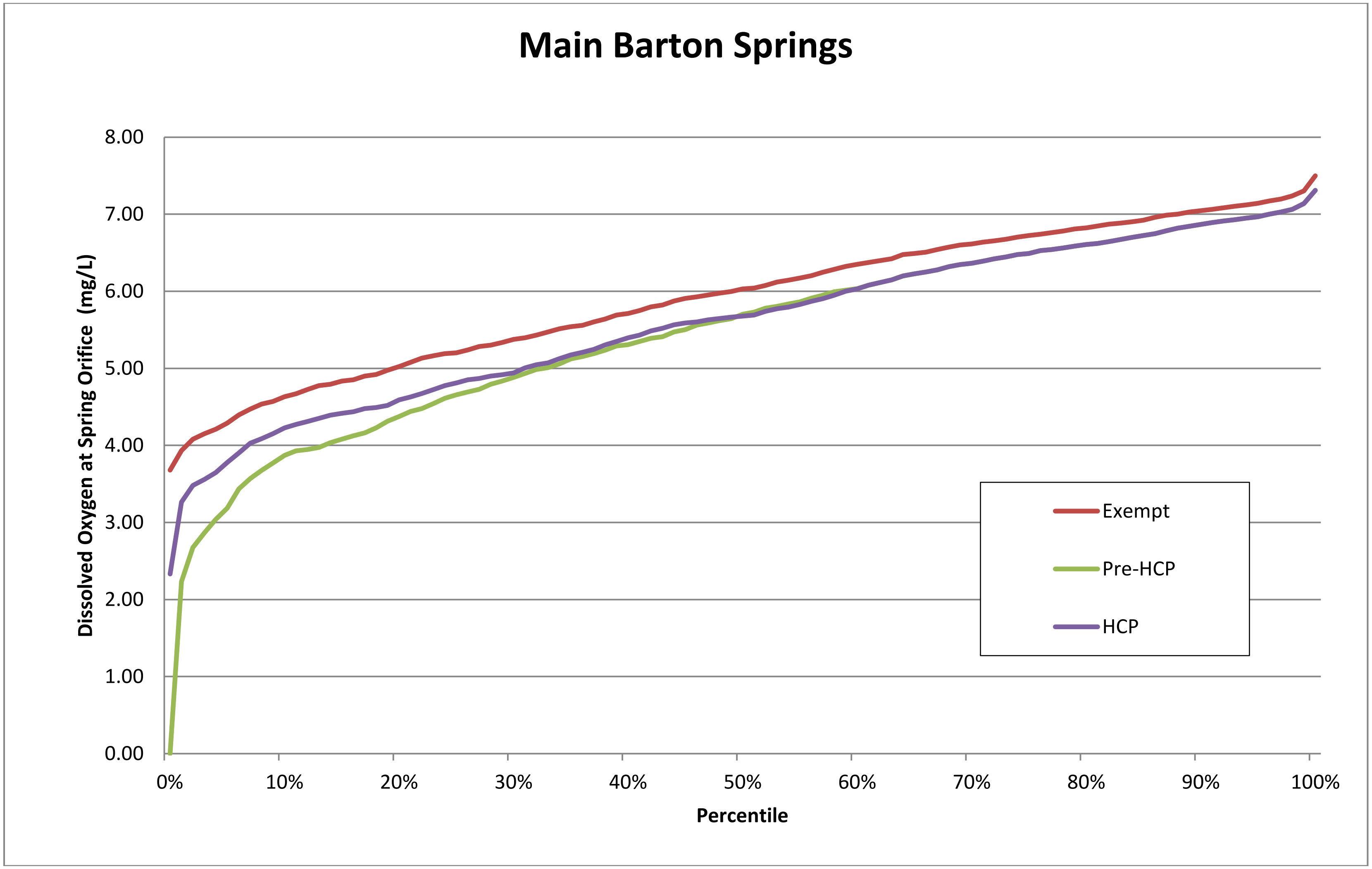


Figure J-2(a). Recurrence frequency of DO (percent of DO concentrations less than values shown) at the Main Springs outlet that corresponds to total springflows for the three pumping scenarios. The DO was calculated on the basis of a selected regression equation (see text) for this outlet based on measured flow-DO pairs under low flow conditions. These curves reflect the DO-springflow relationship for this outlet before any re-aeration benefit.

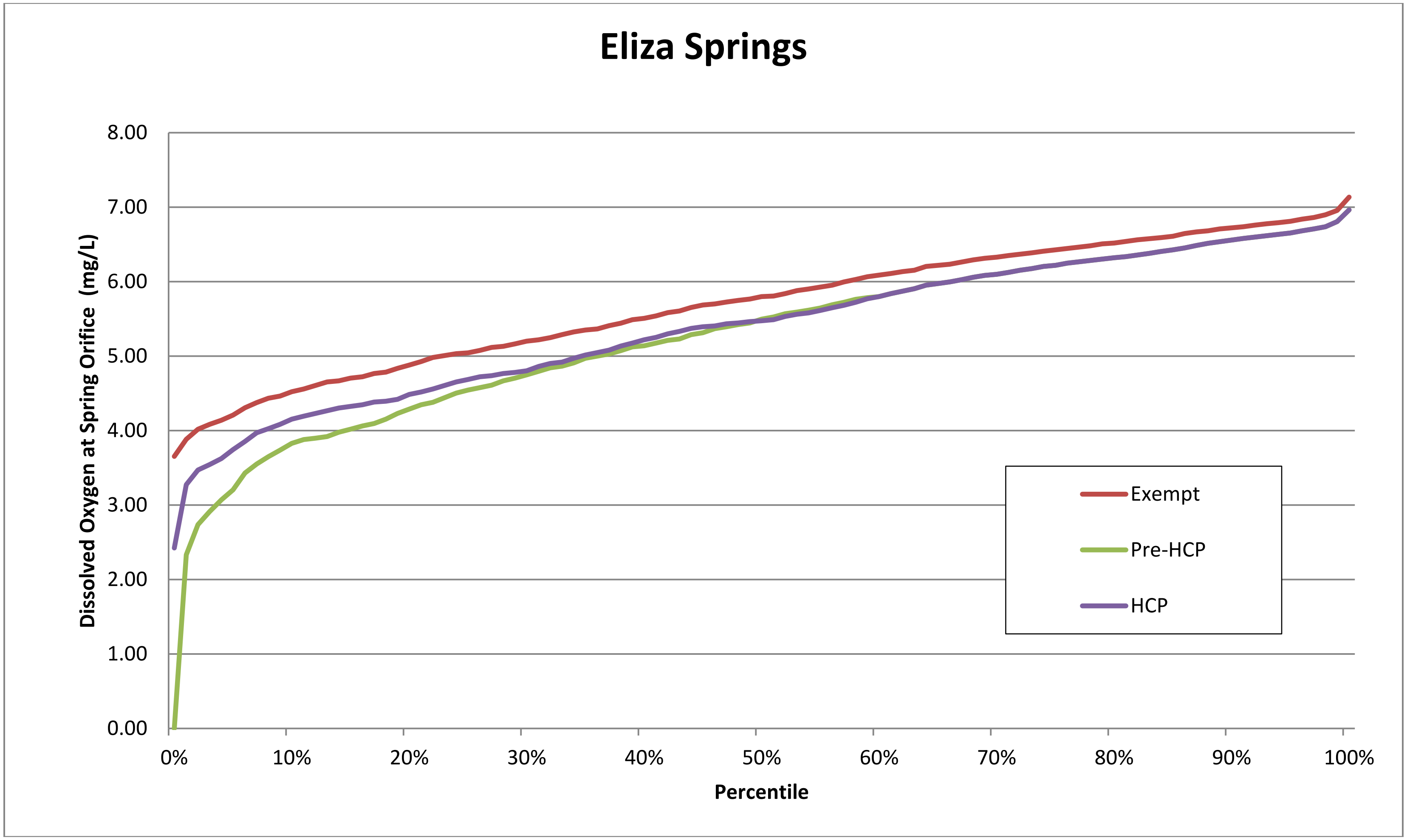


Figure J-2(b). Recurrence frequency of DO (percent of DO concentrations less than values shown) at the Eliza Spring outlet that corresponds to total springflows for the three pumping scenarios. The DO was calculated on the basis of a selected regression equation (see text) for this outlet based on measured flow-DO pairs under low flow conditions. These curves reflect the DO-springflow relationship for this outlet before any re-aeration benefit.

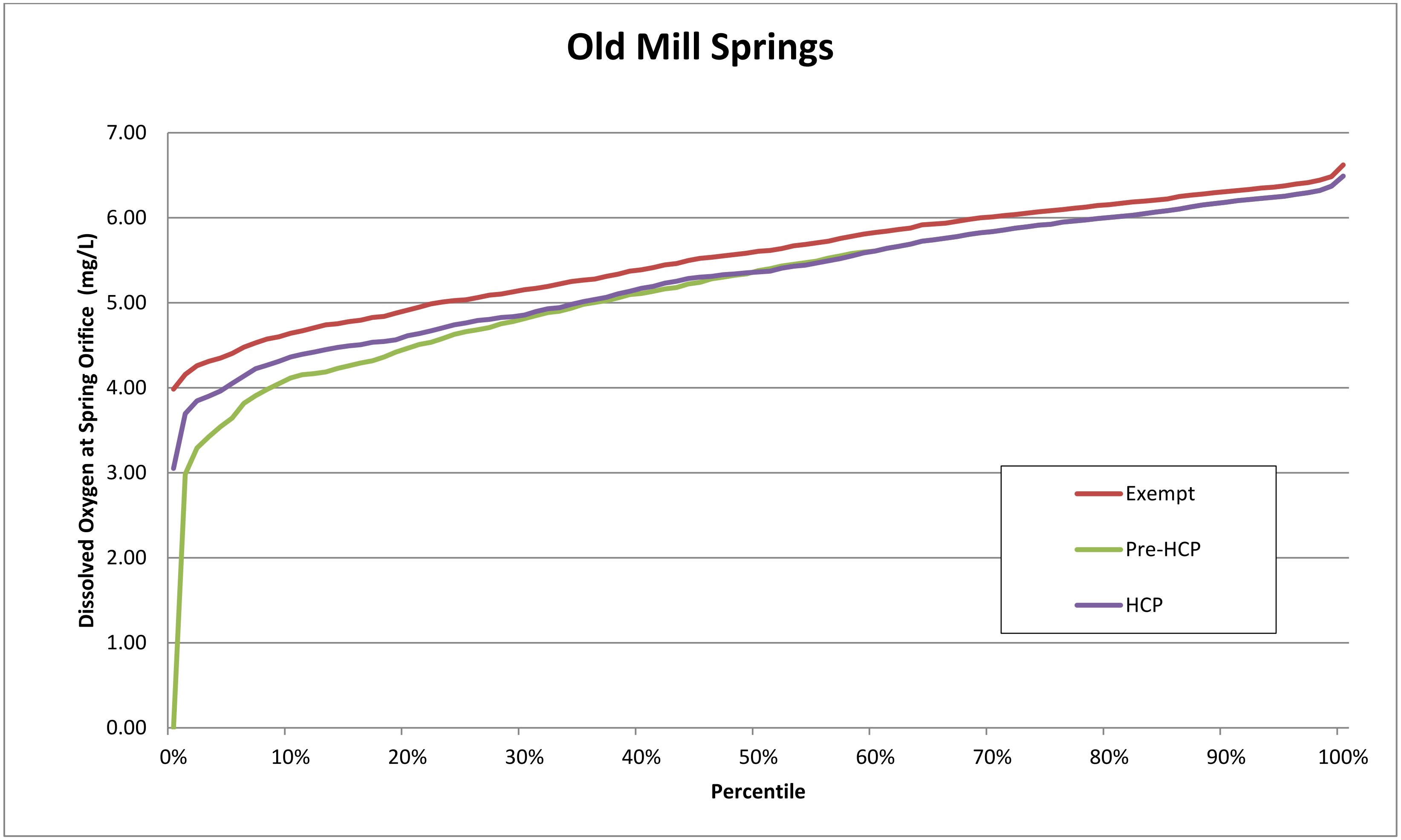


Figure J-2(c). Recurrence frequency of DO (percent of time that DO is below the indicated value) at the Old Mill Spring outlet that corresponds to total springflows for the three pumping scenarios. The DO was calculated on the basis of a selected regression equation (see text) for this outlet based on measured flow-DO pairs under low flow conditions. These curves reflect the DO-springflow relationship for this outlet before any re-aeration benefit.

Table J-2. Calculated DO concentrations at each of the three spring outlets corresponding to groundwater management thresholds for the HCP.

Groundwater Management Thresholds		Calculated DO Concentrations At Each of Three Spring Outlets		
Aquifer Stage	**Total Springflow**	**Main Springs**	**Eliza Spring**	**Old Mill Spring**
Average Flow	53 cfs	6.1 mg/L	5.89 mg/L	5.46 mg/L
Stage II-Alarm	38	5.61	5.47	5.13
Stage III-Critical	20	4.73	4.70	4.49
Stage IV-Exceptional	14	4.34	4.36	4.13
Emergency Response	10	4.04	4.10	3.79
Regulated Minimum	6.5	3.76	3.85	3.36
No Springflow	0	3.16	3.33	0.00

Table J-3. Recurrence Frequencies of DO Less than Designated Concentrations at Three Spring Outlets for the Three Pumpage Scenarios. These percentages correspond to the continuous data shown in Figure J-2. These frequencies are before application of the DO re-aeration adjustments in the HCP scenario described in Section 1.3 of this appendix.

	Main Outlet			Eliza Outlet			Old Mill Outlet		
DO Levels (mg/L)	**Exempt-only Pumping**	**Pre-HCP**	**HCP**	**Exempt-only Pumping**	**Pre-HCP**	**HCP**	**Exempt-only Pumping**	**Pre-HCP**	**HCP**
4.5 or below (LC_5)	7%	22%	18%	10%	24%	20%	6%	21%	6%
4.2 or below (LC_{10})	4%	18%	10%	8%	19%	11%	1%	13%	7%
3.7 or below (LC_{25})	0%	8%	4%	0%	9%	5%	0%	5%	1%
3.4 or below (LC_{50})	0%	0%	1%	0%	6%	2%	0%	3%	0%
0	0%	0%	0%	0%	0%	0%	0%	0%	0%

Step Three: Converting DO to Salamander Mortality Estimates

In actuality the DO concentrations at the outlets shown in Figure J-2 are unlikely to apply to the entire population of the Covered Species there simultaneously. Especially for epigean organisms like the Barton Springs salamander that are motile, some DO stress at the outlet could be relieved by moving away from the outlet to higher-DO water in spring runs, especially following the completion of habitat restoration work under the City's HCP that is intended to increase the re-aeration in the vicinity of the outlets. To account for the improved habitat associated with the City's spring-run rehabilitation projects, the District increased the DO calculated by the regression equations for Eliza and Old Mill springs by a modest 0.3 mg/L before applying it to the populations at those outlets in calculating mortality. Main Springs, which issues within Barton Springs Pool and is not part of the City's HCP rehabilitation project, was not increased.

For subterranean organisms like the Austin blind salamander, moving into epigean habitats for any reason, including DO stress relief, is probably only incidental, as suggested by the low abundance numbers of the censuses. But the Austin blind salamander likely exists at some distance away from the outlets in the subsurface, finding either subterranean zones with higher water velocity that facilitates oxygen exchange and/or subterranean conduits and passages that have a greater proportion of unconfined water being transmitted. As both Lazo-Herencia et al. (2011) and Mahler and Bourgeais (2013) note, unconfined portions of the Aquifer tend to have considerably higher DO concentrations (mean 6.5 mg/L) than confined portions of the Aquifer (mean approximately 2 mg/L). The confined and unconfined portions of the Aquifer converge at the spring outlets, with each outlet having different proportions of each, dependent on the mix of the flow routes that provide water to the particular spring outlet (Mahler and Bourgeais, 2013; Hauwert et al., 2004). For purposes of making the mortality estimate, the beneficial effects of such likely but un-quantified migration of the Austin blind salamander to better aerated areas were substantially discounted, and the DO calculated by the regression equation for all the three perennial outlets of the Aquifer was increased by a rather modest 0.3 mg/L before being applied to the population associated with each outlet in the mortality calculations.

Another fundamental presumption in this step is that the mortality curve developed by Poteet and Woods (2007) applies to both the Barton Springs salamander and the Austin blind salamander, although the confirming metabolic behavior comparisons were only made experimentally between the surrogate San Marcos salamander and Barton Springs salamander. No other information quantitatively relating DO to mortality of Austin blind salamander appears to exist.

Using these presumptions and assumptions along with the mortality curves of Poteet and Woods (2007) and the ecological risk assessment of Woods et al. (2010), the District then assigned and, using the spreadsheet developed for this purpose, applied sequentially and cumulatively the appropriate Lethal Concentrations associated with the calculated DO concentrations at each outlet for each month in various drought periods. No accepted estimates of natality (birth rate) or recruitment (rate of development of juveniles to reproductive age) for either population were available to be included in the spreadsheet, so there is no mechanism for the number of salamanders to increase over the modeled period.

Accordingly, the spreadsheet results are not intended to be a population model, rather a means of computation of the lethal adverse effects of various scenarios to be quantitatively compared.

The results of this analysis demonstrated that springflow-related DO concentrations ranged widely between (a) those associated with no drought conditions that had no lethal biological import for the Covered Species, and (b) those associated with Extreme Drought periods that had very substantial lethal biological import, with periods of various durations at a given DO level. To assist in defining the basis of the take scenario for which an ITP exception is being proposed, the District has specified a "Hybrid Drought" period to be a worst-case groundwater drought scenario that might be *reasonably* expected to occur during the 20-year ITP period, in the District staff's professional judgment. The Hybrid Drought forms part of the basis for the quantitative estimate of cumulative losses in this HCP. To define this drought, the District considered two severe drought periods that actually existed along the continuum between Extreme Drought and no drought:

1. The seven-year period of the Drought of Record (DOR), from June 1950 through May 1957. This period consisted of the largest number of months with the lowest overall DO concentrations and the largest number of consecutive months with lethal concentrations of DO. However, as noted in Section 4.2 of the main text, the recurrence period for the DOR is estimated, on the basis of tree-ring studies, to be at least 100 years, and this period was judged to be too long to be reasonably expected to occur during the ITP term and to be the basis for take estimates.
2. A second, more recent seven-year period of severe drought, from March 2005 through February 2012. This period contained multiple severe drought periods, including the 2011 drought that is regarded as the driest, hottest single-year drought in Texas history, and the 2009 drought that had the lowest Aquifer water levels since the District was formed in 1987. Overall, this period was a less-than- Exceptional Drought but still very severe drought period that, in the District's professional judgment, is likely to be the worst drought expected to occur in a typical 20-year period, which is the ITP term. However, this drought was judged to be not sufficiently severe to serve as the basis for reasonably worst-case take and mortality estimates.

The District then formulated a synthetic drought that was not as severe as the DOR but considerably more severe than the recent severe drought. The natural springflows of the two actual seven-year droughts, which were the estimated/gaged actual springflows with all actual pumping added back in to arrive at total aquifer discharge as springflow, were weighted- averaged on a month by month basis to produce what the District has termed the "Hybrid Drought" for this HCP (Figure J-3). The weighting of the DOR was twice that of the more recent severe drought period in defining the Hybrid Drought. The District considers this Hybrid Drought as a reasonably worst case in the HCP area during the ITP term. This synthetic Hybrid Drought and the DOR were selected to be used for computing and comparing the lethal take component under alternative groundwater management scenarios. These three droughts have the following recurrence frequencies for corresponding seven-year average springflows over the 97-year period of record:

Drought of Record	(26 cfs)	1%
Hybrid Drought	(37 cfs)	11%
Recent Severe Drought	(62 cfs)	57%

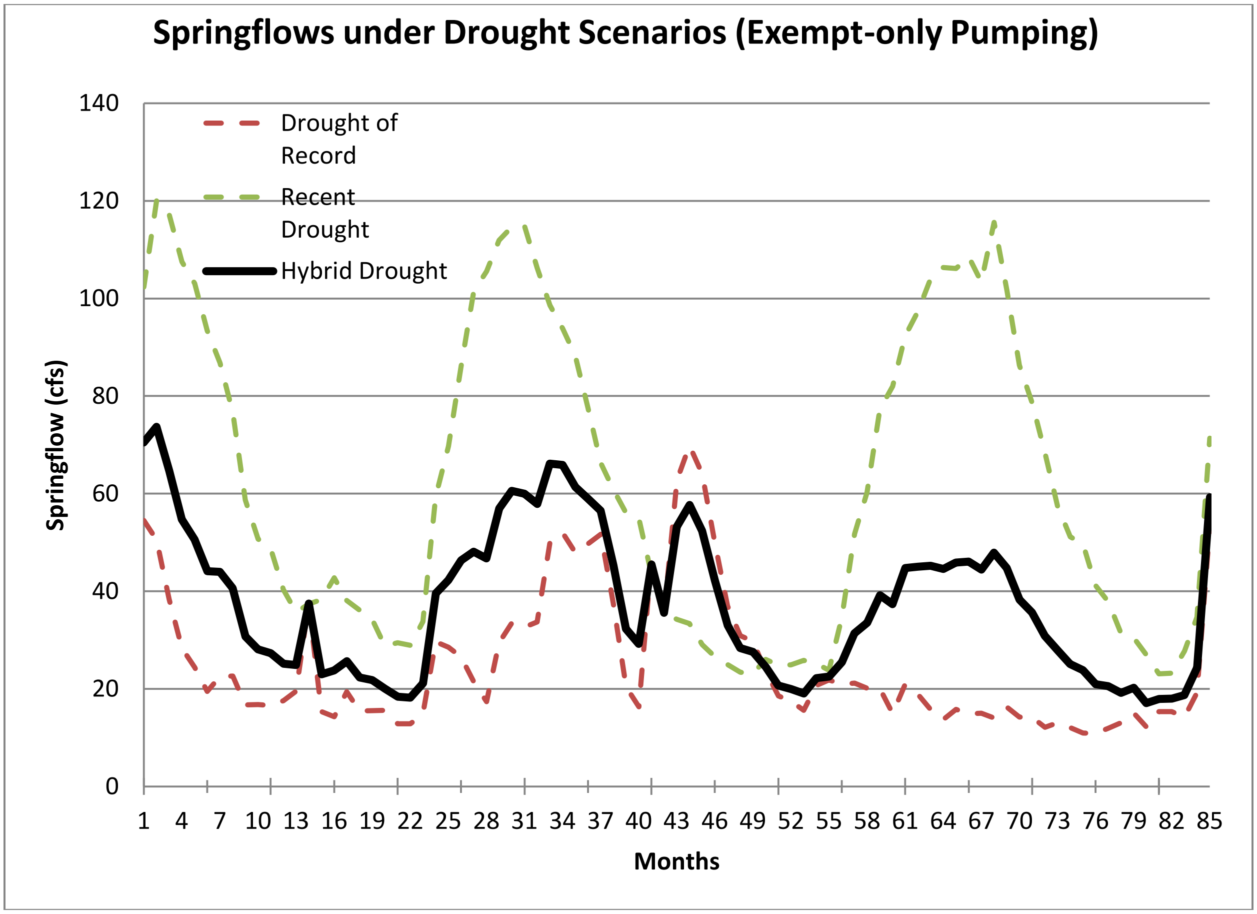


Figure J-3. The Development of the Hybrid Drought from the DOR and Recent Severe Droughts. The Hybrid Drought is considered for this HCP to be the worst drought reasonably expected to occur during a 20-year ITP term.

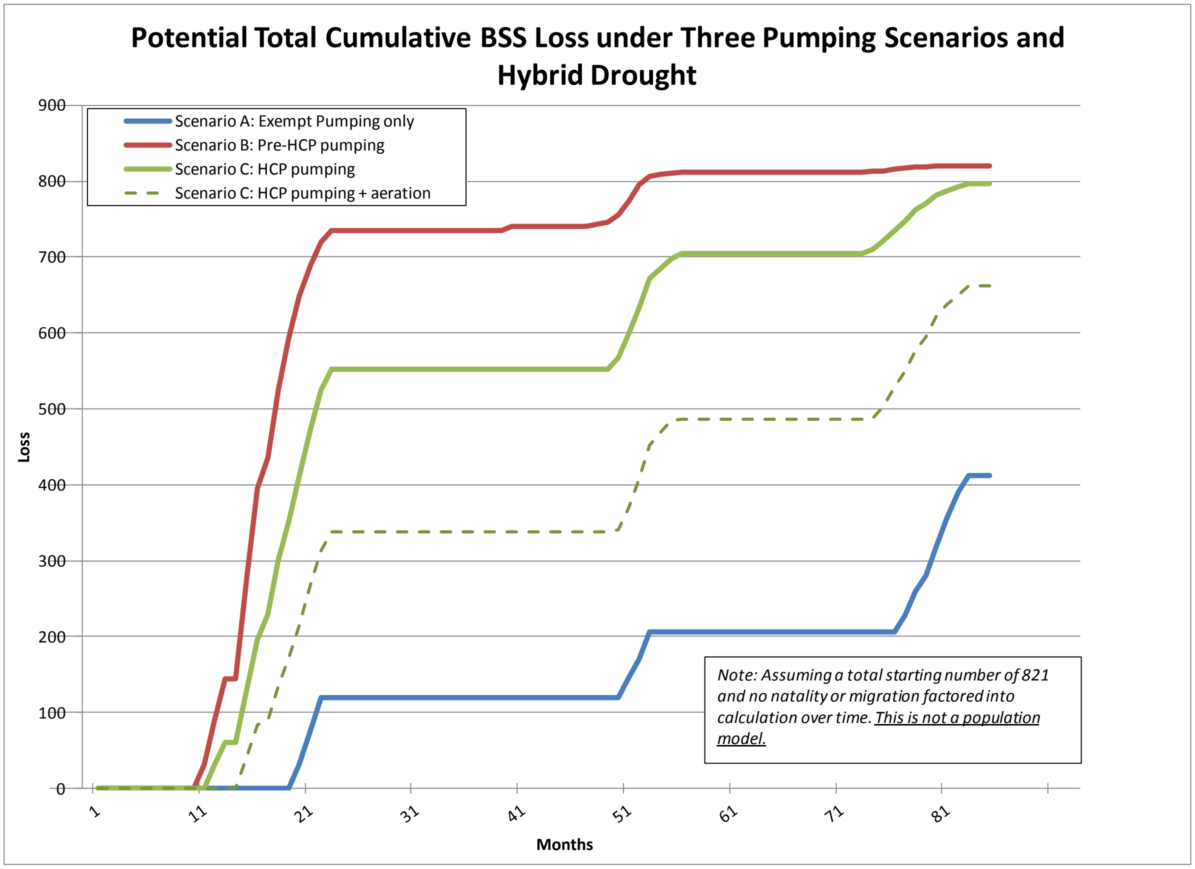
As described in Section 6.2.1 of the main text, the proposed HCP Conservation Measures provide protection in Extreme Droughts, including the DOR, regardless of their anticipated or realized frequencies. So it is important to note that the regulatory program to address droughts ranging from moderate to extremely severe, including the DOR, will already be in place upon ITP issuance.

Step Four: Computing Cumulative Losses as a Mortality Metric

The District then applied the estimated lethal concentrations, based on Woods et al, (2010), that are associated with the prevailing DO for each month of the modeled DOR and Hybrid Drought periods in a sequential, cumulative fashion to the calculated population in the preceding month. The stipulated populations of each of the Covered Species at each of the outlets (Section 5.2.3.1 of the main text) were designated the initial condition for this analysis. The springflow regimes were defined by the three pumping scenarios, described in Step One, and the DO regimes were related in an outlet-specific fashion to the amount of combined springflow after pumping, from Step Two. At the end of the two 85-month modeled drought periods, the cumulative losses for the three groundwater management scenarios were compared as to absolute numbers, the trends in those losses during each of the seven year periods, and between the periods.

Results

The results of this four-step analysis for both Covered Species and for two reference droughts are displayed and discussed in Section 5.2.3.3 and 5.2.3.4 of the main text. An example of the type of output from this methodology is shown in Figure J-4 below. While this analysis is rational and uses the best information available to the District, it obviously requires a number of assumptions and stipulations, so the results should be viewed as a first approximation rather than an absolute certainty in its outcome; the comparisons among scenarios and the relationships among various factors may be more reliably instructive. The District has attempted to provide transparency into the procedure and the rationale for the assumptions and stipulations in this HCP[2].



Note: Assuming a total starting number of 821 and no natality or migration factored into calculation over time. <u>This is not a population model.</u>

Figure J-4. Example of Methodology Output.

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[2] Citations that are referenced in this Appendix are found in Chapter 11 of the main HCP document.

APPENDIX K

The BSEACD Enforcement Plan

Approved by the District Board of Directors on June 25, 2009

BS/EACD Enforcement Plan

(Adopted by the Board on 6-25-09)

The purpose of this enforcement plan is to establish a structure with procedures and guidelines within which the District General Manager (GM) will make decisions relative to the initiation, pursuit, and resolution of enforcement efforts in response to violations of the Barton Springs - Edwards Aquifer Conservation District (District) Rules and Bylaws. The plan is not binding upon the District Board of Directors when acting as the final decision makers in contested cases. The Board of Directors is only bound by the limitations imposed by the District Rules and Bylaws; State statutes, specifically including Chapter 36 of the Texas Water Code; and the District's enabling legislation, SB 988 of the 70th Legislature.

1.0 Enforcement Policy

This plan shall constitute the general policy and procedures of the District in all matters relating to compliance, enforcement, and litigation. This policy does not restrict the District from taking any other actions ordered by the Board of Directors, nor does this policy create any procedural rights for any person inside or outside the District's jurisdiction. It is the policy of the District to file suit to enforce its rules only as a last resort.

2.0 Rule References

The Enforcement Plan conforms to the District Rules and Bylaws currently in effect. It will be modified, if and as necessary, to conform to future rules changes approved by the Board.

3.0 Enforcement Procedures

District enforcement efforts shall be conducted in accordance with the procedures described below. These procedures will be used during the period before litigation is initiated, unless there is a nearly certain and imminent danger to public health or the environment. **Figure 1** depicts the general procedures in a process flowchart form. The enforcement protocol for violations of drought management rules specifically, which is consistent with these procedures, is elaborated in the Appendix to this Plan.

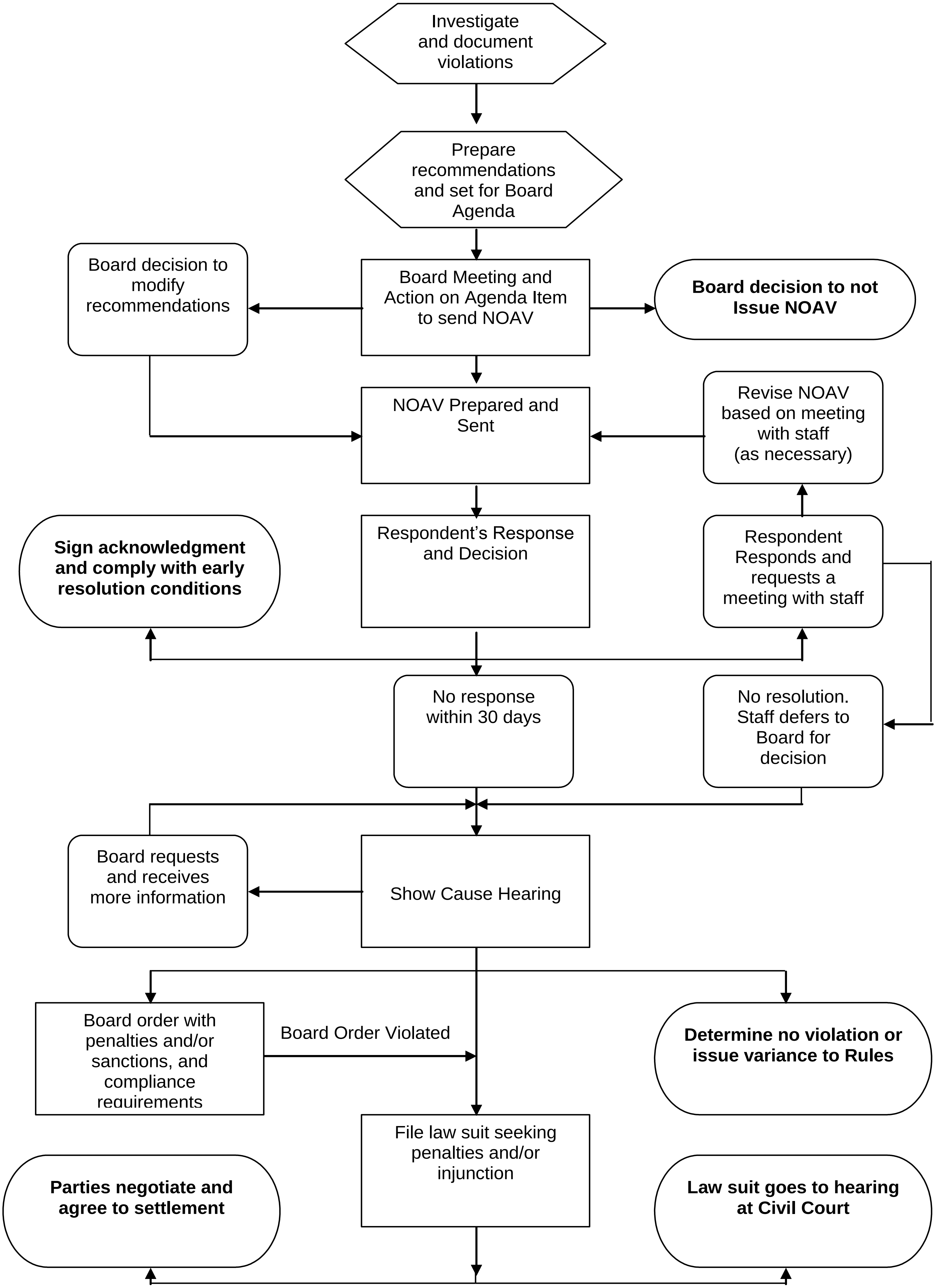
3.1 Complaint Received/Violation Discovered

If a complaint is received or an alleged violation is reported, staff shall obtain sufficient preliminary information to determine if further investigation is necessary:

- Does the District have jurisdiction over the matter?
- Is there enough reliable information to proceed with an investigation?

Once this is determined, staff may proceed with an investigation. Investigations may also be initiated if staff discovers a violation that satisfies these criteria.

Figure 1 - BS/EACD Enforcement Process



3.2 Conduct of Investigation

Investigations shall be conducted by staff in accordance with District Rule 3-8.3. Once the determination has been made to proceed with an investigation, staff shall conduct a full investigation and provide a written report with all of the pertinent findings and information to include:

- Basic Information (i.e. Respondent/Permittees name, contact information, well location if applicable, etc.);
- Investigation Summary;
- Alleged Violations;
- Chronology of Pertinent Events; and
- Pertinent Documentation.

Upon completion of the investigation report, the GM shall determine if sufficient information exists to support Board discussion and possible action related to the issuance of a Notice of Alleged Violation (NOAV).

3.3 Board Action

Should the GM make this determination, the matter will be set on the Board's regular meeting agenda for possible Board action. Staff shall prepare the appropriate materials to be provided with the backup for the next available board meeting to include the investigation report and staff's recommendations. Staff recommendations should include:

- recommended action (i.e. issuance of NOAV);
- indicated penalties for each alleged violation;
- possible sanctions and/or compliance requirements; and
- prospective early resolution conditions.

Penalties recommended by the staff shall be determined in accordance with the *Violations and Penalty Assessment Guidelines* (see Section 4 below) and shall include a discussion of the factors used to determine what amount within the specified penalty range was chosen. Early resolution conditions shall be included to provide an option and an incentive for more or less immediate resolution and compliance, before litigation. The GM will generally recommend a reduced penalty associated with an early resolution incentive based on a 50-75% reduction of the recommended penalty amounts. A reduction outside of this range may also be recommended if appropriate.

If the Board determines that the violations are not substantiated and that an NOAV should not be prepared and sent, the case will then either be investigated further or considered closed, at the Board's direction. Otherwise, staff will prepare an NOAV incorporating the staff recommendations or modify the allegations and conditions in accordance with the instructions provided by the Board.

3.4 Notice of Alleged Violation

Staff will send an NOAV with the Board-approved allegations, penalties, and conditions and a 30 day response time. The NOAV shall also offer an early resolution incentive that shall include an acknowledgment of the violations to be signed by the Respondent, a reduced penalty amount, and a commitment to all necessary compliance requirements. The option for early resolution shall only be available if the acknowledgment is signed and the penalties are paid within the 30-day response time. This requirement will be included in proposed rule-making.

Upon receipt of the NOAV, the Respondent has the option to accept the conditions of the early resolution offer and resolve the case or to contact staff and arrange a meeting for the purpose of discussing the alleged violations. If a meeting is scheduled, staff may modify the original NOAV as necessary based on the discussions or may defer to a public hearing for a Board decision on the matter. If no response is received within the response time, the case will default to a public hearing for a Board decision on the matter. Pursuant to Rule 3-8.2, the public hearing (Show Cause Hearing) is a hearing where the Respondent will be cited to appear before the Board to show cause why an enforcement action should not be initiated.

3.5 Show Cause Hearing

A Show Cause Hearing shall be conducted 1) for all cases not resolved after the issuance of an NOAV, and 2) for all cases where no response to the NOAV was received before the expiration of the response timeframe. At the hearing, staff shall provide the investigation report, pertinent documentation, and testimony to the Board to substantiate the alleged violations. A Show Cause Hearing will follow the contested hearing rules, including notice requirements, under Bylaw 4-9. The Respondent will also have an opportunity to participate and present evidence to show cause to the Board why an enforcement action should not be initiated. The enforcement action(s) by the Board that may result from a show-cause hearing include both seeking of civil penalties to be assessed by a court and/or authorizing sanctions for permittees including written warnings, reprimands, suspension, or revocation of a permit.

On the basis of evidence presented at the hearing, the Board may: 1) dismiss the NOAV because it determines that no violations have occurred; 2) grant a Variance to the District rules; 3) issue an order that amends, revokes, suspends, or otherwise modifies the permit; or 4) file a lawsuit seeking civil penalties and injunction. If a Variance is sought by the Respondent, the Respondent must request the Variance in advance of hearing and also satisfy all of the specified criteria in accordance with Rule 3-1.25 or 3-7.10 to obtain a Variance. The Board may also request additional information and reconsider the additional information once received at a subsequent Show Cause Hearing at a later date.

3.6 Board Order/Civil Suit

If the Board determines that an enforcement action should be initiated, a Board Order will be issued that outlines the findings and either initiates a lawsuit or specifies the appropriate penalties, compliance requirements, and/or sanctions resulting from the Show Cause Hearing. In the latter instance, if the Board Order is violated, the District will send a Notice of Intent to Sue to initiate legal proceedings against the Respondent in District Court. The lawsuit will generally seek civil penalties, court costs, attorney’s fees, and/or injunctive relief. Once a lawsuit is initiated, the parties may at that point negotiate a settlement. If a settlement is not negotiated, the lawsuit will go forward in civil court.

4.0 Violations and Penalty Assessment Guidelines

The Barton Springs/Edwards Aquifer Conservation District (the District) may pursue enforcement penalties in addition to other District compliance efforts and options. Pursuant to Section 3-8.9 of the District's Rules, the District may assess penalties for each act of violation and for each day of violation, and each day a violation continues may be considered a separate, specific violation. Multiple violations of District Rules may result in the assessment of multiple penalties. Pursuit of a penalty outside of the penalty matrix may be permitted only with the express approval of the Board when exceptional circumstances warrant a departure from the Guidelines. Penalties assessed under these Guidelines may be waived by the District Board, following completion by the violator of one or more conservation projects approved by the District. Provisions associated with assessment and pursuit of penalties will be included in proposed rule-making.

4.1 Penalty Assessment Criteria: In determining the amount of a civil penalty to be assessed within the ranges presented, the District will consider the following factors:

(1) The severity or seriousness of the violation;

(2) Whether the violation was willful, intentional, or could have been reasonably anticipated and avoided;

(3) Whether the violator acted in good faith to avoid or mitigate the violation, or to correct the violation after it became apparent and compensate those affected;

(4) The economic gain obtained by the violator through the violation;

(5) Whether similar violations have been committed in the past;

(6) The amount necessary to deter future violations;

(7) Any other matter that justice may require;

The Board may also choose to assess sanctions, including permit suspension or revocation, based on the consideration of these factors. Provisions of this subsection will be included in proposed rule-making.

4.2 Violations by Type and Penalty Ranges

The violations and associated ranges of penalties in the subsections below, including the tiers of non-compliance with drought provisions shown in the Appendix for targeting enforcement activities, will be included in proposed rule-making.

4.2.1 General Violations: Violations of District Rules not covered by other penalty categories, including but not limited to the following specific Rules:

§ 3-1.1: failure to register wells;
§§ 3-1.11(E), 3-1.15, 3-8.7: failure to timely report or failure to report accurate pumpage reports and water-quality reports for non-exempt wells;
§ 3-1.11(F): failure to provide access to well site during normal business hours or emergencies, or the failure to cooperate fully in any reasonable inspection of the well site or in any well monitoring or sampling by the District;
§ 3-1.16(C): non-payment of fees following past due notice by District;
§ 3-5.1: failure to register abandoned, open or uncovered well; and
§ 3-6.7: failure to prepare, adopt or implement a user conservation plan.

Penalty Range: $50-$250 per violation per day

4.2.2 Well Violations: Violations of District Rules relating to the drilling and operation of wells, including but not limited to the following specific Rules:

§§ 3-1.2, 3-1.4, 3-4.1: constructing a well, drilling a well, modifying a well, completing a well, changing type of well use, performing dye tracing operations on a well, plugging a well, abandoning a well or altering well size without District authorization or advance notice;
§ 3-1.3: pumping from or operation of non-exempt wells without a permit;
§ 3-2.1: failure to employ water meter where required;
§ 3-4.4: failure to drill or complete a well in accordance with State well construction standards, District Rules, and/or District Well Construction Standards
§ 3-4.5: installation of pump and /or equipment on wells not registered with the District; and
§ 3-5.3: failure to plug or cap abandoned, open or uncovered wells in accordance with District Rules and Well Construction Standards.

Penalty Range: $250-$500 per violation per day

4.2.3 Falsification/Tampering Violations: Violations of District Rules relating to the falsification of information provided to the District regarding pumping from and monitoring of the groundwater, including but not limited to the following specific Rules:

§ 3-1.4: falsifying information in application for well registration, permits, or well drilling or modification authorization;
§ 3-2.4: false reporting or logging of meter reading, intentionally tampering with or disabling a meter, or similar actions to avoid accurate reporting of groundwater use and pumpage; and,
§ 3-2.5: tampering with, altering, damaging, or removing a water meter seal or tag.

Penalty Range: $500 – $1,000 per violation per day

4.2.4 Waste/Pollution Violations: Violations of District Rules relating to the sealing of abandoned, open or uncovered wells, the wasteful use of groundwater, and the pollution of the groundwater, including but not limited to the following specific Rules:

§ 3-3.1, 3-3.2, 3-3.5: producing or using groundwater in such a manner or under such conditions as to constitute waste;

§ 3-3.3: causing or allowing the introduction of saline-water pollutants or other deleterious matter from another stratum, from the surface of the ground, or from the operation of a well;

§ 3-3.4: causing or allowing pollutants to enter the groundwater reservoir through recharge features, whether natural or manmade; and,

§ 3-5: failure to properly plug or cap an abandoned, open, or uncovered well allowing pollutants to enter the groundwater reservoir through an improperly sealed or capped well.

Penalty Range: $500 - $1,000 per violation per day

4.2.5 Drought Violations: Penalties for the violations of District Rules **§§3-1.11(E), 3-1.15, 3-2.4, 3-3, and 3-8.7** will be assessed in accordance with the ranges specified above during Alarm Stage Drought and at twice that amount during Critical Stage Drought. Violations of District Rules relating to the implementation of user drought contingency measures and other drought related violations, including but not limited to the following specific rules:

§3-7.5 Failure to implement measures of the user drought contingency plan

Penalty Range: $250 - $500 per violation per day and at twice the amount during Critical Stage Drought

§3.7.7 Failure to reduce pumpage during District declared drought in accordance with monthly pumpage limits of the UDCP

Penalty Range: Penalties for violations of 3-3.7 shall be determined on a monthly basis, with each month constituting a new violation. Daily penalties shall be assessed according to the following penalty matrices:

	Daily Penalties During Alarm Stage Drought Rule 3-7.7.B(1)		
Permitted Pumpage	**Overpumpage Level**		
	Level A	***Level B***	***Level C***
Tier 1	$50-$100	$100-$200	$200-$400
Tier 2	$200-$400	$400-$800	$800-$1,600
Tier 3	$800-$1,600	$1,600-$3,200	$3,200-$5,000

	Daily Penalties During Critical Stage Drought Rule 3-7.7.B(2)		
Permitted Pumpage	**Overpumpage Levels**		
	Level A	***Level B***	***Level C***
Tier 1	$100-$200	$200-$400	$400-$800
Tier 2	$400-$800	$800-$1,600	$1,600-$3,200
Tier 3	$1,600-$3,200	$3,200-$6,400	$6,400-$10,000

Where:

Permitted Pumpage (gallons/year):		**% Pumpage over Monthly Limits:**	
Tier 1:	< 12,000,000	Level A:	< 25%
Tier 2:	≥ 12,000,000 and < 120,000,000	Level B:	> 25% and < 100%
Tier 3:	≥ 120,000,000	Level C:	> 100%

Appendix
Drought Management and Enforcement Process

1.0 Drought Enforcement Strategy

The District's approach to drought management described here flows from and is consistent with District Rules 3-7.8 and 3-8. It describes the appropriate implementation mechanisms, public awareness efforts, aquifer and drought monitoring, and permittee performance monitoring and assessment to be used during drought. Compliance and enforcement efforts specified below elaborate District Rule 3-8 and center on assessment of permittee performance on a monthly basis to identify the various levels of non-compliance with mandatory pumpage reductions. This monthly assessment will focus the District's early efforts on permittees with the more egregious levels of over-pumpage, on the basis of both the percentage of pumpage over their monthly pumpage limits and the volumes of their permitted pumpage.

2.0 Implementation Mechanisms

2.1 Drought Declaration Notices

The District will declare the commencement of drought by sending written notice to all District permittees when specified aquifer conditions are met in accordance with the approved District drought trigger methodology and after the Board has approved the declaration. The staff will assess the continuation of and stage of an indicated drought continuously, and notify all permittees when a more or less severe drought stage is declared and when the drought no longer exists

2.2 Public Awareness

Once drought is officially declared by the District, the District will implement measures to provide public awareness including but not limited to:

- Web site updates on aquifer conditions and permittee pumpage performance
- Press releases and guest columns in the local newspapers
- Recurring articles and columns in District newsletter
- Drought and aquifer condition updates provided via e-newsletter to permittees
- Outreach and education by District educators.

2.3 Monthly Compliance Evaluations

- Monthly evaluations of permittee performance and compliance with monthly drought limits will begin on the latest date that all meters readings are required to be submitted each month (the 5th of each month). Staff will identify permittees who have failed to report meter readings by the monthly reporting deadline while in District-declared drought. District will notify all those who have not reported that the District will obtain the meter readings at a fee of $50 to the permittee. District staff will follow up with meter readings for all delinquent permittees to ensure necessary readings are available to assess drought compliance.

- Should a more or less severe drought stage be declared in the middle of a particular month, the District will evaluate and measure compliance with the less stringent drought stage requirements for that month that the status change occurred. Compliance with the measures of the newly declared stage will be required in the following month.

- Staff will generate a list of non-compliant permittees based on permitted volume and percentage over-pumped. Non-compliance will be categorized in tiers in accordance with the following criteria:

Permitted Pumpage (gallons/year)		**% Pumpage over Monthly Limits**	
Tier 1:	< 12,000,000	Level A:	< 25%
Tier 2:	≥ 12,000,000 and < 120,000,000	Level B:	≥ 25% and 100%
Tier 3:	≥ 120,000,000	Level C:	≥ 100%

- Staff will send notices of overpumpage to all non-compliant permittees to notify them of their overpumpage and to inform them of their level of non-compliance. This notice will also include the amount of a drought management fee if a fee is assessed without an equivalent credit.

- Staff will identify and red flag suspect permittee meter readings, on the basis of previous readings, and conduct follow-up meter reading verifications.

- Staff will monitor pumping trends of those permittees that repeatedly over-pump monthly limits while in Drought and take action based on Enforcement Procedures outlined below.

- Staff will evaluate compliance trends of all other permittees to identify efforts to comply or escalating overpumpage.

- Staff will report and update monthly, all non-performing permittees after the third consecutive enforceable month of District declared drought, by posting a list of those permittees not meeting their monthly pumpage limits on the District website and at the District office for public review.

2.4 Imposition of the Drought Management Regulatory Fee for Non-compliance

In accordance with District Rule 3-7.9, the District will impose a drought management fee to all individual permittees permitted for more than 2,000,000 gallons annually (excluding all permittees under general permits) starting after two full months of District declared Alarm or Critical Stage Drought. A credit of the fee will be applied for each month that an individual permittee that does not exceed the monthly pumpage limits as specified in the prevailing UDCP by more than five (5%). The appropriate fees are determined based on the outside diameter of the production zone casing of the permitted well or an average of the casing size of all wells in an aggregate system. The fees are as follows:

- ≤ 5” outside diameter = $100/month
- > 5” or ≤ 10” outside diameter = $250/month
- > 10” outside diameter = $500/month

2.5 Determination of Occurrence of Non-compliance

Determinations of an occurrence of substantial non-compliance will be made based on 1) repeated events of non-compliance, 2) specific causes of overpumpage, and 3) the permittee's response to the reported overpumpage. In determining an occurrence, the District will take into consideration the permittee's demonstrated efforts to achieve pumpage reductions and any documented trends in prior water use reductions.

3.0 Timelines and Phasing of Determinations

Initial Month of a Drought Stage: No enforcement will be initiated for non-compliance in the initial month of Alarm Stage Drought if the timing of the declaration does not allow for a full month (after notice has been provided to the permittees) to begin assessing compliance with monthly limits. Overpumpage notices will be sent to all permittees who over-pumped their monthly pumpage limits to inform them of the on-going pumpage assessment being conducted by the District during drought and to notify them of the District's authority to enforce against non-compliance. For the initial month of Critical Stage Drought, the permittees will only be subject to the conditions of the Alarm Stage Drought until such time that a full month is available to assess compliance.

1-3 Months: Enforcement efforts will focus initially on the more egregious and sustained non-compliance by the large volume permittees. During the first three consecutive enforceable months of District declared drought, monthly assessment of overpumpage violations will focus on *Tier 3* permittees with *Level B/C* non-compliance. As a practical matter, the initial assessment and enforcement activities during this period will focus on *Tier 3* permittees with */Level C* non-compliance plus those who are irrigators.

4-6 Months: After the third consecutive enforceable month of District declared drought, monthly assessment of non-compliance will be expanded to include *Tier 2* permittees. Evaluation of compliance with Critical Stage Drought requirements will be begin after the first full enforceable month and will focus on *Tier 2* and *Tier 3* permittees with *Level B/C* non-compliance*.*

After 6 Months: After the first six (6) consecutive enforceable months of District declared drought, monthly assessment of non-compliance will continue by the same criteria for *Tier 2* and *Tier 3* permittees and will be expanded to include *Tier 1* permittees. Enforcement efforts for *Tier 1* permittees permitted for more than 2,000,000 gallons annually will be reserved for only those occurrences that are egregious and/or recurrent in nature. This will be determined when a *Tier 1* permittee reports six (6) or more months of level B or greater overpumpage or when the monthly volume overpumped equals a volume that would trigger an enforcement action for a *Tier 2* permittee. Enforcement efforts for *Tier* 1 permittees permitted for 2,000,000 gallons or less will generally be reserved only for non-compliance that warrants enforcement as determined by the Board.

4.0 Drought Enforcement Procedures

Levels of non-compliance will be assessed with actions taken in accordance with the Districts Enforcement Plan and Procedures and the following enforcement protocol for those permittees with consistent or increasing levels of non-compliance[*].

1st Occurrence: For the initial occurrence of non-compliance, a meeting or teleconference will be arranged with the permittee representative and the District GM and staff to discuss the particular causes of the non-compliance. The discussion will focus on compliance with the measures of the UDCP and identifying causes of excessive water use/loss or other possible relevant causes for overpumpage. Specific commitments and timelines to achieve pumpage reductions will be requested and documented.

2nd Occurrence: For those permittees with a first occurrence of non-compliance and recurrent months of reported non-compliance, staff may refer the case to the Board with a recommendation to issue a NOAV. Further enforcement efforts will proceed in accordance with the District *Enforcement Procedures* and the *Penalty Assessment Guidelines*.

For those permittees with a first violation who continue to have recurrent months of reported non-compliance but with some improvement, a meeting will be arranged with the permittee representatives, GM and staff, and the appropriate District Director at the District office. Discussion will focus on the implementation of the documented measures, the success or failure of those specific measures, and the commitments to achieve pumpage reductions resulting from the first violation discussions. More detailed analysis of causes for continued non-compliance will be conducted to result in more specific and binding measures for committed pumpage reductions by the permittee.

3rd Occurrence:

For permittees with a second occurrence who continue to have multiple months of reported non-compliance, the GM may refer the case to the Board with a recommendation to issue an NOAV. Further enforcement efforts will proceed in accordance with the District *Enforcement Procedures* and the *Penalty Assessment Guidelines*.

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[*] If a permittee is non-responsive to <u>any</u> of the bulleted elements of these enforcement procedures, the GM may recommend to Board that either an NOAV be issued, a Show Cause Hearing be conducted, or an enforcement action be pursued on the violation immediately, whichever is more likely to elicit a constructive response.