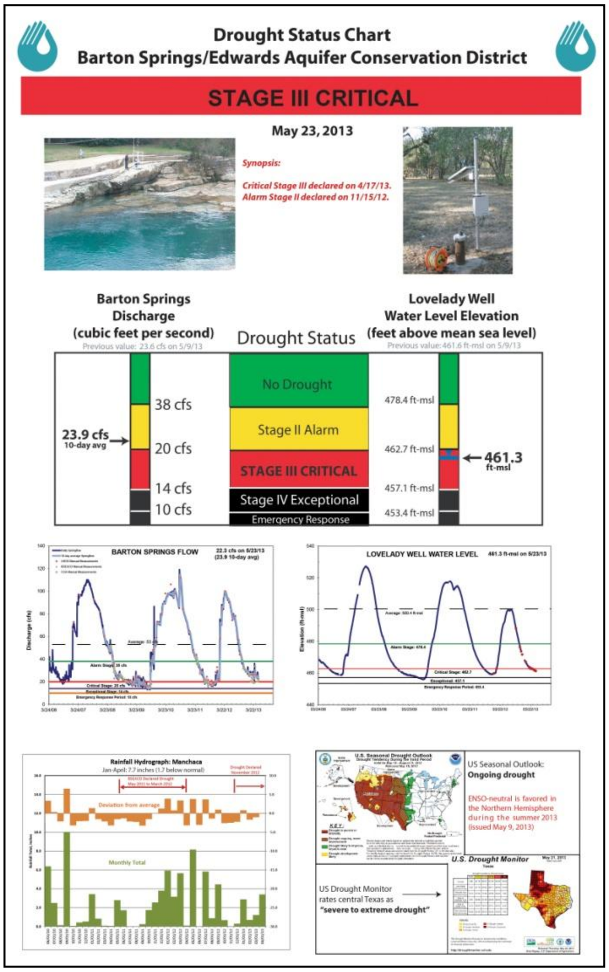
Barton Springs
Edwards Aquifer
CONSERVATION DISTRICT

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

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

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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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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).

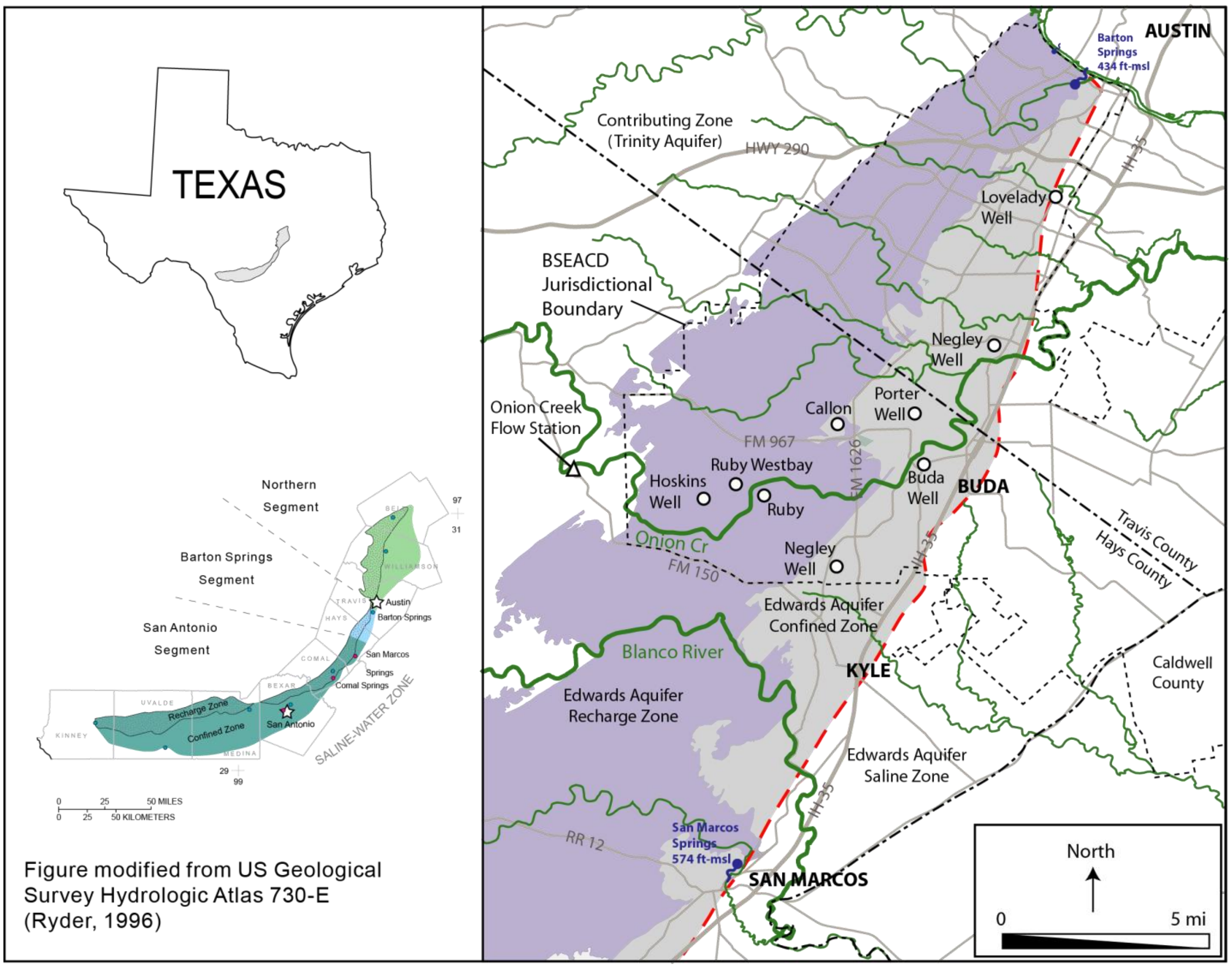

Figure modified from US Geological Survey Hydrologic Atlas 730-E (Ryder, 1996)

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.

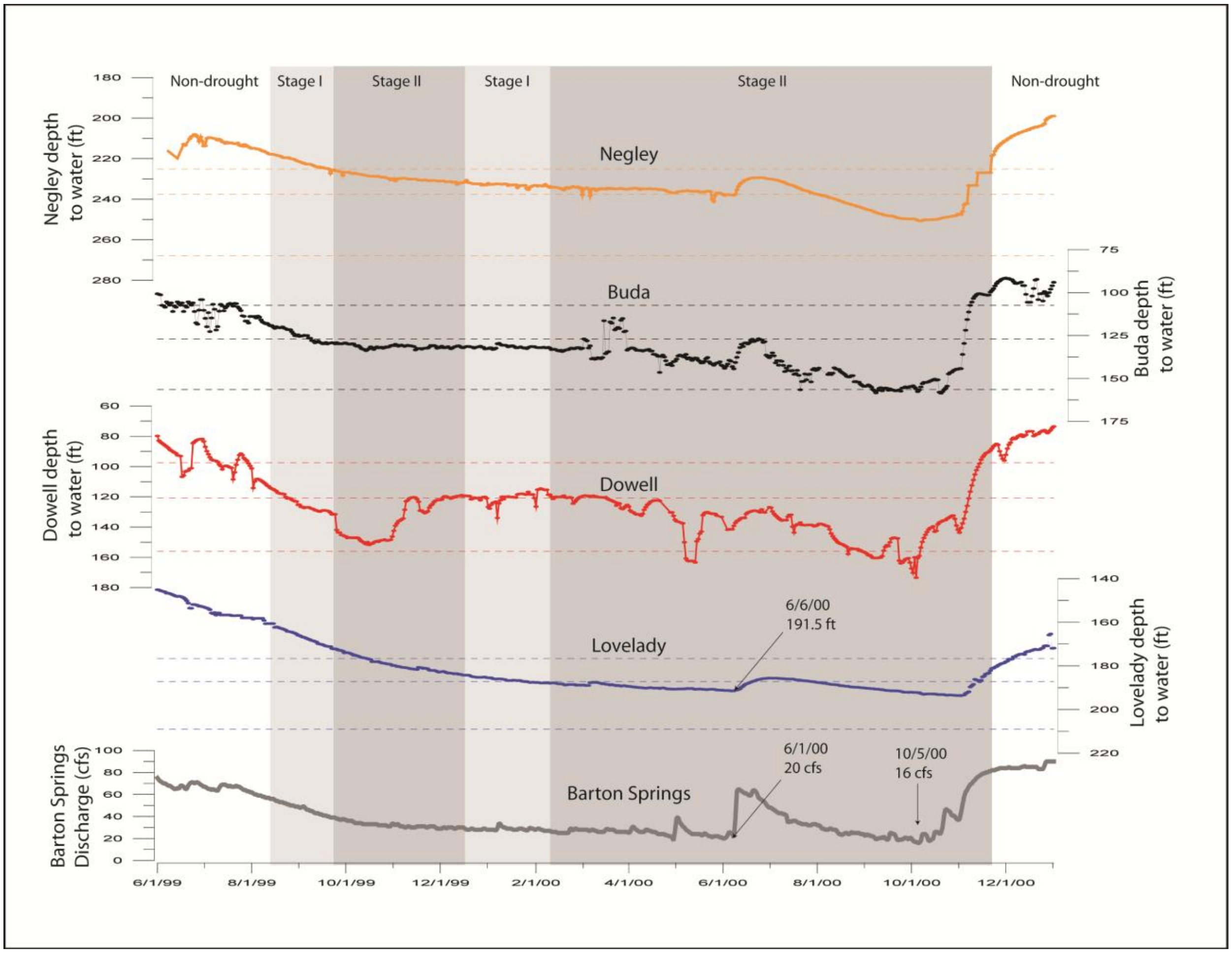

***Figure 2**. Hydrograph of the 2000 drought and the DTM devised by Rauschuber, 1990 (1990 DTM). For the time period in the hydrograph the depths to water in the Lovelady and Negley wells correlate very well to each other (R^2= 0.97) and to Barton Springs discharge (R^2= 0.88). The Buda and Dowell wells 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).

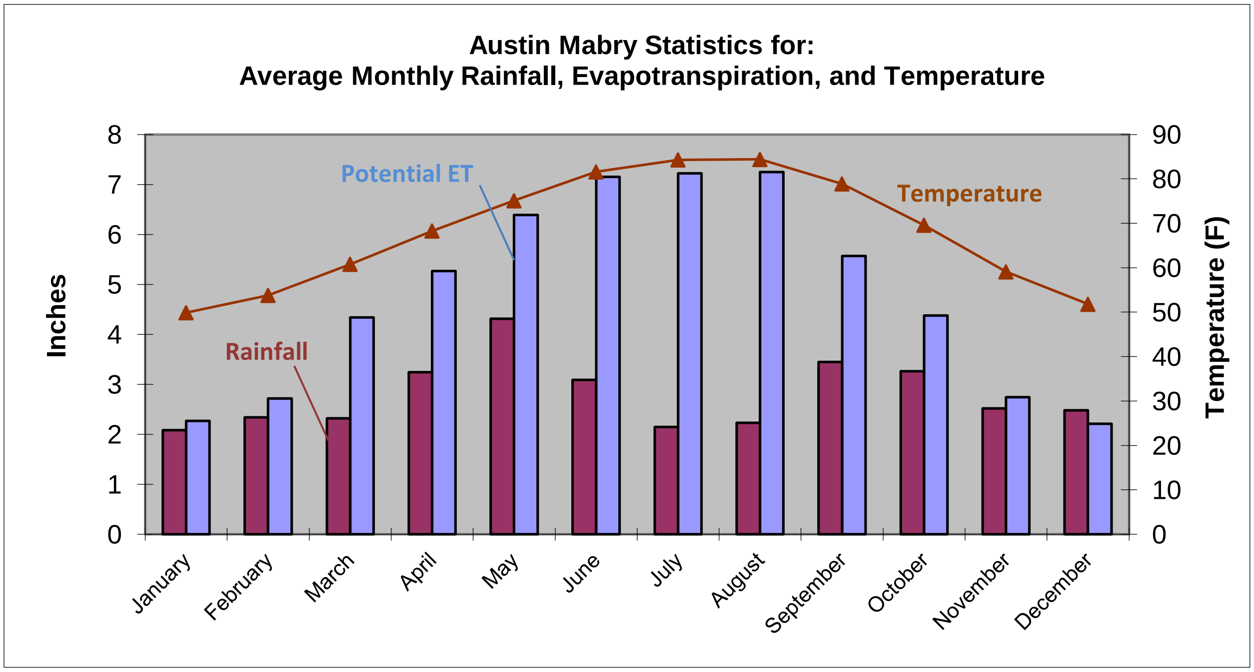

***Figure 3**. Histograms of monthly average rainfall, potential evapotranspiration (Pot. ET), and temperature from Austin's Mueller/Camp Mabry station representing 157, 75, and 155 years of data, respectively.*

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.

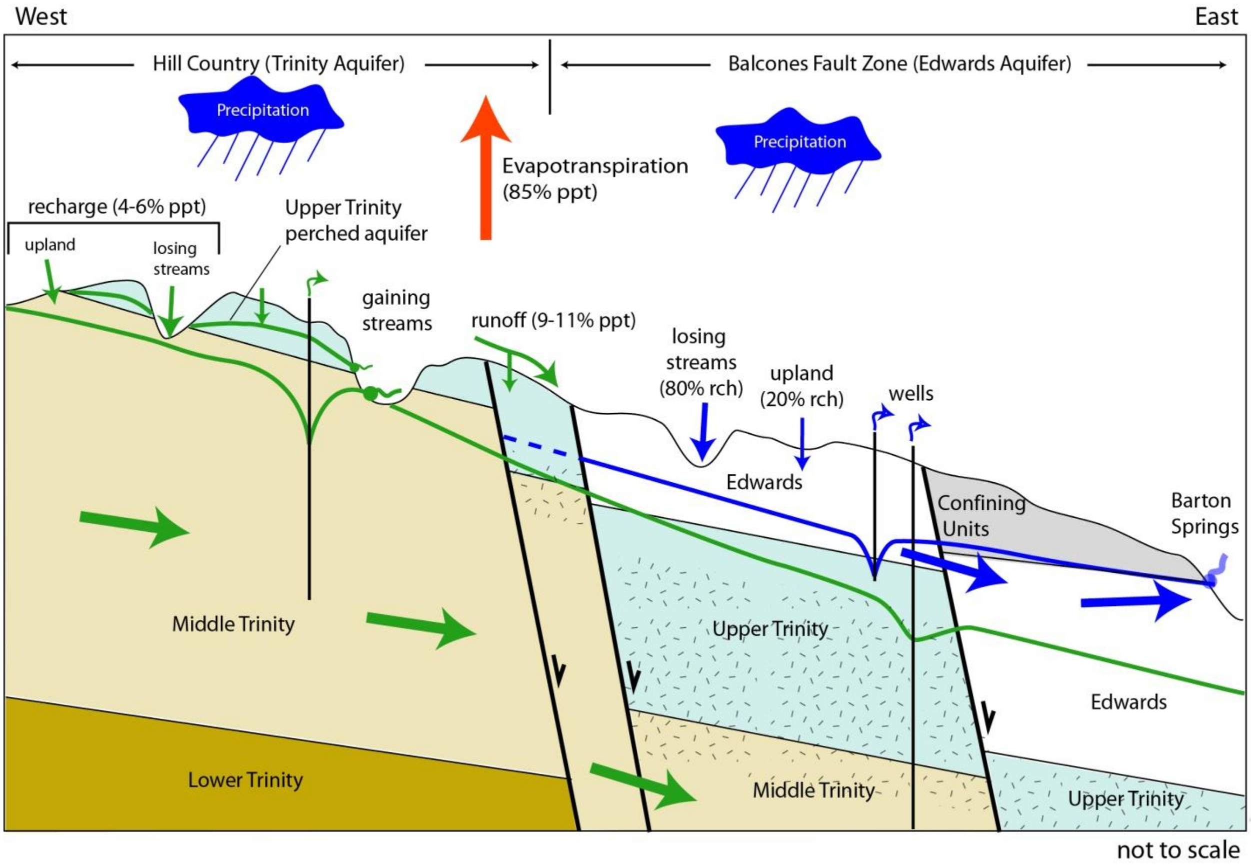

Figure 4. *Conceptual hydrogeologic model of the Edwards and Trinity Aquifer systems in the central Texas Hill Country and Balcones Fault Zones (Hays and Travis Counties). Stippled pattern represents zones of evaporites and low permeability.*

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):

Groundwater drought: "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).

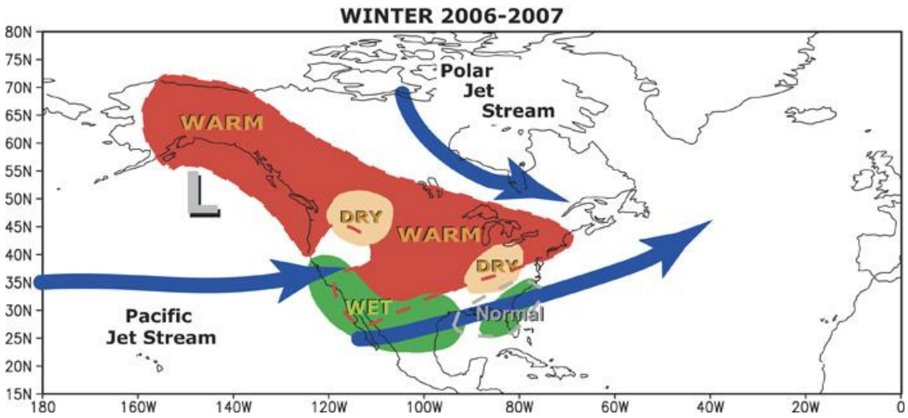

Figure 5. *Map showing the position of the jet streams and climate impacts due to ENSO. This map illustrates El Niño conditions and the general climatic impact to regions in the U.S. Map from NOAA.*

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.

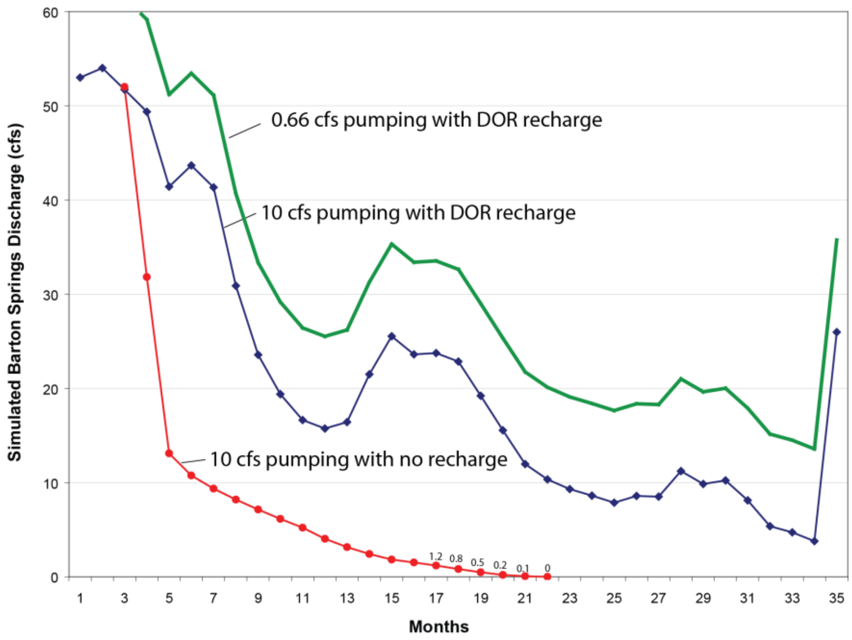

Figure 6*. Hydrograph of simulated Barton Springs discharge for 0.66 cfs and 10 cfs pumping with DOR recharge, and 10 cfs pumping and no recharge. Simulations were performed using the recalibrated GAM model (Smith and Hunt, 2004). The period used is from the first 3 years of the 7-year DOR.*

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.

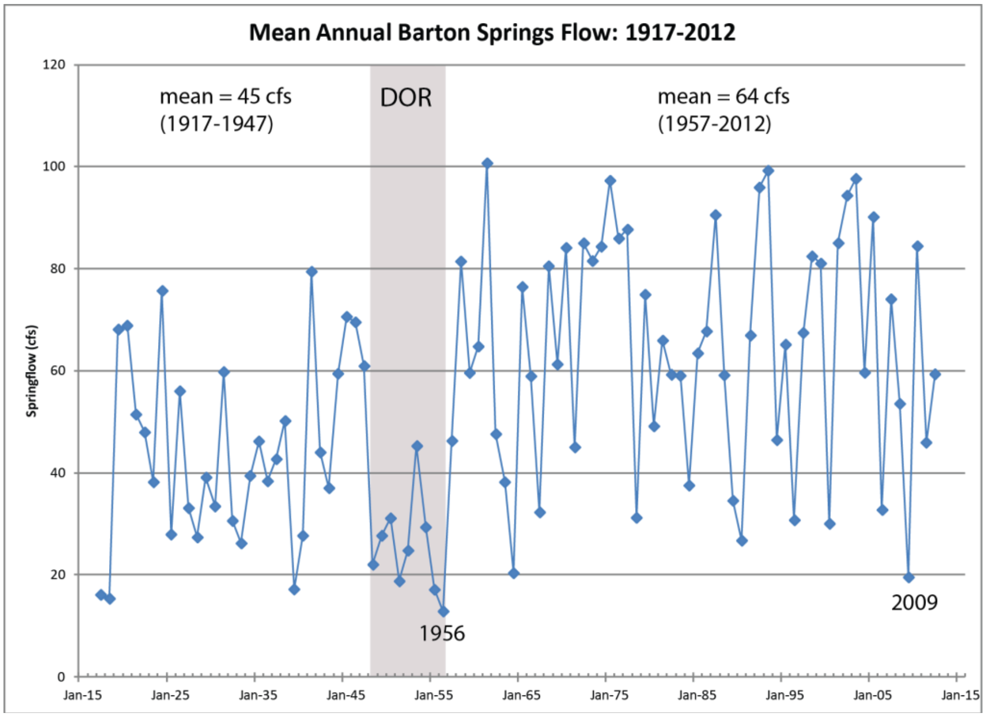

Figure 7. *Mean annual discharge hydrograph for Barton Springs illustrating major droughts over the period of record. During most years considered a drought the discharge at Barton Springs was below the annual average of 40 cfs. A significant shift in the long-term annual average discharge is noted after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

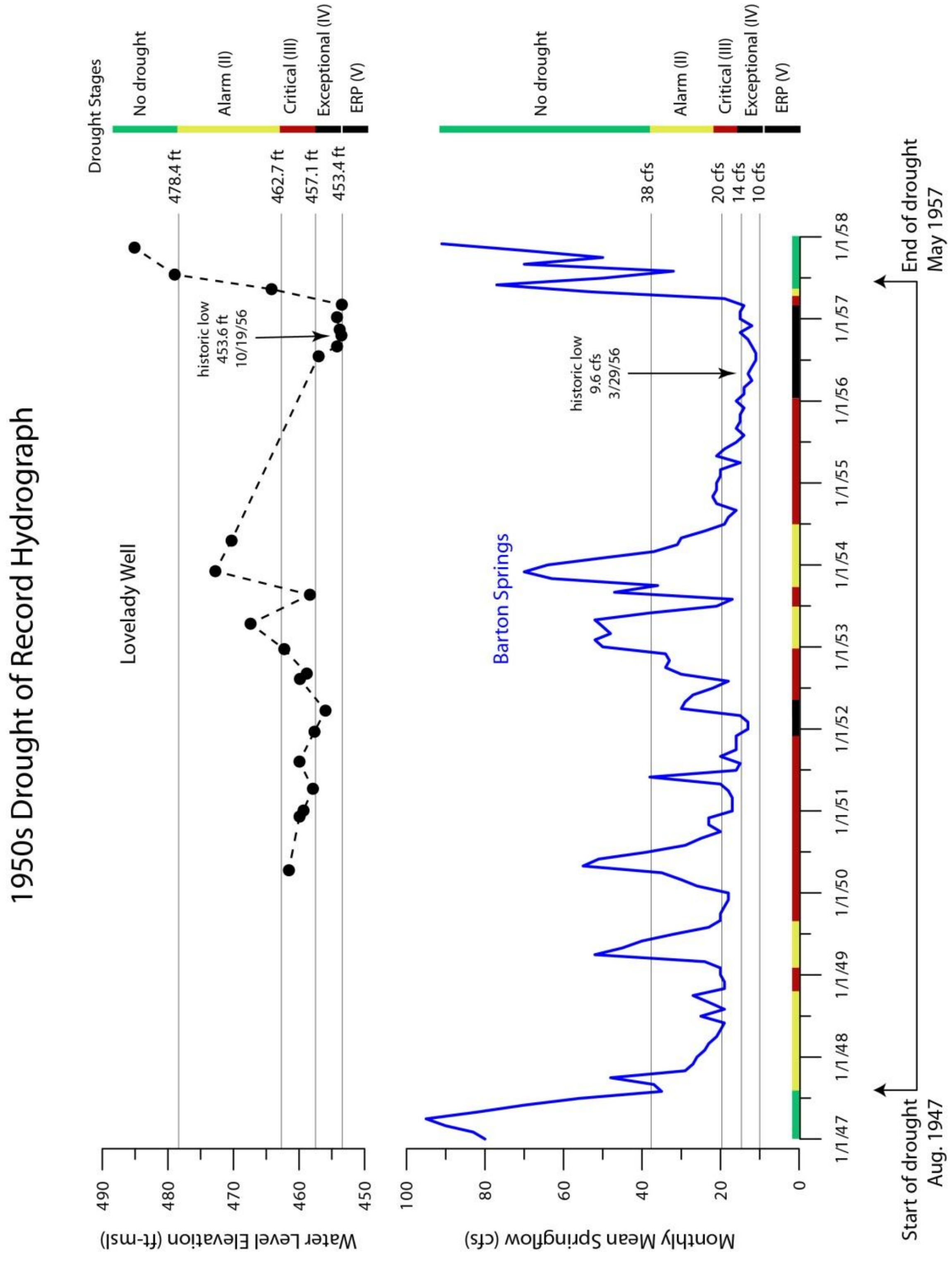

Figure 8. *1950s drought of record hydrograph showing mean monthly springflow at Barton Springs and water levels for the Lovelady Well—drought triggers shown for each indicator.*

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**).

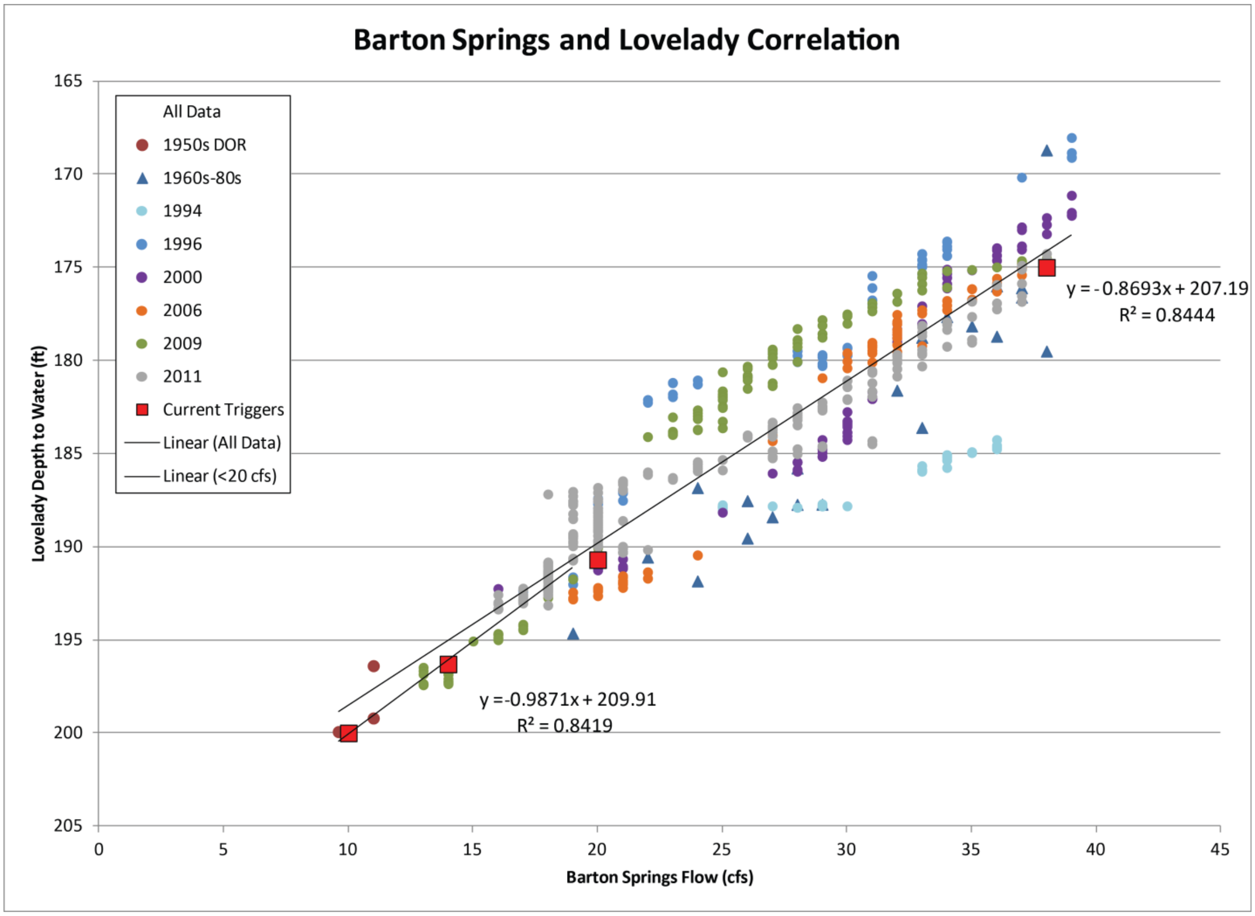

Figure 9. *Barton Springs and Lovelady correlation and regression chart.*

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		

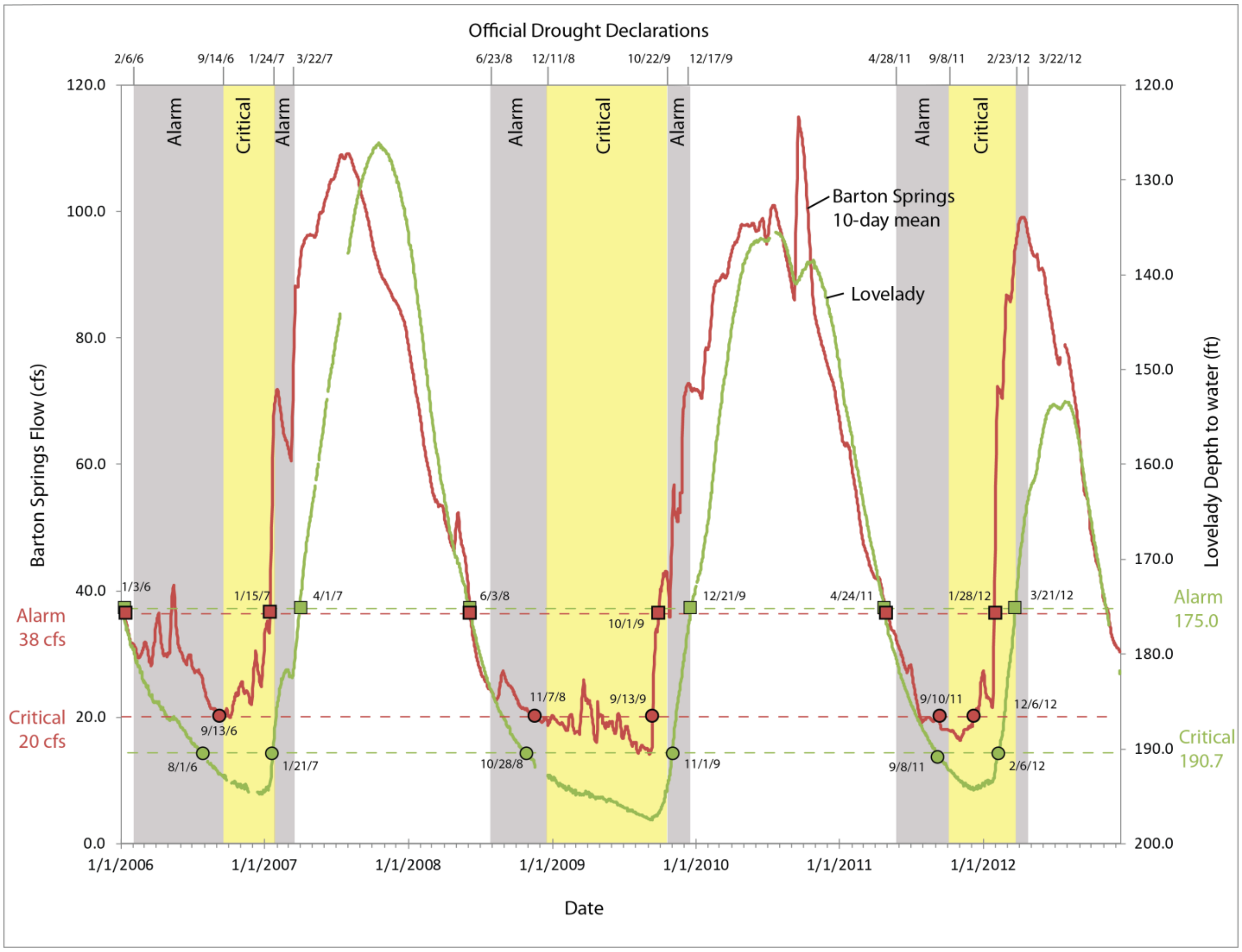

Figure 9. *Hydrograph drought indicators for the 2006-7, 2008-9, and 2011-12 drought periods. Only Alarm and Critical stages have been declared to date (December 2013). Shaded areas indicate official drought periods with dates indicated at top. Circles and squares indicate date at which each indicator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

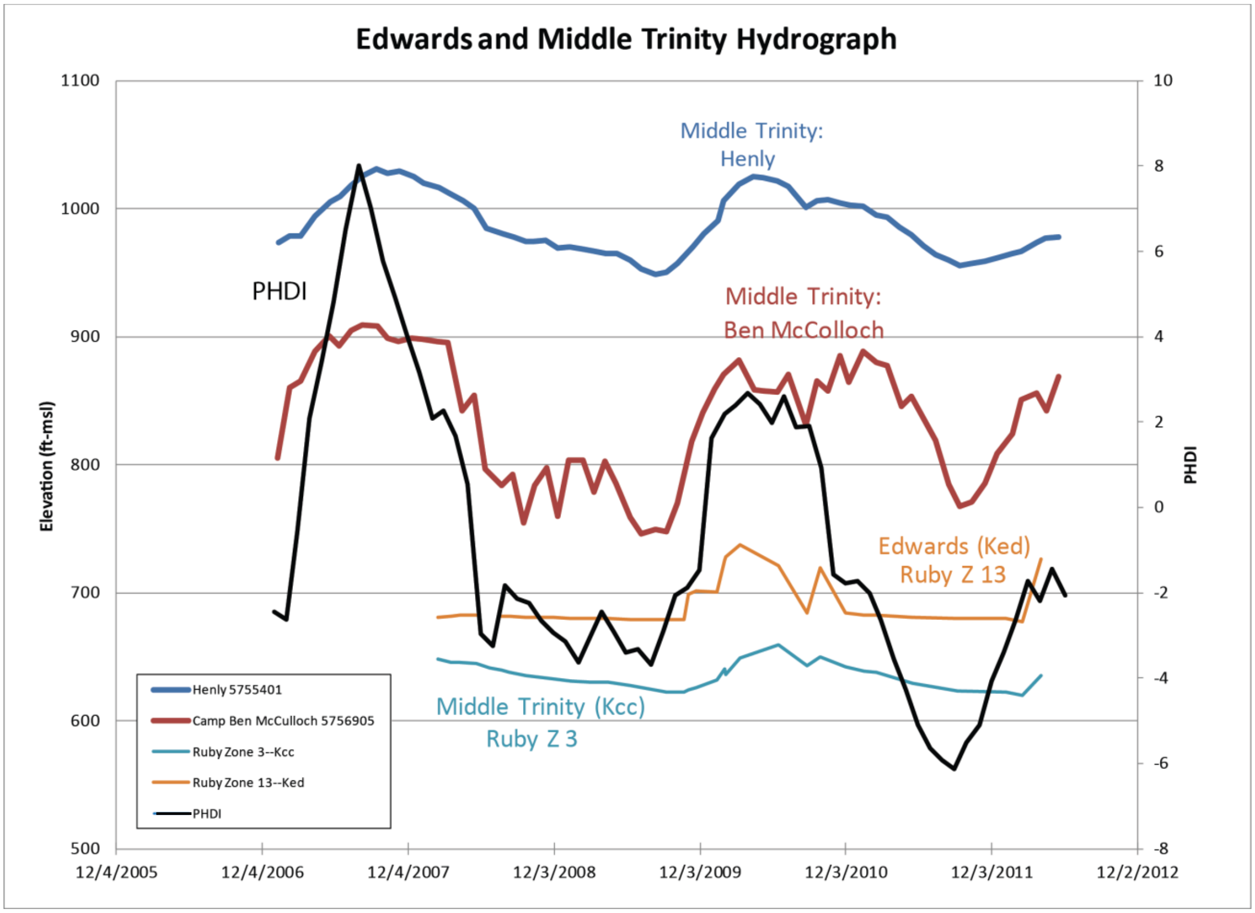

Figure 11. *Hydrograph of the Edwards and Middle Trinity Aquifers compared to a regional drought index, the Palmer Hydrologic Drought Index (PHDI). Edwards and Trinity water levels from the BSEACD's Ruby Ranch multiport monitor well contain both the Edwards and Middle Trinity levels. Other Middle Trinity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

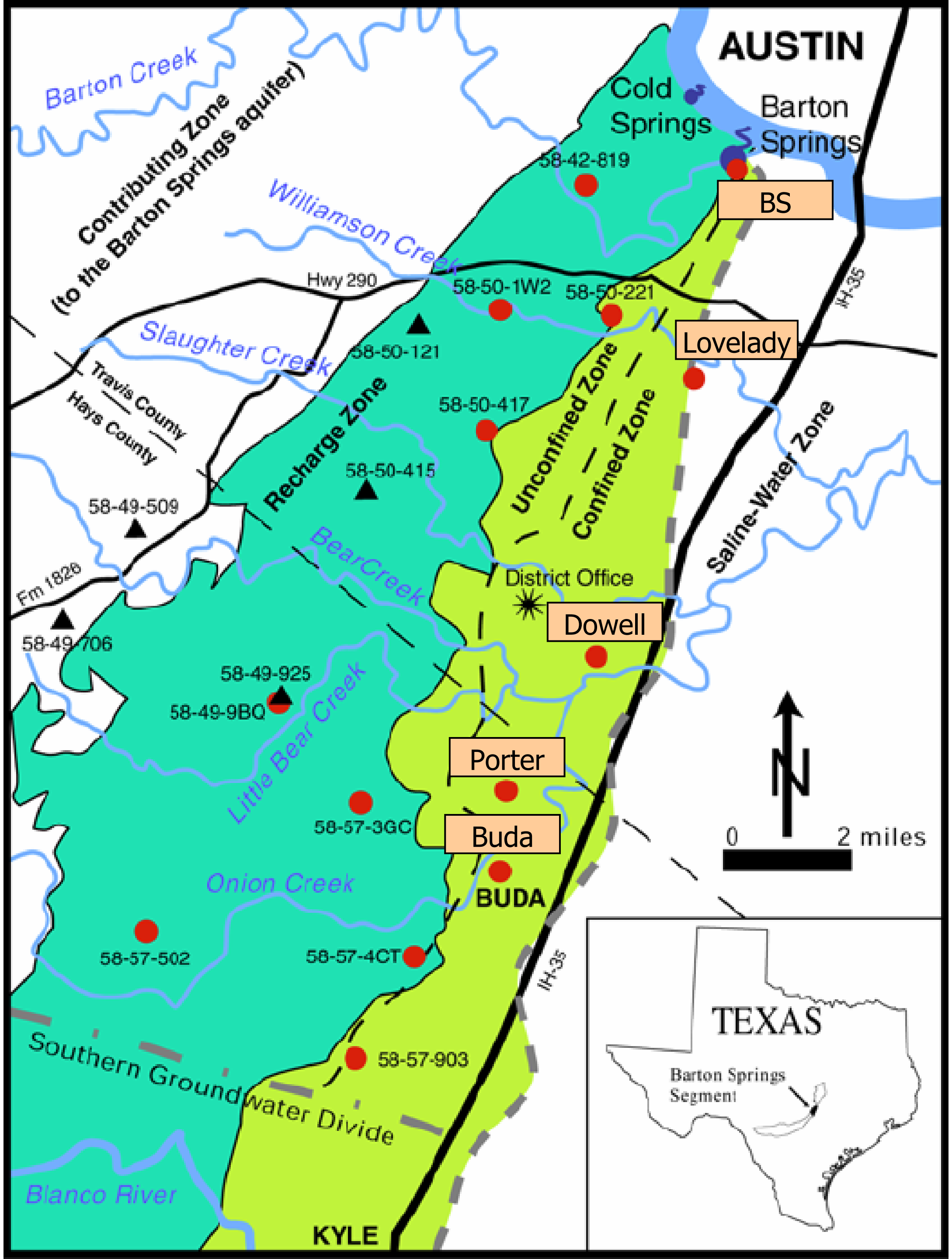
P = Porter Well Level, ft AMSL
L = Lovelady well Level, ft AMSL
logBW = base 10 logarithm of flow (cfs), Blanco at Wimberley

Multivariate Analysis for Barton Springs Drought Triggering Methodology

October 2005

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.

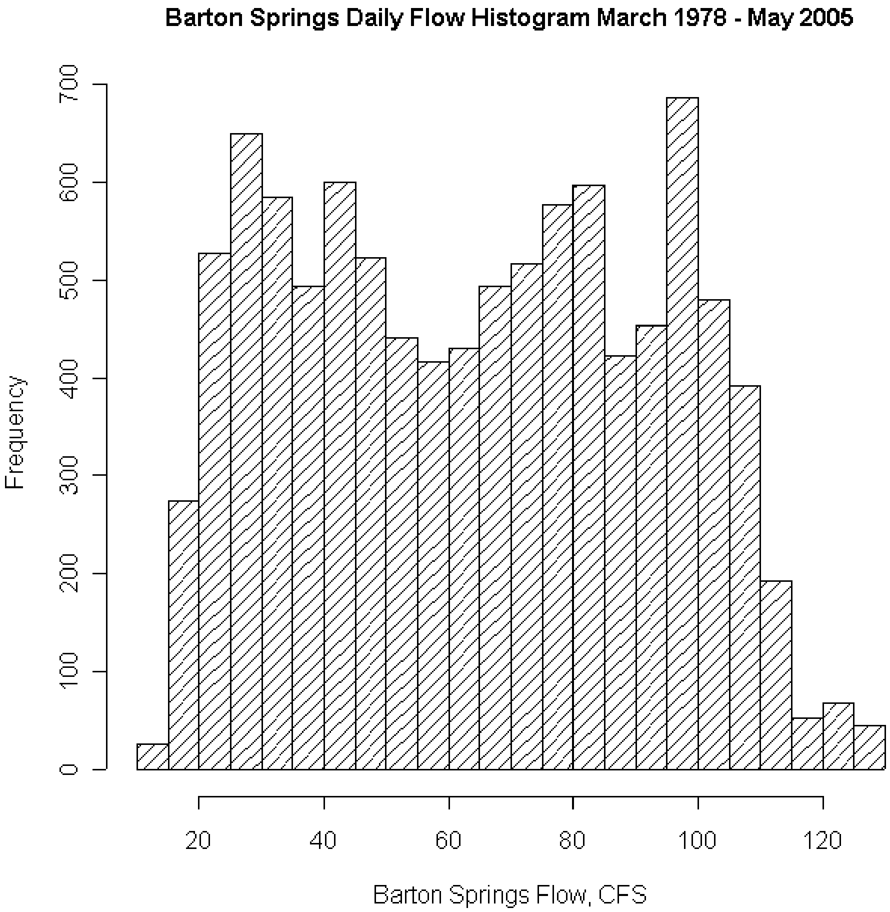


Map Source: BSEACD

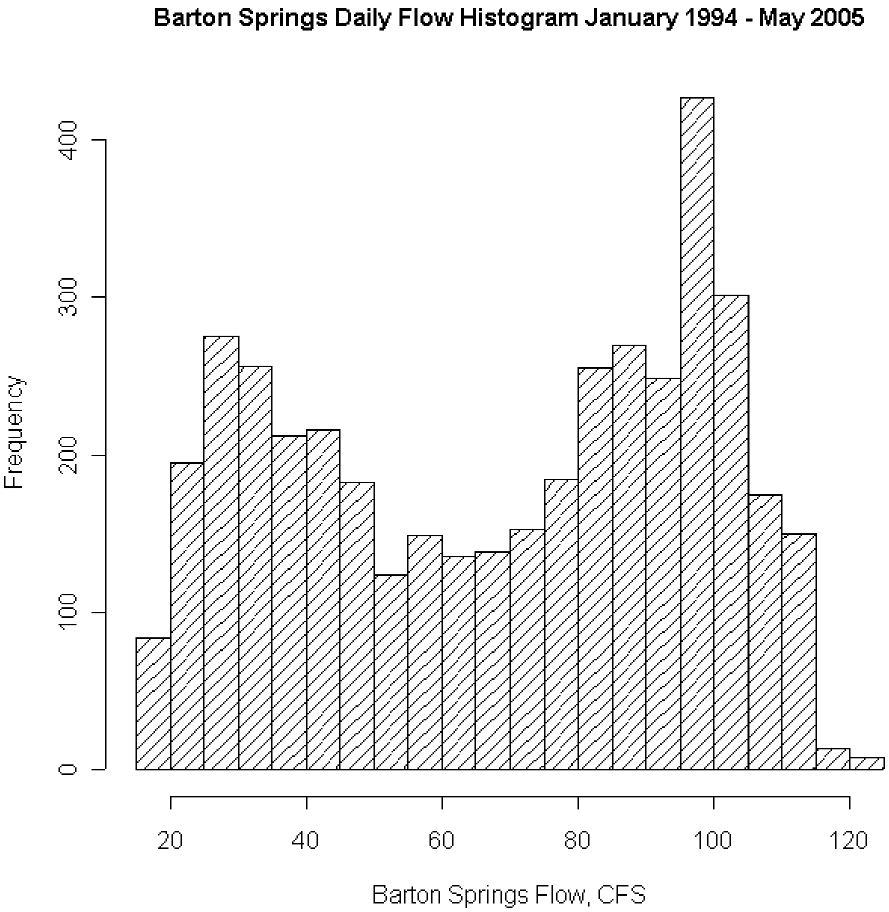
Multivariate Analysis Methodology

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

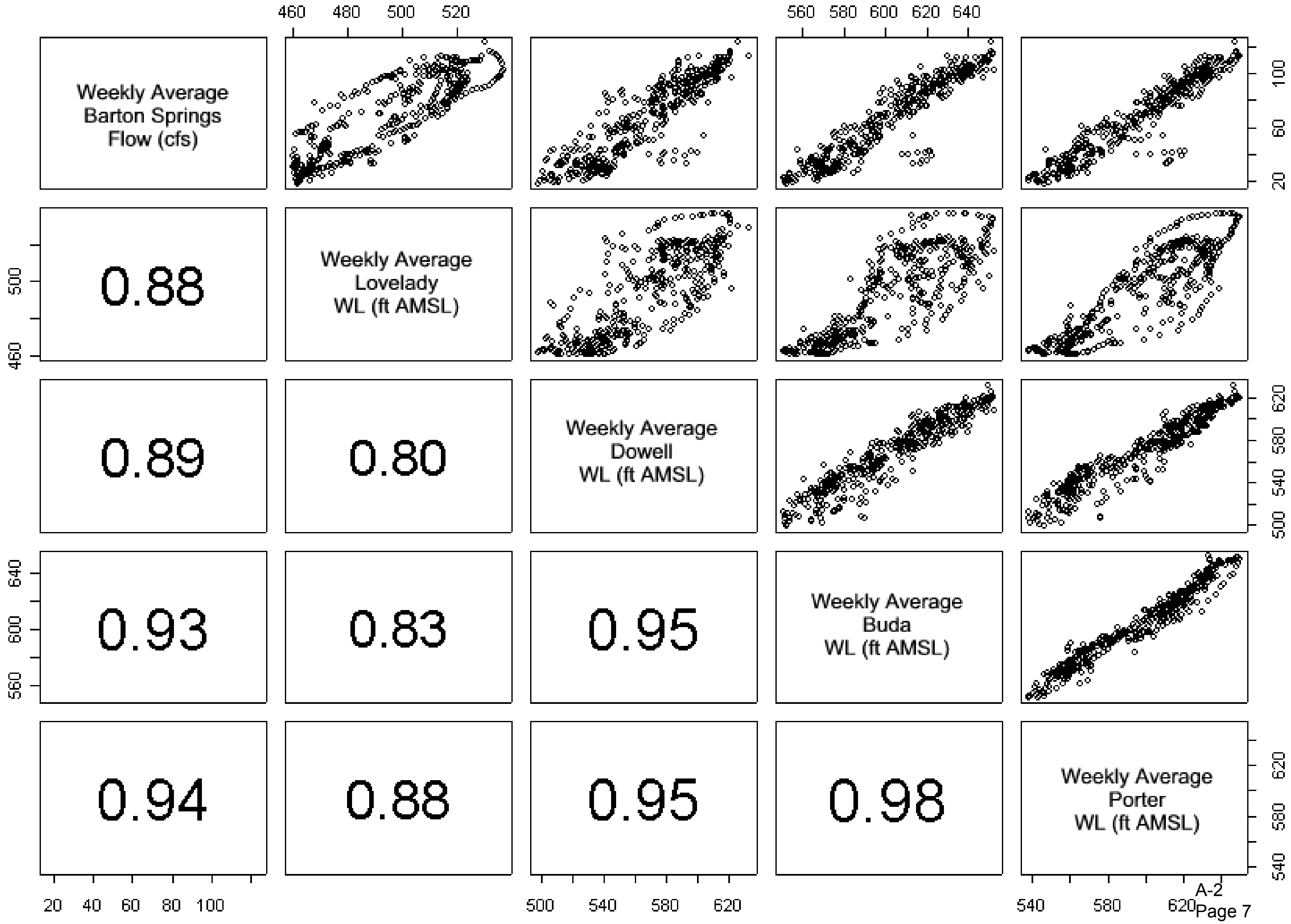

Barton Springs Daily Flow Histogram March 1978 - May 2005

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

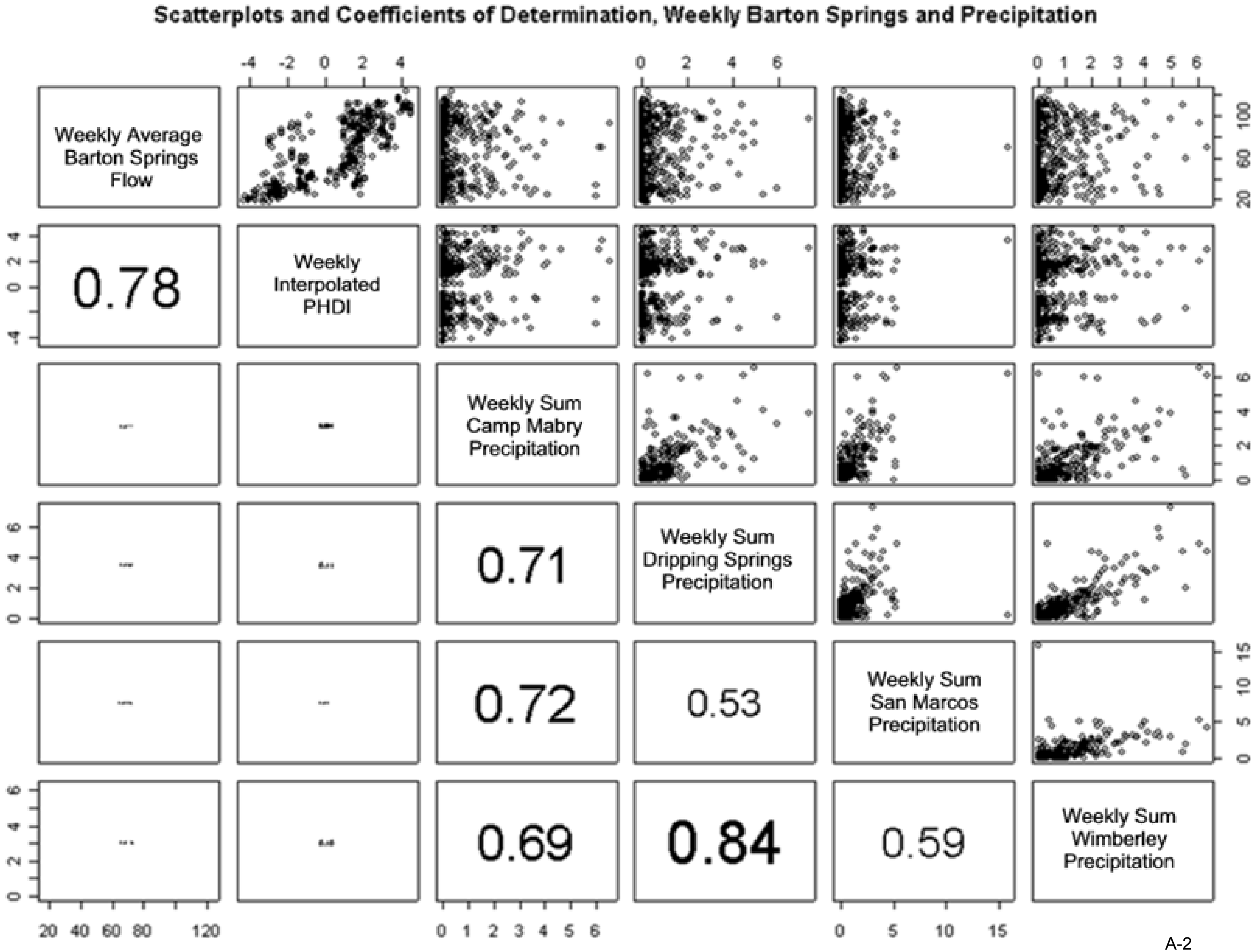

Barton Springs Daily Flow Histogram January 1994 - May 2005

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

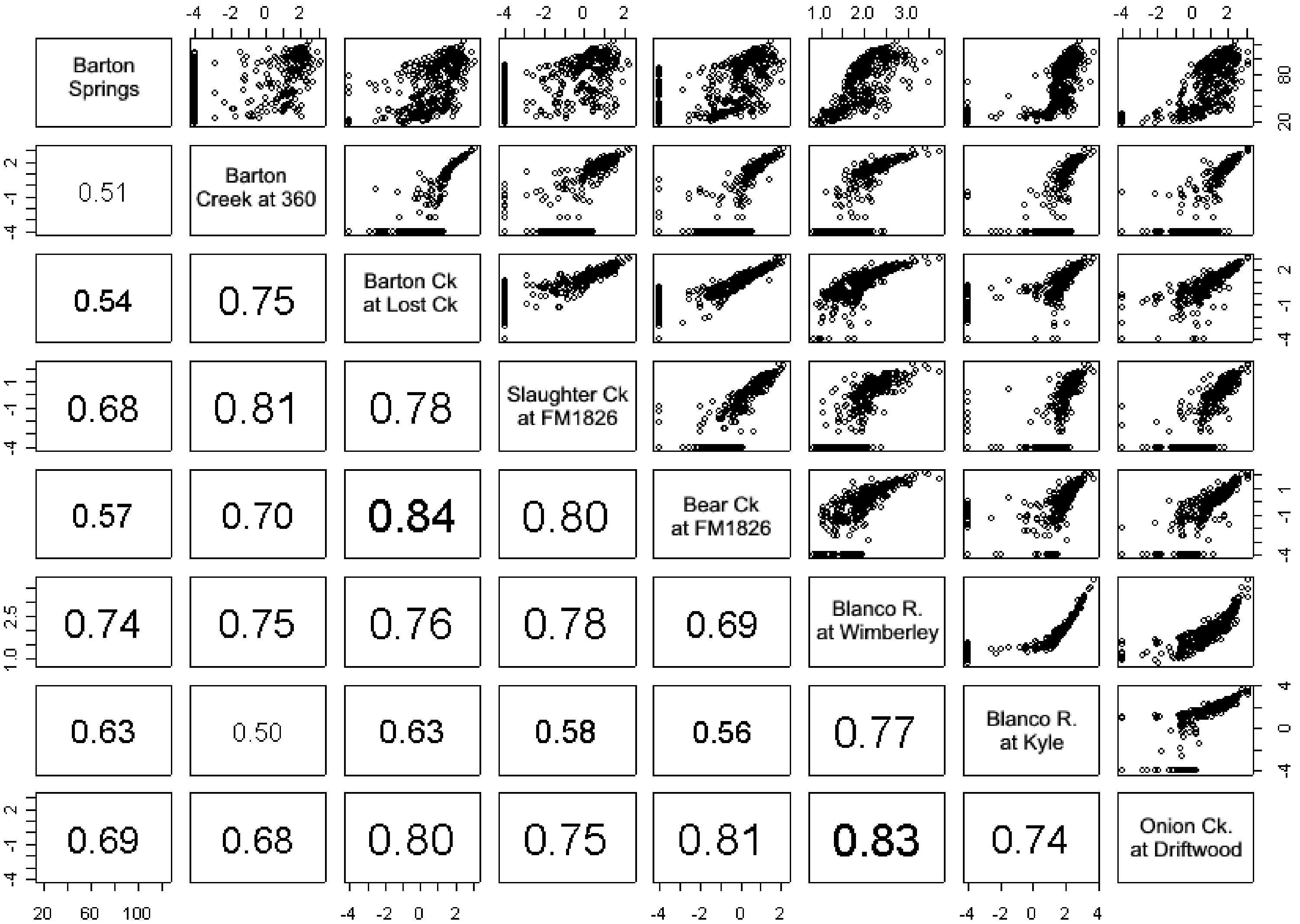
Scatterplot of Springs and Wells


Scatterplots and Coefficients of Determination, Weekly Barton Springs and Wells

Scatterplot of Springs and Precipitation

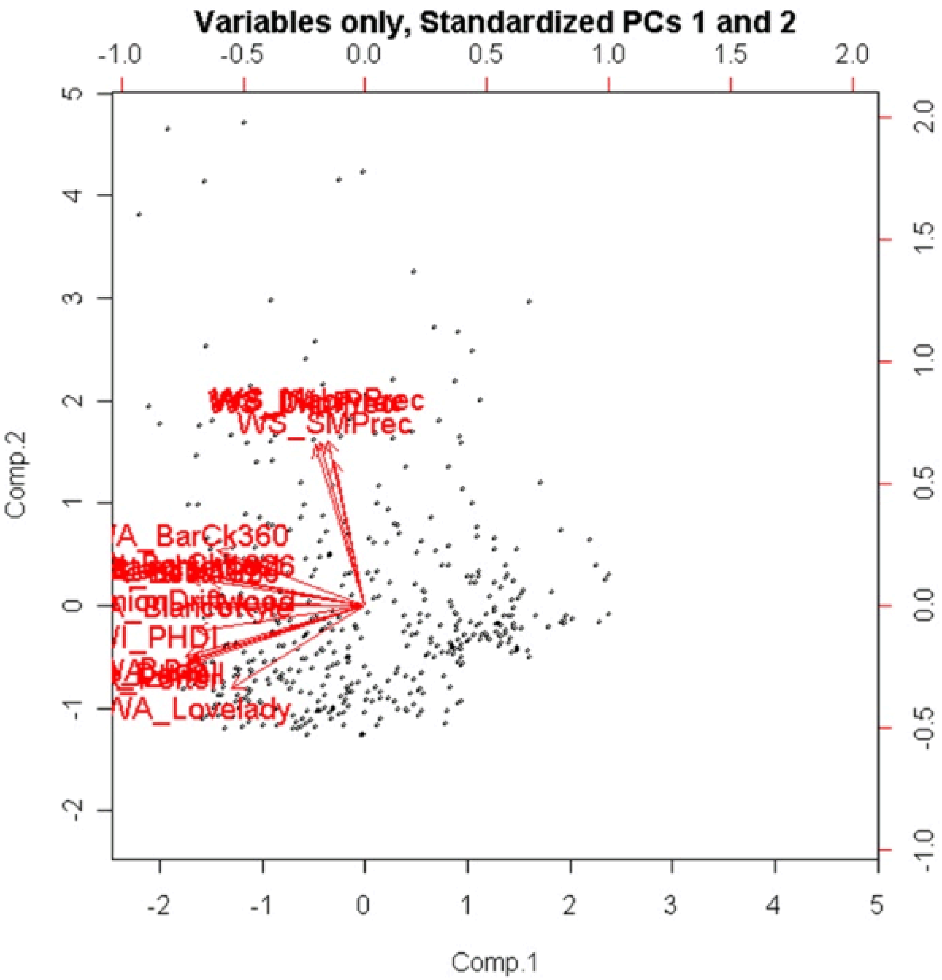


Scatterplot of Springs and log Streamflow



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

Principal Components Analysis Summary

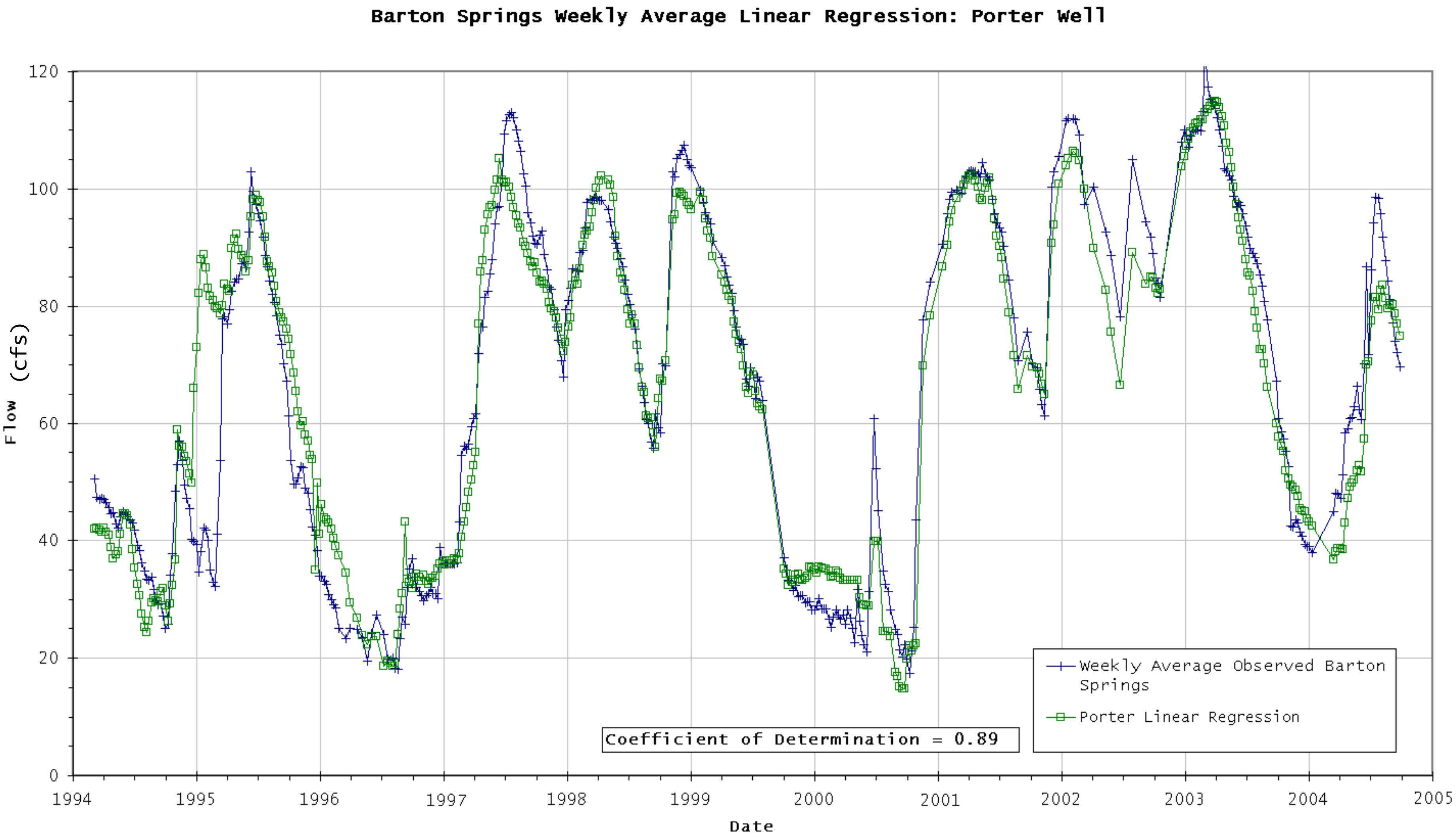


- Springflow, water levels, log streamflow, and PHDI are loaded on the first component, and account for about 56% of system variance.
- The second component is a precipitation component, and is uncorrelated with the other variables. It accounts for about 19% of system variance.
- The Buda, Dowell, and 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.

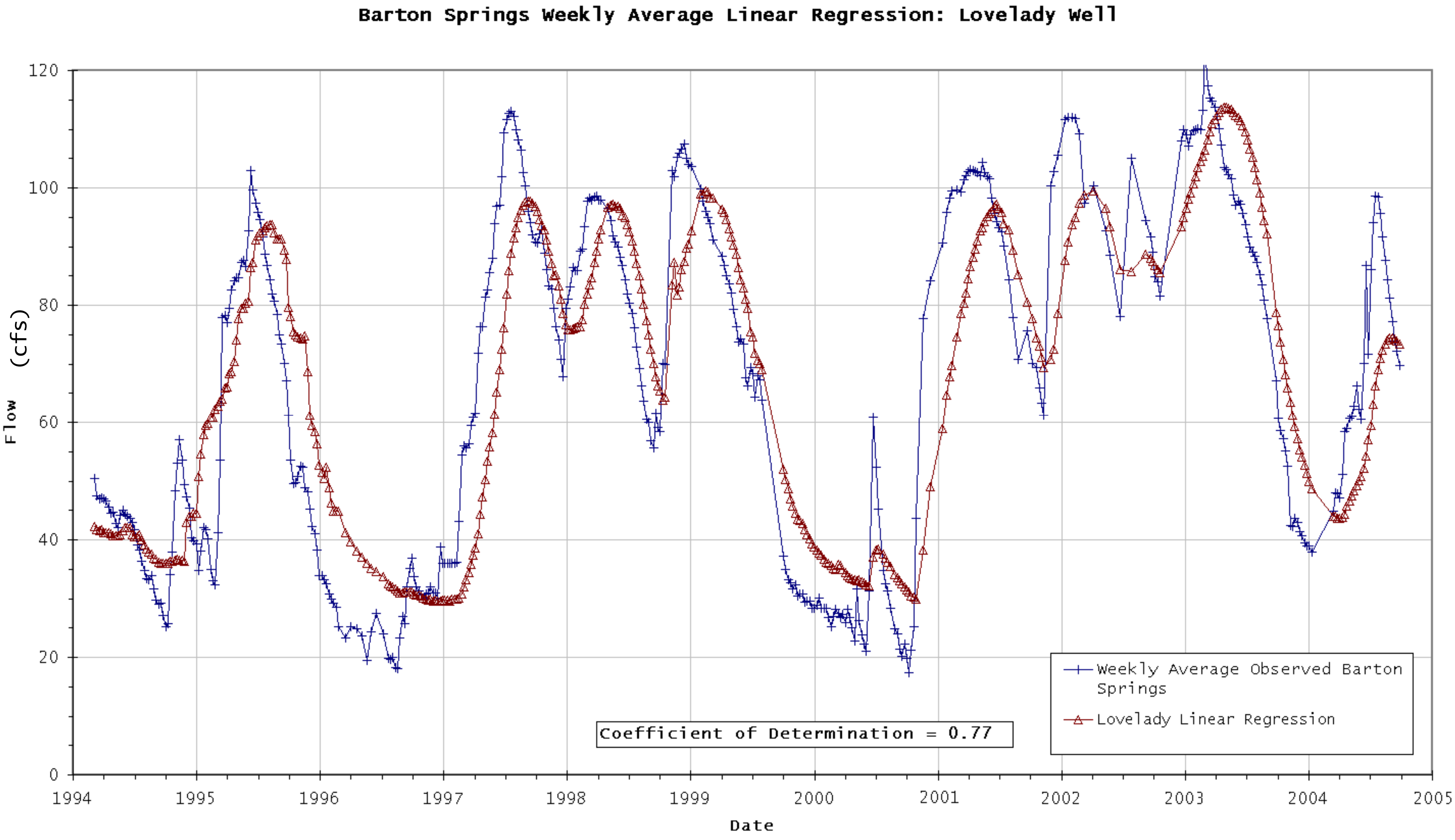
Multiple Linear Regression

- 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.

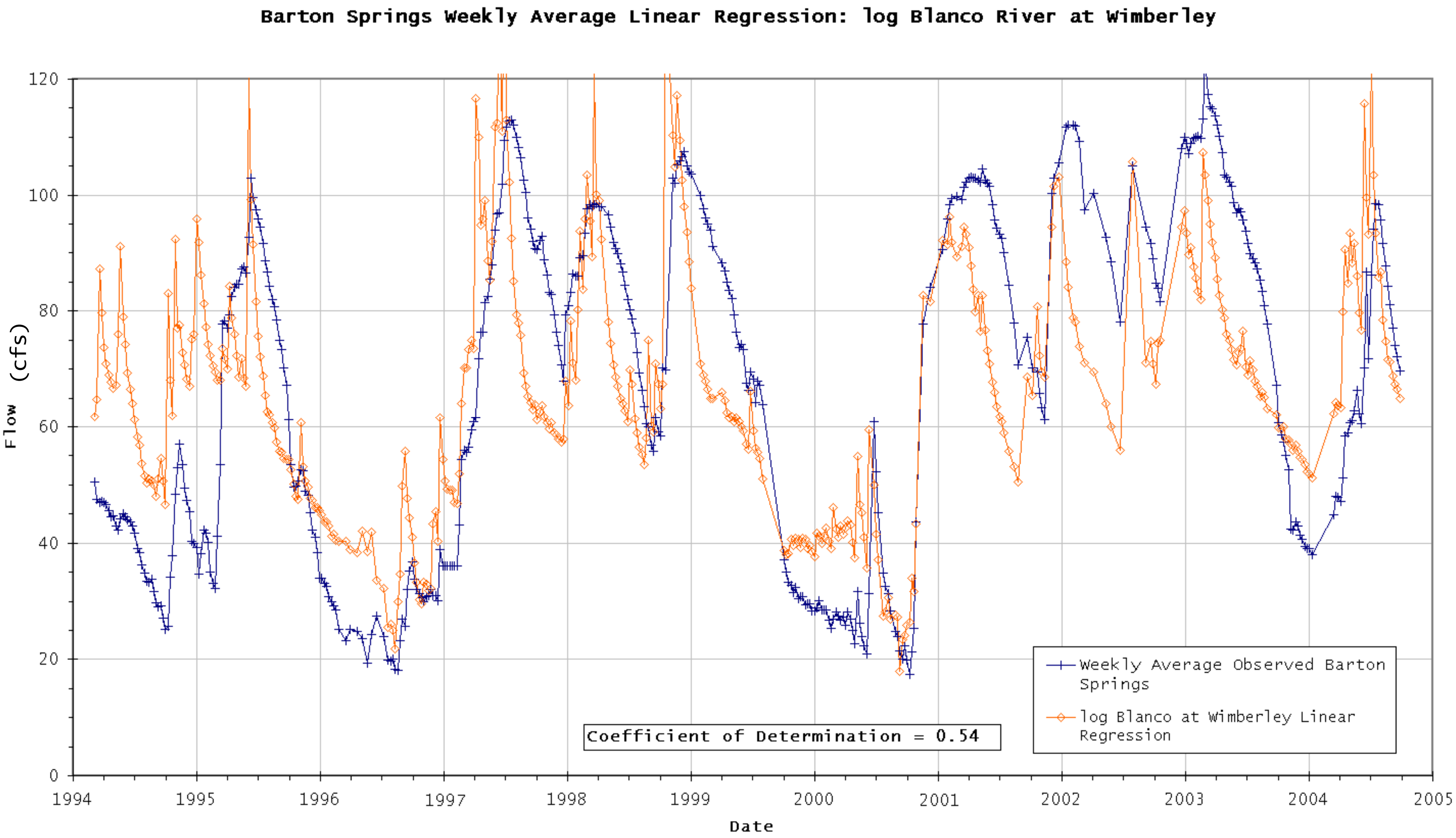
Linear Regression on Porter Well



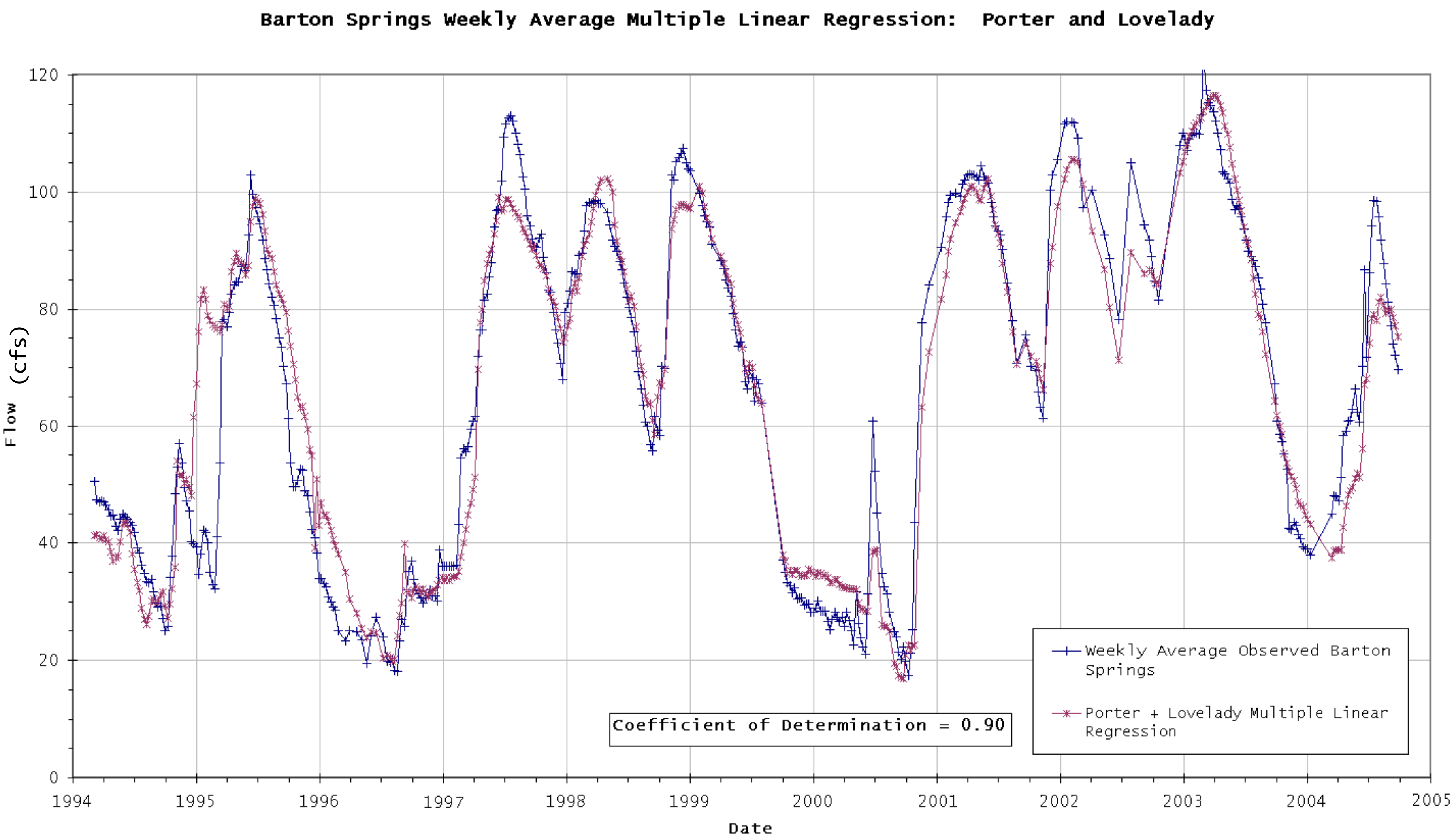
Linear Regression on Lovelady Well



Linear Regression on log Blanco River at Wimberley

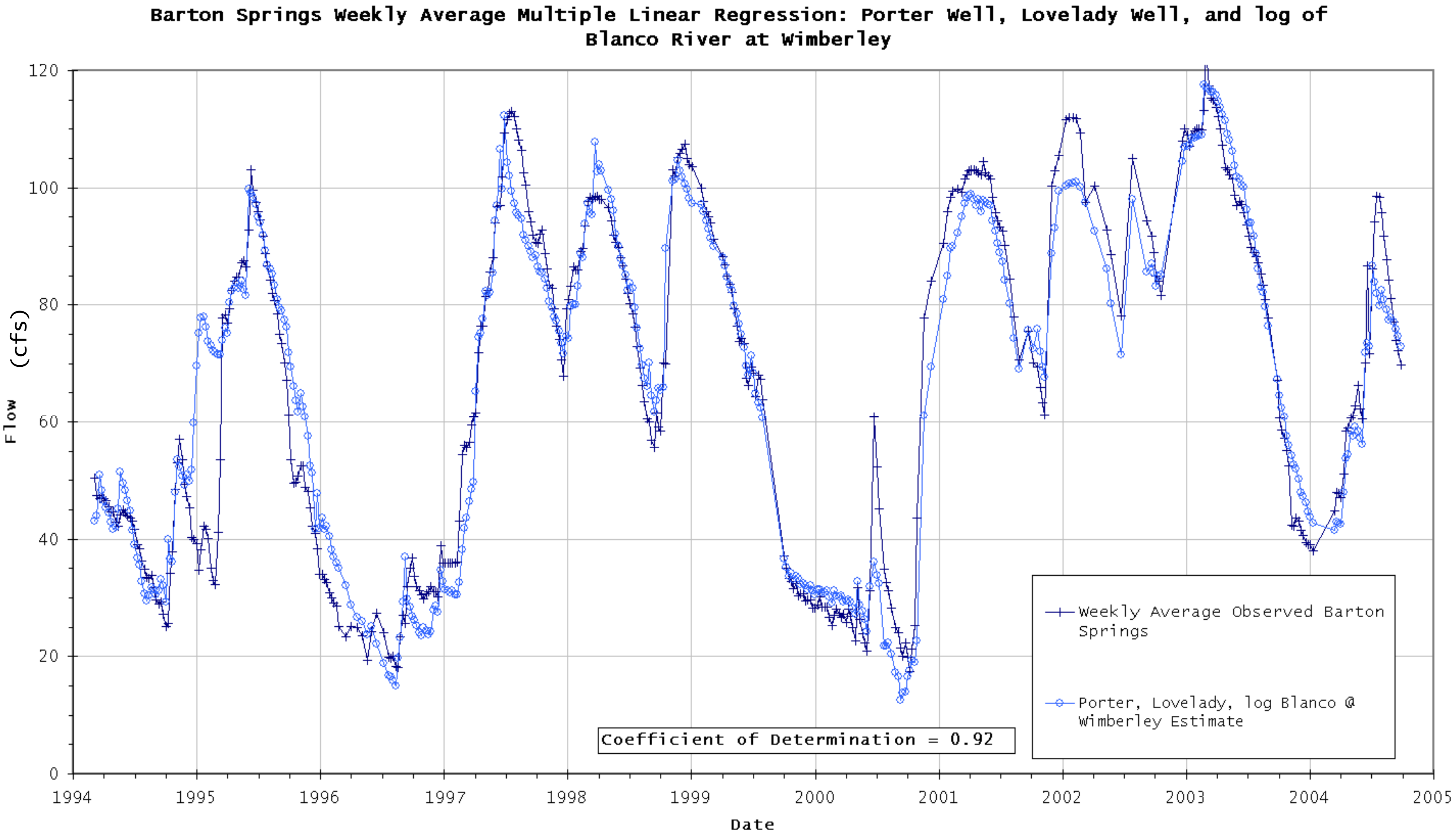


Multiple Linear Regression on Porter and Lovelady Wells



LBG GUYTON

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



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

Using Weekly Average Values:

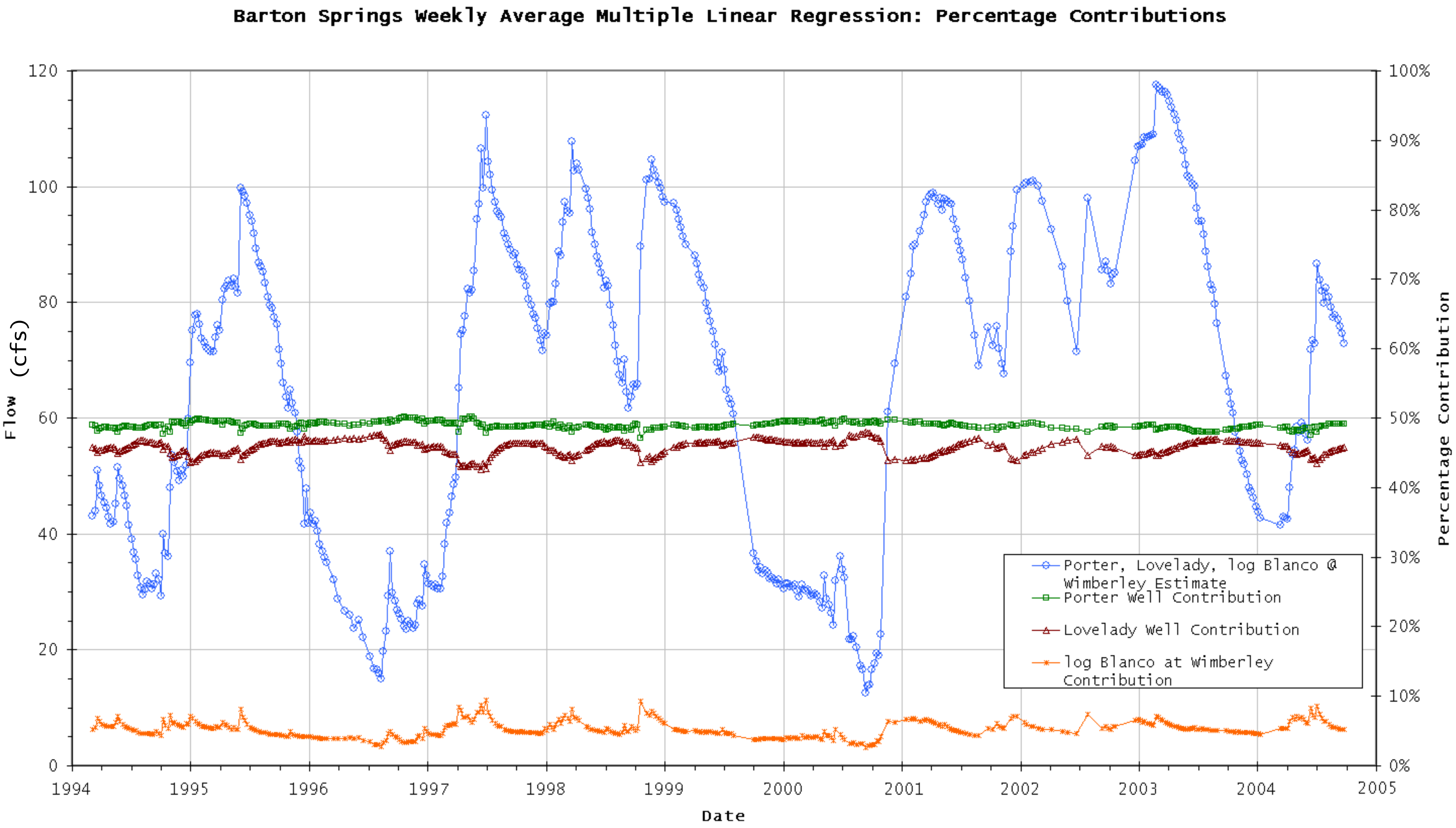
$$\textbf{Aquifer Index} = 0.420P + 0.474L + 14.2\log BW - 445$$

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

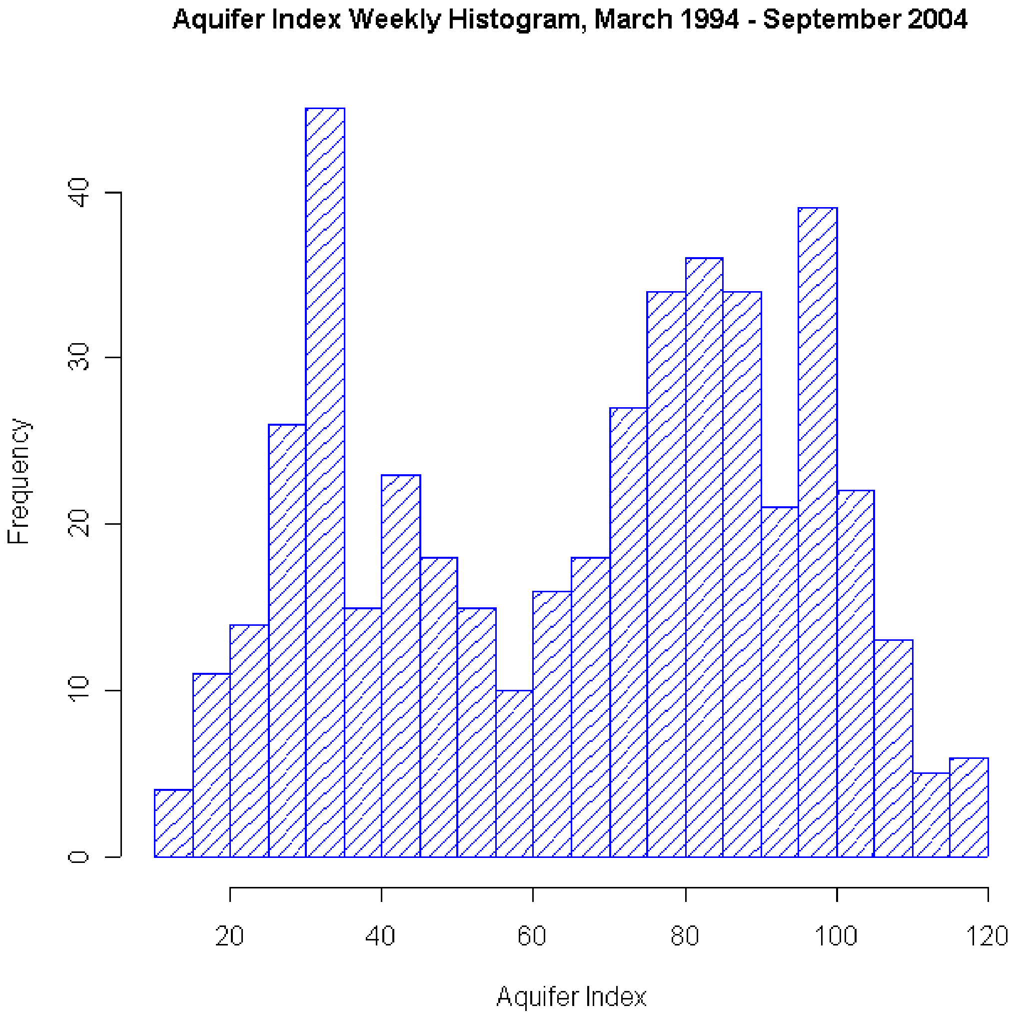
Comments:

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


Aquifer Index Weekly Histogram, March 1994 - September 2004

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

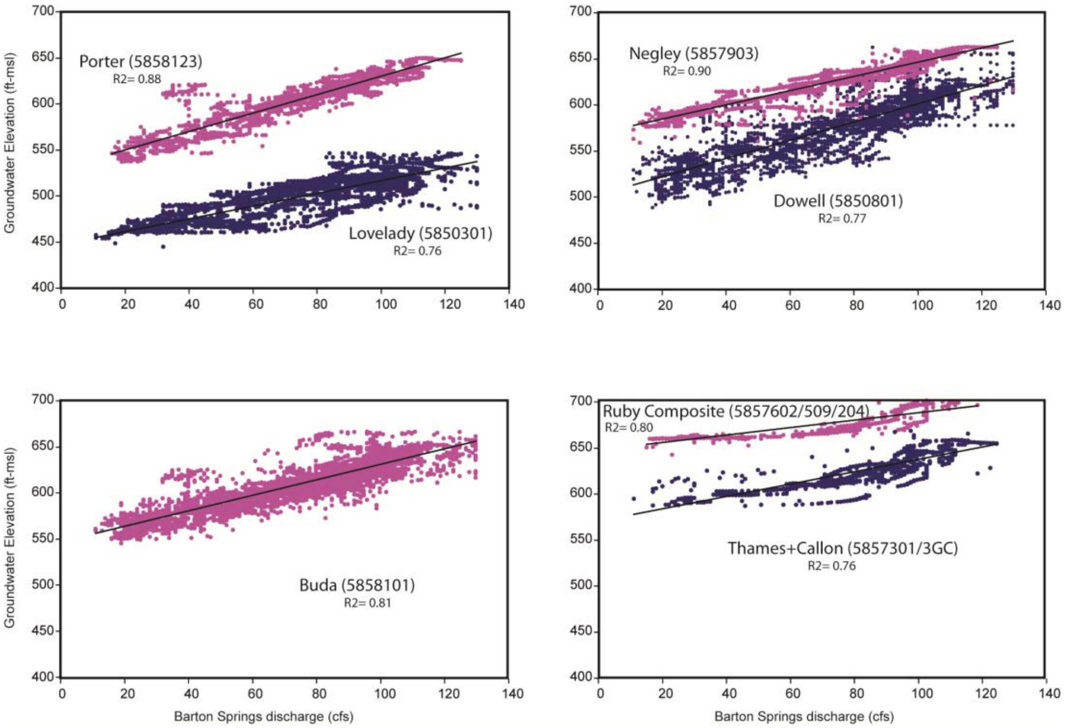


Figure A3-1. Water level and springflow correlations from selected wells. These correlations reflect the entire data set for each well (**Table 8**). There is a good correlation between water levels and springflow in most wells.

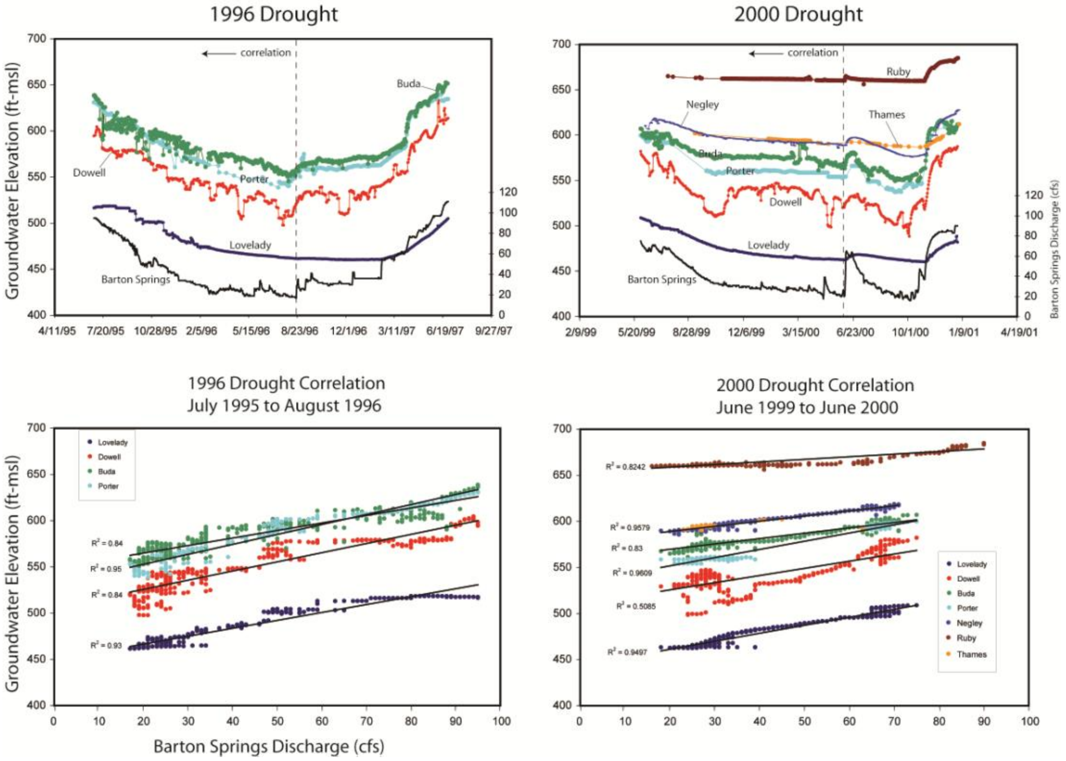


Figure A3-2. The top two figures are hydrographs from the 1996 and 2000 droughts with water levels and Barton Springs discharge. The bottom two figures are correlations of water levels to Barton Springs during each drought period for the time indicated.

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, or the elevation of the water level in the Lovelady Drought Indicator Well is equal to or less than 478.4.0 feet (msl), and 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, or the elevation of the water level in the Lovelady Drought Indicator Well is equal to or less than 462.7 feet (msl), and 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, or 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), and 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.