Analysis of Species Requirements in Relation to Spring Discharge Rates and Associated Withdrawal Reductions and Stages for Critical Period Management of the Edwards Aquifer

Report to the Steering Committee
for the Edwards Aquifer Recovery Implementation Program

The Edwards Aquifer Area Expert Science Subcommittee
for the Edwards Aquifer Recovery Implementation Program

December 28, 2009

The photograph on the preceding page is of a flowing well in San Antonio from the 1890s (Hill and Vaughan 1896).

December 28, 2009

To: The Steering Committee for the Edwards Aquifer Recovery Implementation Program

From: The Edwards Aquifer Area Expert Science Subcommittee

Attached please find a final report titled *Analysis of Species Requirements in Relation to Spring Discharge Rates and Associated Withdrawal Reductions and Stages for Critical Period Management of the Edwards Aquifer*. This report meets the requirements of Article 12, Senate Bill 3, Regular Session, 80th Texas Legislature, Section 1.26A(j).

At our meeting held on December 16, 2009, Dr. Robert Mace called for a motion to approve the findings in the report. Mr. Sam Vaugh made the motion which was seconded by Dr. Glenn Longley. There were no objections; thus, the motion passed and consensus was reached. Fourteen of the 15 members were present at the meeting. Dr. Ron Green was not able to attend the meeting; however, Dr. Mace learned that Dr. Green had no objections to the findings in the report.

If you have any questions, please do not hesitate to contact our chair, Dr. Robert E. Mace with the Texas Water Development Board, at (512) 936-0861 or robert.mace@twdb.state.tx.us.

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The Edwards Aquifer Recovery Implementation Program
Edwards Aquifer Area Expert Science Subcommittee

Chair

Robert E. Mace, Ph.D., P.G., Texas Water Development Board

Facilitator

Susan Aragon-Long, U.S. Geological Survey (non-voting)

Members

Rene Barker, P.G., Texas State University
Norman Boyd, Texas Parks and Wildlife Department
Thomas Brandt, Ph.D., U.S. Fish & Wildlife Service
Michael Gonzales, San Antonio River Authority
Ron Green, Ph.D., P.G., Southwest Research Institute *(not in photo)*
Charles Kreitler, Ph.D., P.G., LBG-Guyton Associates
Glenn Longley, Ph.D., Texas State University
Robert E. Mace, Ph.D., P.G., Texas Water Development Board
Doyle Mosier, Texas Parks and Wildlife Department
Mary Musick, P.G., Musick Groundwater Consulting
Edmund L. Oborny, Jr., BIO-WEST, Inc.
Jackie Poole, Texas Parks and Wildlife Department
Sam Vaugh, P.E., HDR Engineering, Inc.
Shirley Wade, Ph.D., P.G., Texas Water Development Board
John Waugh, P.G., San Antonio Water System

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Executive summary

In 2007, the 80th Texas Legislature passed Senate Bill 3 which, among other items, formalized the Edwards Aquifer Recovery Implementation Program. The legislation requires a group of stakeholders in a Steering Committee to develop a Program Document. The Program Document provides recommendations for withdrawal adjustments to protect threatened and endangered species at all times and includes provisions to pursue funding for programs to achieve that goal.

The Steering Committee is served by several subcommittees, one of which is the Edwards Aquifer Area Expert Science Subcommittee (subcommittee). Senate Bill 3 requires the formation of the subcommittee, with its members appointed by the Steering Committee. The subcommittee's initial charges were to (1) evaluate designating a San Marcos Pool, (2) evaluate the necessity of maintaining minimum springflows, and (3) evaluate whether adjustments to drought triggers for San Marcos Springs should be made. The subcommittee delivered a report in November 2008 titled *Evaluation of Designating a San Marcos Pool, Maintaining Minimum Spring Flows at Comal and San Marcos Springs, and Adjusting the Critical Period Management Triggers for San Marcos Springs* in response to these charges. The subcommittee concluded in this report that (1) there is not sufficient data to support the designation of a separate San Marcos Pool, (2) minimum springflows are required within the context of a system flow regime for the survival and recovery of each species, and (3) trigger levels for San Marcos Springs should not be adjusted at this time.

Senate Bill 3 also required the subcommittee to (1) analyze species requirements in relation to spring discharge rates and aquifer levels and (2) develop withdrawal reduction levels and stages for critical period management associated with the species requirements. This report is in response to these legislative charges.

It is important to note that the results presented in this report are driven by science only and do not consider or include policy implications or any actions that the Edwards

Aquifer Recovery Implementation Program Steering Committee may recommend as part of its Program Document. Actions recommended in the Program Document will likely affect these results; therefore, the results in this report can be considered as the beginning of a conversation among scientists, stakeholders, and various agencies on the ultimate management of the Edwards Aquifer to protect the endangered species that rely on springflow for survival.

When evaluating specific flow requirements for the listed species, the subcommittee (1) examined the overall condition of the system as it is today, (2) examined the available information to assess when impacts to a given species might first be evident, and (3) evaluated potential flow-related thresholds for the species. Throughout our assessment, we started with actual monitoring data when available, proceeded to modeling results when available, considered the historical hydrology, and finally confirmed or rejected hypotheses based on professional judgment.

The subcommittee chose to address our charges within the context of a flow regime for the protection of all listed species as well as the integrity of each ecosystem. Our interpretation of a protective flow regime is one that will ensure the "survival and recovery of the species in the wild". To accomplish this goal, the subcommittee determined that the recommended flow regime must sustain an overall trend of maintaining or increasing the populations of the threatened and endangered species. This by definition means that conditions cannot go beyond thresholds necessary for survival of any of the listed species.

The subcommittee selected the following components of the flow regime based on a comprehensive review of the best available science for the listed species in these systems:

- a long-term average flow,
- a minimum 6-month average flow, and
- a minimum 1-month average flow with an embedded minimum flow requirement (1 day).

Based on the analyses described in the body of this report, the subcommittee has determined the following spring discharge rates incorporated into a flow regime in association with the assumptions presented herein are necessary for the long-term survival of the aquatic communities of the Comal and San Marcos springs, in particular the federally listed species.

- Comal Springs Flow Regime:
    - Long-term average flow: 225 cubic feet per second
    - Minimum 6-month average flow: 75 cubic feet per second
    - Minimum 1-month average flow: 30 cubic feet per second with no flow below 5 cubic feet per second
- San Marcos Springs Flow Regime:
    - Long-term average flow: 140 cubic feet per second
    - Minimum 6-month average flow: 75 cubic feet per second

- Minimum 1-month average flow: 60 cubic feet per second with no flow below 52 cubic feet per second

The subcommittee made a conscious decision not to add a margin of safety to the proposed recommendations. It was our interpretation of our charges to evaluate the best available science objectively, clearly state the assumptions associated with the recommendations, and acknowledge the need for further study where appropriate. For instance, if it is later revealed that significant impacts are not captured in the model results or efforts to control parasites, exotic species, sedimentation, or recreation are not in place or successful in the future, then one needs to be cautious with strict implementation of the proposed flow recommendations. However, should information come forward that these species are able to tolerate short periods of lower flow conditions or more frequent occurrences without significant consequence, or mitigation activities are in place that could be effective in providing additional levels of protection, then the proposed flow regime recommendations would also need to be revisited. One thing is clear, long-term monitoring is essential and further study and research specifically during critical low-flow periods (or simulated critical low flows) are needed to accurately determine the potential impacts to the species.

This task is focused on developing withdrawal reductions and stages for critical period management based on the flow requirements for eight threatened and endangered species found in the Comal and San Marcos springs ecosystems (fountain darter [*Etheostoma fonticola*], San Marcos gambusia [*Gambusia georgei*], Texas blind salamander [*Eurycea rathbuni*], San Marcos salamander [*Eurycea nana*], Texas wild-rice [*Zizania texana*], Comal Springs dryopid beetle [*Stygoparnus comalensis*], Comal Springs riffle beetle [*Heterelmis comalensis*], and Peck's cave amphipod [*Stygobromus pecki*]). We assumed that our task was limited to adjusting withdrawal (pumping) reduction levels and stages for critical period management. We did not suggest changes to the overall permitting cap or how the act or the authority implements withdrawal reductions or permitting (although we did request model runs at different levels of constant pumping to better understand how the aquifer responds to different levels of pumping). Therefore, we restricted ourselves to considering adjustments of (1) the current number of stages; (2) the current trigger levels for J-17, J-27, Comal Springs, and San Marcos Springs; and (3) reductions in pumping at each of the stages. Based on our interpretation of the task, we developed withdrawal reductions and stages for critical period management that met or exceeded the flow requirements for the endangered species—we did not consider minimum pumping (or additional water supply infrastructure) needed to maintain health and human safety or any management actions that could be taken to lower springflow requirements. Our understanding is that these policy issues will be considered by the Steering Committee during the development of a habitat conservation plan.

We used an existing numerical groundwater flow model of the Edwards Aquifer and its associated management module to develop withdrawal reductions and stages for critical period management. We used the model to look at meeting or exceeding the three flow criteria for each of the two springs. After 38 model runs, the last run showed that pumping needed to be reduced 85 percent in a single stage to meet or exceed the springflow requirements. Therefore, the final critical period management scenario that meets or exceeds the final springflow recommendations is

San Antonio Pool

Comal (cfs)	San Marcos (cfs)	J-17 (feet)	Stage -	Reduction (%)
<225	<96	<665	I	85

Uvalde Pool

J-27 (feet)	Stage -	Reduction (%)
< 865	I	85

where cfs is cubic feet per second.

Several other model runs also met or exceeded the spring flow recommendations. One of these runs assumed constant pumping (that is, no critical period management) of 75,000 acre-feet per year, and another run had two critical period management stages, the first with a 30 percent reduction in pumping and the second with a 100 percent reduction in pumping.

We believe further study is needed to (1) improve springflow measurement, (2) conduct sensitivity analyses, (3) run optimization models, (4) estimate the probability of recurrence of the 1950s drought, (5) evaluate the potential effects of climate variability on recharge, (6) conduct additional runs to refine withdrawal reductions, (7) update the model, (8) refine the calibration of the model, (9) enhance the management module, and (10) refine model calibration between San Marcos and Barton springs.

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Introduction

The Edwards Aquifer is recognized as a vital water resource for a multitude of agricultural, environmental, industrial, municipal, and recreational uses. Several springs, specifically Comal Springs and San Marcos Springs, provide habitat for a number of species protected under the federal Endangered Species Act. After a lawsuit and the specter of federal control of the aquifer, the Texas Legislature created the Edwards Aquifer Authority to regulate pumping in the aquifer and to ensure that, by December 31, 2012, endangered and threatened species dependent on springflow are protected to the extent required by federal law.

In 2007, the Texas Legislature passed Senate Bill 3 which, among other items, formalized the Edwards Aquifer Recovery Implementation Program. The legislation requires a group of stakeholders in a Steering Committee to develop a Program Document. The Program Document provides recommendations for withdrawal adjustments to protect threatened and endangered species at all times and includes provisions to pursue funding for programs to achieve that goal. The Program Document may be in the form of a Habitat Conservation Plan used in the issuance of an Incidental Take Permit by the U.S. Fish and Wildlife Service. The Edwards Aquifer Authority, the Texas Commission on Environmental Quality, the Texas Water Development Board, and the U.S. Fish and Wildlife Service must approve and execute the Program Document no later than September 30, 2012, with the document going into effect by December 31, 2012.

The Steering Committee is served by several subcommittees, one of which is the Edwards Aquifer Area Expert Science Subcommittee (subcommittee). Senate Bill 3 requires the formation of the subcommittee, its members appointed by the Steering Committee (see Appendix A for information on the formation and operation of the subcommittee). The subcommittee's initial charges were to (1) evaluate designating a San Marcos Pool, (2) evaluate the necessity of maintaining minimum springflows, (3) evaluate whether adjustments to flow triggers for San Marcos Springs should be made, and (4) submit the results to the Steering Committee and all other stakeholders involved in the Recovery Implementation Program by December 31, 2008 (see Appendix B for the exact words in statute). In response to these charges, the subcommittee delivered a report in November 2008 entitled *Evaluation of Designating a San Marcos Pool, Maintaining Minimum Spring Flows at Comal and San Marcos Springs, and Adjusting the Critical Period Management Triggers for San Marcos Springs* (EAAESS 2008). The subcommittee concluded in this report that (1) there is not sufficient data to support the designation of a separate San Marcos Pool, (2) minimum springflows are required within the context of a system flow regime for the survival and recovery of each species, and (3) trigger levels for San Marcos Springs should not be adjusted at this time.

Senate Bill 3 also charged the subcommittee to (1) analyze species requirements for springflow and aquifer levels as a function of recharge and withdrawal levels, (2) develop withdrawal reductions for critical period management associated with those requirements, and (3) submit results to the Steering Committee and all other stakeholders involved in the Recovery Implementation Program by December 31, 2009 (see Appendix B for the exact words in statute). In conducting its work, the statute required the subcommittee to consider all "reasonably available science" and to base its conclusions "solely on the best science available" (see Appendix B for the exact words in statute).

The purpose of this document is to report the r 1 of these latter charges. This report is organized according to the major charges in sta

Task 1: Analyze species requirements for springflow and aquifer levels as a function of recharge and withdrawal levels, and

Task 2: Develop withdrawal reductions for critical period management associated with the species requirements.

Under each task, we list our results, followed by our interpretation of the task, the information we considered, and the results of our analysis. Supporting documentation is included in the appendices where appropriate.

Because Task 1 was primarily a biological task and Task 2 was primarily a hydrological task, the subcommittee divided into two workgroups—one of biologists and one of hydrologists—to focus on their respective tasks. The full subcommittee continued to meet to discuss progress on both tasks and to coordinate activities where needed. All workgroup meetings were open to the general public. The nature of these two tasks was such that Task 2 depended upon the results of Task 1. The ambitious deadlines required by statute required us to make concessions on what information we considered (for example, work to update the habitat models for bathymetry and vegetation at the springs was not available in time for us to consider in this report) and what analyses we conducted (for example, we could have investigated other critical period management scenarios or refined the scenarios if given more time).

Task 1: Analyze species requirements in relation to spring discharge rates

Results: Based on the analyses described in the body of this report, the Edwards Aquifer Area Expert Science Subcommittee has determined the following spring discharge rates in association with the assumptions presented herein are necessary for the long-term survival of the aquatic communities of the Comal and San Marcos springs, in particular the federally listed species.

Comal Springs Flow Regime:

- **Long-term average: 225 cubic feet per second**
- **6-month average: 75 cubic feet per second**
- **1-month average: 30 cubic feet per second with no flow below 5 cubic feet per second**

San Marcos Springs Flow Regime:

- **Long-term average: 140 cubic feet per second**
- **6-month average: 75 cubic feet per second**
- **1-month average: 60 cubic feet per second with no flow below 52 cubic feet per second**

The Edwards Aquifer, including its two largest spring ecosystems, Comal and San Marcos springs, maintains a diversity of species, many of which are endemic. The species listed under the Endangered Species Act identified in Section 3.1 of the Edwards Aquifer Recovery Implementation Program Memorandum of Agreement (EARIP 2007) consist of eight threatened and endangered species found in the Comal and San Marcos springs ecosystems. These include two fish [fountain darter (*Etheostoma fonticola*) and San Marcos gambusia (*Gambusia georgei*)], two salamanders [Texas blind salamander (*Eurycea rathbuni*) and San Marcos salamander (*Eurycea nana*)], one plant [Texas wild-rice (*Zizania texana*)], and three invertebrates [Comal Springs dryopid beetle (*Stygoparnus comalensis*), Comal Springs riffle beetle (*Heterelmis comalensis*), and Peck's cave amphipod (*Stygobromus pecki*)]. Of these, only the San Marcos salamander is listed as threatened by the U.S. Fish and Wildlife Service (USFWS 1996); the rest are listed as endangered.

Each of these species has a restricted distribution limited to springs associated with the Edwards Aquifer, and several are found in either Comal Springs or San Marcos Springs but not both. Originally, only the fountain darter was believed to occupy both spring ecosystems, but recent collections of the Comal Springs riffle beetle in Spring Lake at the headwaters of the San Marcos River (Gibson and others 2008) reveal that this species is also found in both ecosystems. Among the other species, San Marcos salamander and Texas wild-rice occur only in the San Marcos River, while the Texas blind salamander is found in the aquifer below San Marcos and nearby springs. Two of the three invertebrates, Comal Springs dryopid beetle and Peck's cave amphipod, are found only in

Comal and nearby springs (that is, Hueco and Fern Bank springs). The San Marcos gambusia is considered extinct as no individuals have been collected since 1982, despite subsequent intensive surveys (USFWS 1996).

Our interpretation of the task

We interpreted the legislative charge to have the following focus:

(1) an emphasis on surface dwelling species that are directly influenced by "spring discharge rates",

(2) springflow will be used as the driving variable in the assessment, with the underlying acknowledgment that there are additional driving variables in these systems, and

(3) spring discharge rate does not simply mean a minimum flow, but as described in EAAESS (2008) represents a flow regime that will be protective of the species.

While the aquifer and its spring systems are closely associated with respect to water quality, water quantity, and thermal conditions, the Edwards Aquifer supports a highly adapted biological assemblage that differs considerably from those species found in the spring ecosystems. It is assumed that the individual species within the subterranean biological assemblage have adapted to seasonal and weather-related variations in groundwater levels. These levels have been known to change rapidly (for example, after a heavy rainfall event), but the water temperatures and water quality within the aquifer remains consistent (McKinney and Sharp 1995). Therefore, it is our interpretation of this task that the focus of this assessment should be on species inhabiting Comal and San Marcos springs that directly rely on spring discharge. For the surface-dwelling species, such as the fountain darter, San Marcos salamander, Texas wild-rice, and Comal Springs riffle beetle, some amount of springflow is necessary for survival and for recovery, and thus a detailed examination of individual species requirements for springflow is presented below. For the aquifer-dwelling listed species such as the Texas blind salamander, Peck's cave amphipod, and Comal Springs dryopid beetle, maintaining the same amount of discharge needed for the protection of surface dwelling species would likely protect these species also; however, potential impacts on these species are considered.

A host of environmental attributes shapes the partitioning of habitat and controls distributions of the various species in the Comal and San Marcos springs ecosystems. These attributes include depth, current velocity, temperature, substrate size and distribution, oxygen and carbon dioxide content, turbidity, and other physical and chemical conditions that combine with biotic influences to control population dynamics of individual species (USFWS 1996). Although each of these parameters is important individually, they are influenced by springflow as a group. As such, springflow will be treated as the driving variable for the discussion, although in instances where an individual environmental attribute (for example, water temperature) influenced by springflow appears to be the driving function, it will be highlighted. Additionally, it is acknowledged that these spring ecosystems are highly dynamic environments which react to many drivers, only one of which is springflow. Other factors influencing the springs and their environment are pumping, meteorology, physiographic modifications, local watershed and recharge zone activities, recreational pressures, and many others. Any one or more of these factors can be of primary importance in influencing spring ecosystem conditions at any point in time. Our interpretation of the charge is that springflow is to be treated as the major driver and we have included assumptions pertaining to these other factors in the report.

We have previously described the importance of springflow to the aquatic ecosystems associated with Comal and San Marcos springs (EAAESS 2008). As described in EAAESS (2008), minimum flows are a necessary part of a flow regime of a given aquatic ecosystem for the protection of its component species, but the maintenance of minimum flows alone is not considered sufficient to maintain a sound ecological environment. The recommendation in EAAESS (2008) was that "minimum springflows are required within the context of a system flow regime for the survival and recovery of each species listed under the Endangered Species Act identified in Section 3.1 of the Edwards Aquifer Recovery Implementation Program Memorandum of Agreement. A system flow regime includes low flows which support the survival of individuals for limited periods of time, normal flows which support reproduction within the population, and higher flows that periodically rejuvenate the system." We continued to build upon that recommendation in the assessment of the legislative charge.

Approach

Our charge was to use the best biological information within the timeframe and resources currently available to assess the species requirements relative to springflow (used interchangeably with "flow", "spring discharge rate", and "total discharge"). This assessment will assist in predicting biological impacts (positive and negative) associated with changes in flow resulting in a flow regime that promotes survival and recovery of the threatened and endangered species of the Comal and San Marcos springs ecosystems.

Species requirements relative to spring discharge rate are very complex and any tool used to assess these relationships has pros and cons. Scientists have used instream flow modeling with species specific life-history information or more ecosystem based approaches, natural flow theory, and professional judgment to try and tease out these answers over the past several decades. We used components of all of these assessment tools to assist the decision with the following understanding of their limitations and applicability. A brief overview of each technique is provided in the following sections. Following the textual overview is a summary of the major data sources and key components that have been used to analyze the species requirements in relation to spring discharge rates at Comal and San Marcos springs. This summary is not meant to be all inclusive as we evaluated many individual research efforts and additional references; however, the summary is representative of the major sources that were directly applied while addressing the legislative charge.

In addition to this substantial body of work that exists on both the Comal and San Marcos rivers, the Edwards Aquifer Recovery Implementation Program contracted with Dr. Thomas Hardy to compile existing data for both systems and to provide analyses of the relationships between flow and habitat for protected species for which sufficient data were available (Hardy 2009). Additionally, Dr. Hardy convened a workgroup consisting of biologists with knowledge of various aspects of the life history of the protected species being evaluated. Dr. Hardy convened facilitated work sessions to identify factors that are important to the survival of the federally listed species and their associated aquatic communities. This information was graphically represented as influence diagrams for each target species and was useful in identifying key parameters and issues that may directly, or indirectly, impact the long-term survival of the species. While an emphasis was placed on flow-dependent variables, the diagrams also provided a good overview of intrinsic and extrinsic factors that are recognized as potential or actual threats that have not been adequately addressed. We have identified many of these issues as recommended studies.

Instream flow modeling

Basically, all commonly used models and methods for setting instream flow requirements have been criticized for their overly simplistic and reductionist treatment of complex ecosystem processes and interactions (Mathur and others 1985, Orth 1987, Gore and Nestler 1988, Arthington and Pusey 1993, Stanford 1994, Castleberry and others 1996, Williams 1996). Although these methods may be useful for assessing protective flow regimes for some individual species, they provide little insight into complex ecosystem dynamics involving multivariate habitat influences, biotic interactions, and complex and varied life histories of riverine species (Richter and others 1996). Management decisions based on information or objectives keyed to a limited number of species and a limited number of their habitat requirements may actually result in undesirable effects on the ecosystem as a whole (Sparks 1992).

Despite the noted shortcomings, researching life history requirements of individual species and modeling projected conditions with respect to protective flow regimes provides vital information. This methodology has been used by both state and federal resource agencies on both the Comal and San Marcos springs systems to address the flow requirements of individual species and the ecosystem overall. The study design and justification of these efforts were well founded and, although somewhat limited by the number of habitat parameters considered, the studies have provided valuable information with respect to specific requirements of individual organisms. An overview of the major instream flow modeling studies used for our legislative charge assessment including key components and references is provided below.

- **Texas Parks and Wildlife Department instream flow study—San Marcos Springs**

KEY COMPONENTS: Ecosystem approach
Habitat modeling—native vegetation including Texas wild-rice
Temperature modeling

REFERENCE:

Saunders, K.S., Mayes, K.B., Jurgensen, T.A., Trungale, J.F., Kleinsasser, L.J., Aziz, K., Fields, J.R., and Moss, R.E., 2000, An evaluation of springflows to support the Upper San Marcos Spring ecosystem, Hays County, Texas: Texas Parks and Wildlife Department.

- **U.S. Fish and Wildlife Service instream flow study—Comal Springs**

KEY COMPONENTS: Species specific approach
Habitat modeling—Fountain darter
Temperature modeling

REFERENCE:

Hardy, T.B., Bartsch, N.R., Stevens, D.K., and Connor, P.J., 2000, Development and application of an instream flow assessment framework for the fountain darter (*Etheostoma fonticola*) in Landa Lake and the Comal River system, U.S. Fish and Wildlife Service.

- **U.S. Fish and Wildlife Service instream flow study—San Marcos Springs**

KEY COMPONENTS: Species specific approach
Habitat modeling—Fountain darter and Texas wild-rice
Temperature modeling

REFERENCE:

Bartsch, N.R., Hardy, T.B., and Connor, P.J., 2000, Development and application of an instream flow assessment framework for the fountain darter (*Etheostoma fonticola*) and Texas wild-rice (*Zizania texana*) in Spring Lake and the San Marcos River System: U.S. Fish and Wildlife Service.

- **Dr. Thomas Hardy "j Charge" technical report—Comal and San Marcos springs**

KEY COMPONENTS: Overview and revision of aspects of U.S. Fish and Wildlife Service's instream flow studies
Species specific approach
Habitat modeling—Fountain darter and Texas wild-rice
Habitat modeling for Comal Springs riffle beetle—spring run surface habitat only

REFERENCE:

Hardy, T.B., 2009, Technical assessments in support of the Edwards Aquifer Science Committee "j" Charge"—Flow regime evaluation for the Comal and San Marcos river systems: Prepared for the River Systems Institute, Texas State University.

Biological monitoring/life history studies

Biological monitoring programs and specific life history studies also provide vital information relative to an evaluation of species requirements for spring discharge rates.

The positive with this type of information is that it is typically based on data from the wild, not models, and thus the level of confidence in the results is greater. The negative is that in order to have sufficient data for analysis, the monitoring must be quite robust and continue for an extended period of time covering a wide range of discharge conditions. Fortunately, two such programs exist relative to Comal and San Marcos springs: the long-term Texas wild-rice annual monitoring conducted by Texas Parks and Wildlife Department and the Edwards Aquifer Authority variable flow monitoring program. Additionally, numerous individual studies have been conducted over the years to evaluate life-history components of the threatened and endangered species both through research activities conducted at the San Marcos National Fish Hatchery and Technology Center and Texas State University among others, and specific laboratory studies supported by the Edwards Aquifer Authority variable flow program, San Marcos National Fish Hatchery and Technology Center, U.S. Fish and Wildlife Service, Texas State University, and others. Although caution must be applied when interpreting laboratory results in the context of the wild, this information can be very informative and was used in our assessment. An overview of the major biological monitoring and life history studies used for the legislative charge assessment including key components and references is provided below.

- **Texas Parks and Wildlife Department Texas wild-rice annual monitoring**

KEY COMPONENTS: Species specific approach
Texas wild-rice spatial distribution and reproduction

REFERENCES:

Poole, J.M., 2002, Historical distribution of Texas wild-rice (*Zizania texana*) from 1989 to 2001: Section 6 Final Report: U.S. Fish and Wildlife Service, Albuquerque, New Mexico.

Texas Parks and Wildlife Department unpublished data 2002–2009.

- **Edwards Aquifer Authority variable flow study—Comprehensive and critical period monitoring program**

KEY COMPONENTS: Ecosystem and species specific approach
Aquatic vegetation, water quality
Fountain darter, Comal Springs riffle beetle, Comal Springs dryopid beetle, Peck's Cave amphipod, San Marcos salamander, and Texas wild-rice

REFERENCES:

BIO-WEST, 2002a–2010a, Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the Comal Springs/River aquatic ecosystem: Final reports to the Edwards Aquifer Authority, San Antonio, Texas.

BIO-WEST, 2002b–2010b, Comprehensive and critical period monitoring program to evaluate the effects of variable flow on biological resources in the San Marcos Springs/River aquatic ecosystem: Final reports to the Edwards Aquifer Authority, San Antonio, Texas.

- **Edwards Aquifer Authority variable flow study—Special studies and laboratory evaluations**

KEY COMPONENTS: Species specific approach
Comal Springs riffle beetle—range evaluation
Comal Springs riffle beetle—flow response
Fountain darter—water temperature, parasite, and reproduction
Native aquatic vegetation, including Texas wild-rice—response to water quality and carbon dioxide concentrations

REFERENCES:

BIO-WEST, 2002c, Comal Springs riffle beetle habitat and population evaluation: Final report to the Edwards Aquifer Authority, San Antonio, Texas, 24 p.

BIO-WEST, 2002d, Comal Springs riffle beetle laboratory evaluation study: evaluation under variable flow conditions: Final report to the Edwards Aquifer Authority, San Antonio, Texas, 27 p.

BIO-WEST, 2004c, Aquatic vegetation laboratory study: Phase 1: Observations of water quality changes and plant growth under various flows, Phase 2: Effects of carbon dioxide level on aquatic plants found in the Comal and San Marcos springs/River Ecosystems: Final report to the Edwards Aquifer Authority, 25 p.

McDonald, D.L., Bonner, T.H., Oborny, E.L., and Brandt, T.M., 2007, Effects of fluctuating temperatures and gill parasites on reproduction of the Fountain Darter, *Etheostoma fonticola*: Journal of Freshwater Ecology, v. 22, no. 2, p. 311–318.

- **Edwards Aquifer Authority variable flow sponsored studies**

KEY COMPONENTS: Species specific approach
Gill parasite response to flow conditions
Fountain darter—water temperature, parasite, and reproduction
Gill parasite response to fountain darter
Invertebrates response to flow variability

REFERENCES:

Bolick, A.E., 2007, The effects of springflow on the abundance of Heterophyid Cercariae in the Comal River, New Braunfels, Texas: M.S. Thesis, Texas State University, 58 p.

Cantu, V., 2003, Spatial and temporal variation of *Centrocestus formosanus* in river water and endangered fountain darters (*Etheostoma fonticola*) in the Comal River, Texas: M.S. Thesis, Texas State University, 58 p.

McDonald, D.L., 2003, Effects of fluctuation temperature and an introduced trematode on reproduction and mortality of *Etheostoma fonticola*: M.S. Thesis, Texas State University, 35 p.

Norris, C.W., 2002, Effects of variable flows on invertebrate drift in Comal Springs, Texas: M.S. Thesis, Southwest Texas State University, San Marcos, Texas, 112 p.

- **National Fish Hatchery and Technology Center sponsored studies**

KEY COMPONENTS: Species specific approach
Fountain darter—water temperature and reproduction

REFERENCES:

Bonner, T.H., Brandt, T.M., Fries, J.N., and Whiteside, B.G., 1998, Effects of temperature on egg production and early life stages of the fountain darter: Transactions of the American Fisheries Society, v. 127, p. 971–978.

Brandt, T.M., Graves, K.G., Berkhouse, C.S., Simon, T.P., and Whiteside, B.G., 1993, Laboratory spawning and rearing of the endangered fountain darter: Progressive Fish-Culturist, v. 55, p. 149–156.

- **Other studies**

KEY COMPONENTS: Species specific approach
Texas wild-rice—spatial distribution, habitat characterization, genetics, life history and reproductive strategies, transplantation

REFERENCES:

Beaty, H.E., 1975, Texas wild-rice: Texas Horticulturist, v. 2, p. 9–11.

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Natural flow theory

Another approach commonly employed to evaluate protective flow regimes is the Natural Flow Paradigm. At the extreme interpretation, this theory implies that the perpetuation of the native aquatic biodiversity and ecosystem integrity depends upon maintaining or restoring some semblance of natural flow variability (Minckley and Meffe 1987, Sparks 1992, Kinsolving and Bain 1993, Walker and Thoms 1993, Richter and others 1996). The probability of survival of native species and communities is reduced if the environment is altered outside of the range of its natural variability (Resh and others 1988, Swanson and others 1993).

In instances where natural flow variability can be maintained or restored (that is, by modifying a single parameter and restoring the ecosystem to pre-human contact), benefits to the native communities can be substantial. However, this is an unrealistic scenario in most cases, and it is implausible in the Comal and San Marcos springs ecosystems. These two spring ecosystems have been altered by humankind for at least 150 years. Alterations have included aquifer pumping, dam placement, extensive channelization, high recreational demands, extensive development in the riparian zone as well as the watershed, stormwater runoff, point and nonpoint source pollution, exotic species introduction (including parasites on native species), and others. These impacts have played a major role in the makeup and interactions of the residing aquatic communities over the past 150 years.

As such, the evaluation of the recorded hydrograph at both springs was used to some extent in our assessment. The premise to the flow analysis presented herein is that maintaining a flow regime similar to the recorded hydrograph, taking into consideration species-specific biological needs, might provide a valid approach for maintaining or enhancing endangered and threatened species in the Comal and San Marcos springs ecosystems. With the exception of the San Marcos gambusia, each of these species is currently present in its respective spring ecosystem. This indicates persistence through the drought of record for all species (though likely extinct now, the San Marcos gambusia was sampled subsequent to the drought of record) with the major exception of the fountain darter at Comal Springs. The fountain darter at Comal Springs was extirpated during the drought of the 1950s and reintroduced from San Marcos populations in the mid-1970s (Schenck and Whiteside 1976). One assumption that has been debated is that these species will continue to survive if flows do not go lower than historically recorded. Because of the changed conditions in these systems since the 1950s, we determined that a conservative strategy should be the goal at historically low flows. For example, while it is impossible to state unequivocally that the stoppage of springflow at Comal Springs was the sole cause for the disappearance of the fountain darter in that system in the 1950s or that Texas wild-rice survived in the San Marcos River without human intervention, there is consensus that any period of zero flow or flows below what was historically observed would greatly increase the risk for reduced survival of the surface dwelling species. Therefore, our assessment evaluates the past hydrological records within the context of being protective when faced with the uncertainties surrounding risk at the lowest historical flows. The hydrology used for this assessment was taken directly from the U.S. Geological Survey gage data for both the Comal and San Marcos rivers.

Professional judgment

Our membership consists of dedicated scientists that, in some cases, have spent much of their careers working with the threatened and endangered species in these springs' ecosystems. As such, all analysis conducted has been reviewed and interpreted within the context of this institutional knowledge base. Based on that review, professional judgment is inherently embedded in our decisions. We have used the best available science for the determination of recommendations which in some cases is a direct result of professional judgment at this time.

Analysis, assumptions, and recommendations

Impacts to the flora and fauna within the Comal and San Marcos springs ecosystems are directly related to the amount and quality of occupied and potential habitat that is available to each species. The dynamic nature of stream ecosystems dictates that the amount of habitat available to each species will fluctuate in response to a number of variables, one of the most significant being streamflow. Instream flow must be sufficient to meet the necessary requirements of the species dependant on the stream system. Periods of drought pose risks to several species of concern in both the San Marcos and Comal springs systems because of the resulting periods of low-flow and probable loss of occupied and potential habitat. Although water quantity is a major factor determining such habitat for these species, other requirements include adequate water quality; preferred vegetation composition; low incidence of competitive, non-native species; and other species-specific conditions.

Flow regime

We chose to address the legislative charge within the context of a flow regime for the protection of all threatened and endangered species as well as the integrity of the ecosystem. In order to ensure the "survival and recovery of the species in the wild", we determined that the suggested flow regime must sustain an overall trend of maintaining or increasing the populations of the threatened and endangered species. This by definition means that conditions cannot go beyond thresholds that would not allow for the survival and recovery of any of these species in their natural environment.

Based on a comprehensive review of the best available science for the threatened and endangered species and professional judgment coupled with the underpinnings of instream flow science and, to a limited extent, natural flow theory, we selected the following components of the flow regime for evaluation:

- long-term average flow,
- minimum 6-month average flow, and
- minimum 1-month average flow with an embedded minimum flow requirement.

The long-term average provides high quality habitat conditions throughout most of the spatial distribution of the species evaluated. Maintaining this condition on average over a long time period will provide habitat conditions necessary for survival and recruitment under limited to no stress. The most important component of the long-term average is that, by having this requirement, the system would not be able to have repeated 6-month or 1-month events also prescribed in the flow regime. As such, the lower flow criteria were developed with the understanding that they would rarely be experienced in the future.

The minimum 6-month average flow was incorporated into the flow regime to provide a safeguard from extremely low flow events. The 6-month flow is sufficient to maintain populations, albeit declining, through the short term. Under these flow conditions, it is assumed that there would be reduced habitat availability and populations of target species would be declining but would not be reduced to critically low numbers. The reproductive capability of the target species will be maintained, although perhaps at a reduced level. This discharge condition is one whose goal is to be protective of occupied aquatic habitat within the higher quality habitat areas of the system. The 6-month average is interpreted to be a rare hydrologic event.

The minimum 1-month average flow was incorporated into the flow regime to provide a threshold condition below which, for ecological reasons, the system should not fall. Should the system fall below this threshold, the probability of severe ecological impact considerably increases. The minimum 1-month average flow incorporates a minimum flow condition within the requirement. This threshold condition was included because it is widely acknowledged in the scientific literature that ecological systems are naturally defined by extreme events on both the high- and low-flow end of the spectrum. Having occasional extremes supports populations of native species that have evolved life history strategies in response to the natural flow regime (Poff and Allan 1995, Poff and others 1997, Bunn and Arthington 2002). Experiencing these natural extremes puts stress on non-native species and promotes the survival of the native flora and faunal community (Poff and Allan 1995, Poff and others 1997, Bunn and Arthington 2002). However, the frequency and duration of these extreme events are of critical importance and, if extended beyond the natural tendency of the system, can be detrimental to the resident ecological community. As such, the minimum 1-month average is only supported within the context of our recommended flow regime. It is important to understand that during this short time period, limited habitat would be supported within the system. However, sufficient habitat and water quality conditions would be maintained to ensure continued existence of the species in the wild. This may mean that the temperature is too warm for successful reproduction of fountain darters throughout most of the system during this month. However, the temperature within the entire system has been modeled to show that it would likely not be lethal to any of the endangered species. The minimum 1-month average flow incorporates a minimum daily flow condition within the requirement.

We reviewed and considered two additional flow regime aspects (high flow pulses and seasonality). We acknowledge that high flow pulses are very important in both the Comal and San Marcos springs ecosystems to flush the system, remove vegetation mats, move sediment, and occasionally scour out vegetation. Impacts to habitat or the species themselves (in the case of Texas wild-rice) often occur during these events but, following the events, habitat rejuvenation usually occurs, providing refreshed habitat conditions for the species. Texas wild-rice sometimes rebounds from these events. However, the 1998 flood scoured the lower section of the San Marcos River below the Interstate 35 bridge, removing 20 percent of the total areal coverage. Over 10 years later, Texas wild-rice has still not recovered in this area. We evaluated high flow pulses within the context of each of the threatened and endangered species and made the determination that as these events are driven by precipitation, they would occur naturally.

Instream flow studies often embed a seasonality component within a proposed flow regime to attempt to mimic the normal patterns of climatology in the region. We reviewed this aspect in the consideration of the flow regime and determined that, because of the erratic climate of Central Texas, more or less stable nature of the spring systems and the reproductive potential of the species being considered, this component would be taken care of via natural recharge conditions and the variable flow conditions embedded in the flow regime recommendation which should address pumping withdrawals.

Species response to flow

We reviewed information from the aforementioned studies and direct observation to examine the influence of flow on species response. As previously stated, the best available science for the threatened and endangered species and their ecosystem was reviewed to assist in the determination of species requirements that could be incorporated within each of the proposed flow components. We also reviewed information from a more holistic approach using the aforementioned studies and observations to indirectly try and establish flow requirements deemed protective of the species via the habitat conditions that those flows are predicted to achieve.

The following section provides an overview of the distribution and habitat requirements of the species within each spring system. Additionally, this section provides an overview of our assessment which was conducted within the context of the flow regime components discussed above. When evaluating specific flow requirements for the threatened and endangered species we first started by (1) examining the overall condition of the system as we know it today, (2) followed by examining the available information to assess when impacts to a given species might first be evident, and (3) concluding with an evaluation of potential flow-related thresholds for the species. Throughout our assessment, we started with actual monitoring data when available, proceeded to modeling results when available, considered the historical hydrology, and finally confirmed or rejected based on professional judgment. Separate analysis, assumptions, and recommendations are provided for the Comal and San Marcos springs ecosystems.

Comal Springs analysis and assumptions

- Fountain darter (*Etheostoma fonticola*)

Fountain darters were collected for the first time in the Comal River in 1891. The last collection of fountain darters in the Comal River before its apparent extirpation was 1954. Whiteside and Schenck released 457 adult fountain darters, collected from the San Marcos River (mostly from below Rio Vista Dam), into the Comal Springs system from February 1975 through March 1976. A reproducing population has been reestablished and is now found throughout the entire Comal aquatic ecosystem from Landa Lake to the vicinity of the Comal/Guadalupe River confluence.

Habitat requirements for the fountain darter are dominated by water quantity, quality, water temperature, and vegetation composition attributes (Schenck and Whiteside 1976, Bonner and others 1998, Linam and others 1993). Biological monitoring conducted over the past nine years (BIO-WEST 2002a-2010a) has focused on four reaches of the Comal Springs system: Upper Spring Run (upstream most portion of the system to Spring Island), Landa Lake (Spring Island to the outflow to Old and New channels), Old Channel, and New Channel (Figure 1). Data collected via the Edwards Aquifer Authority variable flow study suggest that the highest quality fountain darter habitat at all flows in the Comal Springs system is in Landa Lake. Landa Lake maintains a diverse aquatic vegetation community, supports year round reproduction of fountain darters, and exhibits exceptional water quality conditions. These factors contribute to the continuance of large populations of fountain darters within Landa Lake. Prior to 2004, the old channel of the Comal River also supported similar conditions. However, the reconstruction of a new culvert system on the Old Channel coupled with an extended period of high flow conditions (facilitated by the new culvert system) led to a scouring of the native filamentous algae from this reach, which was subsequently repopulated with mostly non-native vegetation. As a result, habitat quality and resulting population numbers have both decreased within the Old Channel. Fountain darter reproduction in recent times in the Old Channel has shifted to primarily seasonal (spring time) peaks, evidence of lesser quality habitat conditions.

The Upper Spring Run and New Channel in the Comal River (Figure 1) have variable habitat conditions for fountain darters relative to spring discharge (BIO-WEST 2002a–2010a). The Upper Spring Run maintains high quality fountain darter habitat during moderate to higher flow (greater than 200 cubic feet per second total Comal Springs system discharge) conditions because of the expansion of bryophytes during these periods and subsequent use by fountain darters. Periodic pulses scour out the bryophytes and make this reach less suitable for darters. Additionally, lower flows (less than 200 cubic feet per second total Comal Springs system discharge) limit the amount of spring upwelling in this reach, which limits the amount of carbon dioxide (CO_2) in the water column. This limitation also causes a decline the in the CO_2 obligate bryophytes leading to lesser quality habitat for fountain darters. The New Channel reach acts somewhat in an opposite fashion to the Upper Spring Run reach. The New Channel supports higher quality habitat at below average flow (~250 cubic feet per second total Comal Springs system discharge) conditions because at these flows the establishment of aquatic

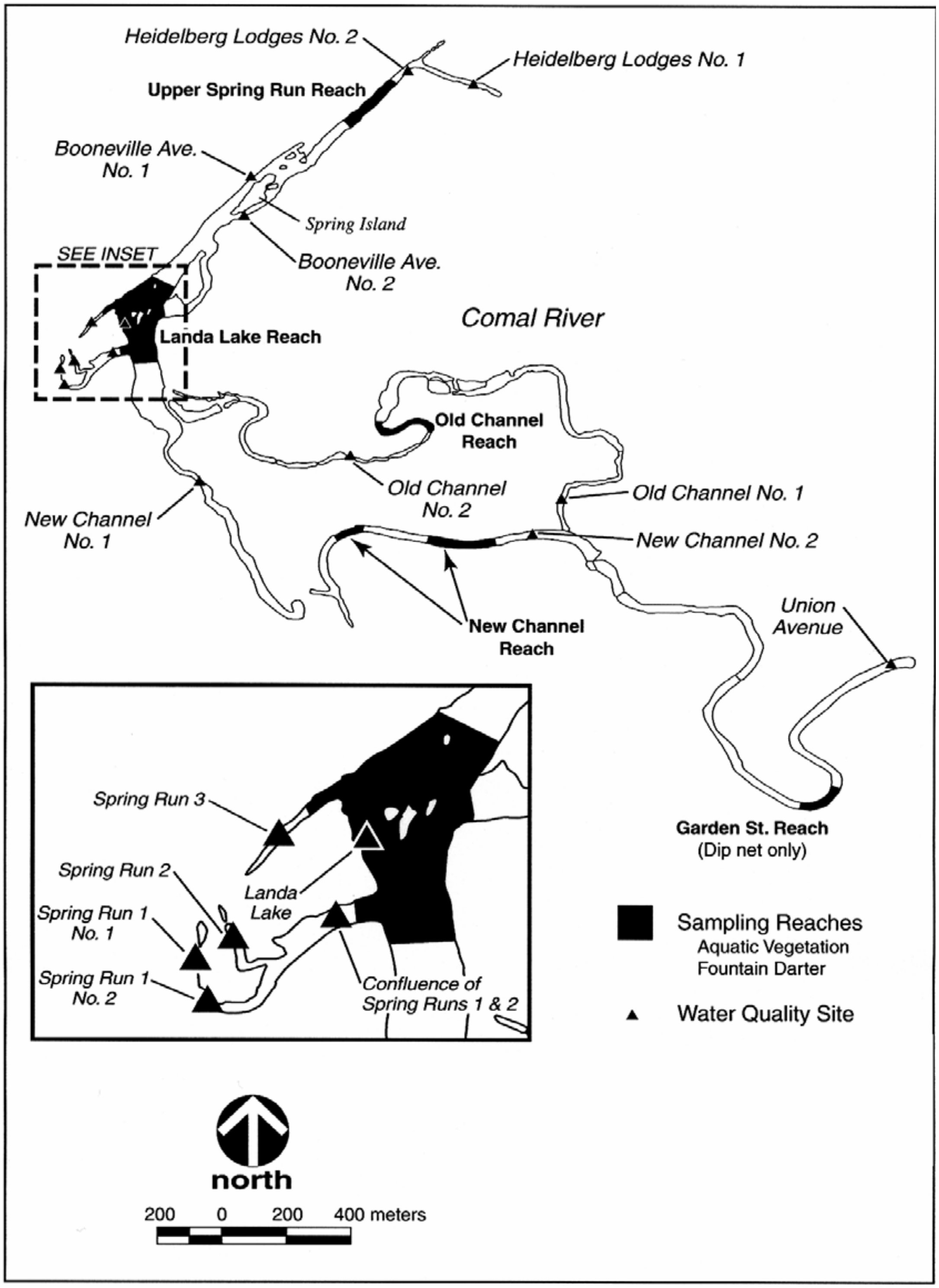


Figure 1: Comal River water quality and biological sampling areas for the Edwards Aquifer Authority variable flow study (BIO-WEST 2009a).

vegetation is possible throughout much of the reach. More aquatic vegetation leads to higher quality fountain darter habitat in the New Channel. Total Comal Springs system discharge greater than 350 cubic feet per second or high flow pulses cause a combination of factors that lead to lesser quality habitat in this reach. First, high flow pulses or sustained high flows scour out the aquatic vegetation in this highly altered reach. Secondly, higher flow conditions (greater depths) coupled with recreational use (which causes more turbidity) collectively cause less light penetration to sustain aquatic vegetation growth. Ultimately, these conditions lead to reductions in aquatic vegetation and quality of fountain darter habitat.

Over the past nine years of monitoring (BIO-WEST 2002a–2010a), total Comal Springs system discharge greater than 225 cubic feet per second has been shown to provide high quality fountain darter habitat throughout most of its range, not considering high flow events. Considerable habitat alteration has occurred several times over the years as a result of high flow pulses (heavy localized rain events) scouring out extensive areas of aquatic vegetation. These time periods are generally short-lived (hours to days) and the aquatic vegetation typically recovered and/or expanded in one to six months. BIO-WEST (2007c) has concluded that in most cases these represent flow events that have direct impacts on fountain darter habitat but only on a temporary time scale. One exception to date was the non-native vegetation that replaced native vegetation after high flow conditions in the Old Channel resulting in lower quality habitat. During the nine years of monitoring at Comal Springs, springflow has been documented to cease horizontal flow over the concrete wall at Spring Run 5 (Upper Spring Run reach, near Heidelburg Lodge 2; Figure 1) at approximately 150 cubic feet per second total discharge in the Comal Springs system. At this total discharge level, the flow through the Upper Spring Run reach becomes limited. This, coupled with warm weather conditions present in the summer, leads to the development of extensive mats of green algae (this is not the filamentous algae previously described as high quality habitat). Under those conditions, fountain darter habitat quality related to discharge was reduced, thus indicating a good starting point for discussion as when impact to fountain darter habitat starts to occur in the Comal Springs system. At 150 cubic feet per second total system discharge, conditions observed (albeit for only a short period of time) in Landa Lake and subsequent downstream habitat in the Comal Springs system indicated no signs of aquatic habitat reductions.

Another example of a direct flow-related impact to fountain darter habitat on the Comal Springs system happened following the reconstruction of the culvert system on the Old Channel. This reconstruction, coupled with extended periods of wet weather, led to higher than average flow (greater than 80 cubic feet per second Old Channel discharge) conditions in the Old Channel that resulted in considerable alteration in fountain darter habitat. Exotic vegetation has subsequently colonized areas of the Old Channel that previously maintained filamentous algae and other native vegetation, which has caused this section of river to not return to the pre-impacted condition. A detailed description of this impact is presented in BIO-WEST (2007c). Prior to the recent conditions described for the Old Channel, it supported higher populations of fountain darters (Linam 1993, Hardy and others 2000, BIO-WEST 2002a, BIO-WEST 2003a).

The U.S. Fish and Wildlife Service, in conjunction with Utah State University, conducted a study in the early 1990s to determine the amount of habitat available to the fountain darter under various streamflow conditions in the Comal Springs ecosystem. The designation of suitable habitat included the presence of water (wetted perimeter), preferred vegetation composition, and water temperature (Hardy and others 2000). This is the same study reviewed and presented in the Hardy (2009) report.

The results presented in the Hardy and others (2000) study indicate that a 50 percent decrease in discharge (from 300 cubic feet per second to 150 cubic feet per second) has very little impact on predicted fountain darter habitat (99.2 percent of the suitable habitat is maintained) (Table 1). Available habitat remains relatively high (>90 percent overall) as flow is reduced to 100 cubic feet per second. The spring runs are the only areas where substantial reductions (more than 40 percent, Table 1 (b)) begin to occur at 100 cubic feet per second total discharge.

In all probability, however, the impact of habitat loss in the spring runs is minimal for the fountain darter; fountain darters are rarely collected or observed within the spring runs, and modeling predicts that even at a flow of 300 cubic feet per second, suitable spring run habitat comprises only 1.3 percent of the total calculated area (Table 1(c)).

Based on the modeling efforts of Utah State University and the U.S. Fish and Wildlife Service, when total springflow drops to 60 cubic feet per second and 30 cubic feet per second in the Comal Springs system, about 75 percent and 60 percent, respectively, of total darter habitat remains (Table 1(b)). The majority of this habitat loss is due to thermal conditions that cause a reduction in the survival of larval fountain darters (Figure 2). Temperature remains a variable of primary importance because individuals farthest downstream periodically experience temperatures that reach or exceed 77º F (25º C). This is the value at which research indicates spawning success and juvenile growth rates of fountain darters are reduced (Brandt and others 1993, Bonner and others 1998, McDonald and others 2007). Although spawning success and larval growth begin to decline at this temperature, it is a conservative upper temperature limit; the critical thermal maximum for the fountain darter is 94.6º F (34.8º C) (Brandt and others 1993). Figure 2 shows that at 60 cubic feet per second only the middle portion of the Upper Spring Run reach and lower portion of the Old Channel provide unsuitable temperatures for fountain darters. At 30 cubic feet per second, the unsuitable area increases, but no affects are predicted in the upper portion of the Old Channel or within Landa Lake. Modeled temperature conditions throughout the entire Comal Springs system remain suitable for some fountain darter survival at both these flow conditions.

The Hardy and others (2000) findings also suggest that 40 cubic feet per second should be diverted into the Old Channel reach whenever total Comal Springs springflow allows. The weighted usable area calculated in that report doubles at flows between 30 cubic feet per second and 40 cubic feet per second in the Old Channel.

A major factor in the Comal Springs system is the continued presence of an Asian trematode, *Centrocestus formosanus*. This parasite was first discovered on fountain darters in the Comal River during October 1996. The parasite attaches to the fish’s gill filaments causing extensive gill tissue proliferation and damage (Mitchell and others

Table 1: (a) Predicted area of suitable fountain darter habitat ($x10^3$) at various levels of total springflow from Comal Springs, (b) suitable habitat that remains as a percent of the segment, and (c) suitable habitat remaining as a percent of the total area in the system.

(a) Predicted Fountain Darter Habitat [a]

Total Springflow Rate (cfs)	Landa Lake (ft^2)	New Channel (ft^2)	Main Spring Runs 1-3 (ft^2)	Old Channel (ft^2)	Total Area (ft^2)
300	811.9	210.8	18.0	344.2	1384.9
150	798.0	218.9	13.1	344.1	1374.1
100	680.6	220.4	10.7	341.3	1253.0
60	544.9	223.4	6.5	267.3	1042.0
30	524.3	178.9	2.9	125.4	831.5

(b) Percent of Segment [a]

Total Springflow Rate (cfs)	Landa Lake	New Channel	Main Spring Runs 1-3	Old Channel	Total Area
300	100.0	100.0	100.0	100.0	100.0
150	98.2	103.8	72.8	100.0	99.2
100	83.8	104.6	59.4	99.2	90.5
60	67.1	106.0	36.1	77.7	75.2
30	64.6	84.9	16.1	36.4	60.0

(c) Percent of Total Area [a]

Total Springflow Rate (cfs)	Landa Lake	New Channel	Main Spring Runs 1-3	Old Channel	Total Area
300	58.6	15.2	1.3	21.9	100.0
150	57.6	15.8	0.9	24.8	99.2
100	49.1	15.9	0.8	24.6	90.5
60	39.3	16.1	0.5	19.3	75.2
30	37.9	12.9	0.2	9.1	60.0

Source: USFWS draft report (2000).

[a] For these calculations, a total springflow level of 60 cubic feet per second directs 50 cubic feet per second into the New Channel and 10 cubic feet per second into the Old Channel, while a total springflow level of 30 cubic feet per second directs 25 cubic feet per second into the New Channel and 5 cubic feet per second into the Old Channel. Cfs = cubic feet per second; ft^2 = square feet.

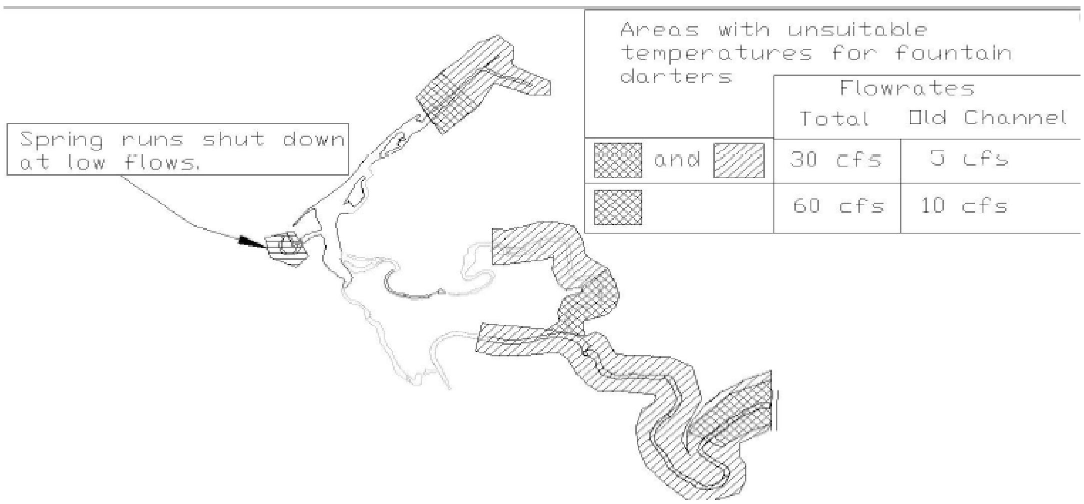


Figure 2: Predicted areas of unsuitable temperatures ("unsuitable" refers to a reduction in the spawning success of fountain darters and declines in larval growth) for fountain darters at a total discharge of 60 cfs and 30 cfs in the Comal Springs system (Hardy 2009) (cfs = cubic feet per second).

2000) with mortality in the wild being reported following the discovery in 1996 (Thomas Brandt, personal communication). A non-native snail, *Melanoides tuberculatus*, that has been in Central Texas since 1964 (Mitchell and others 2005) has been confirmed as its Central Texas first intermediate host (Mitchell and others 2000). Upon emergence from its egg, *Centrocestus formosanus* begins life as a few swimming larva that penetrates its first intermediate host, a snail. Within the first intermediate host the trematode will encyst, then metamorphose into free-swimming cercaria that emerge from the snail. The cercaria will then seek out a fish to serve as a secondary intermediate host. Various species of fish-eating waterfowl serve as the definitive host. Parasite monitoring via examination of presence on fountain darter gills to determine *Centrocestus formosanus* levels in the Comal and San Marcos rivers has been ongoing since the late 1990s by the U.S. Fish and Wildlife Service, Texas State University, and BIO-WEST, (partially funded by the Edwards Aquifer Authority). Brandt (U.S. Fish and Wildlife Service) speculates the parasite became well established in the Comal River in 1997, as 100 percent of collected fish were infected with an average of 100 cysts per fish. The parasite probably increased to fountain darter life-threatening levels in the Comal River during 1998 because dropping or slowly rising springflows between 1994 and 1998 allowed *Melanoides tuberculatus* numbers to build (Tom Brandt, personal communication). *Melanoides tuberculatus* does well in nutrient-rich, flowing environments, that are not subjected to spates (rapidly rising water levels—flash floods) (Giovanelli and others 2005). Brandt speculates the parasite numbers in the Comal River dropped during the 2000s because of floods during mid-1998, mid-2000, mid-2002, and above normal flows during 2003, 2004, and most of 2005. The drought beginning in 2007 allowed the numbers of *Melanoides tuberculatus* and *Centrocestus formosanus* to start building in both rivers (Tom Brandt, personal communication).

Bolick (2007) conducted her masters project in coordination with U.S. Fish and Wildlife Service, Texas State University, and BIO-WEST to evaluate the effect of the gill parasite with respect to flow in the Comal Springs system. Bolick (2007) concluded that neither total stream discharge (measured at the U.S. Geological Survey gage) nor wading discharge (measured at each transect when collections were taken) were found to be a useful predictor of cercarial abundance during the flow conditions (204 cubic feet per second to 441 cubic feet per second) present during her efforts. Cercarial abundance differed between sites and increased with distance downstream. Downstream sites received cercarial drift from their immediate area, as well as areas upstream. Abundance differed in relation to sun intensity as well, with higher cercarial counts on sunny days rather than cloudy days. Season also seemed to influence abundance of cercaria with the period from late fall to early spring having the highest abundance of the parasite. In order to reduce confounding effects of site, sunlight intensity, and season, the dataset was restricted to include only samples from the upstream-most site (Houston Street) on sunny days from late fall to late spring. However, even after removing these confounding effects, all measured variables (including moderate to high flows) were still found to be poor predictors of cercarial abundance. Results suggest that fountain darter populations in the Comal River will not experience increased infection pressures from *Centrocestus formosanus* within the range of total Comal Springs system discharges (204 to 441 cubic feet per second) observed during this study (Bolick 2007). The mean cross-section discharges at the three study sites over the study period ranged from 14 cubic feet per second (Upper Spring Run reach) to 50 cubic feet per second (Old Channel). Should moderate flow exist for several years without any flash floods followed by low flows due to drought conditions, it is anticipated that cercarial abundance may increase to a more severe level (Tom Brandt, personal communication).

Additional concerns include the presence of exotic species, water quality degradation, and recreation which all have consequences on the fountain darter populations in the Comal Springs system. Studies have shown that many fishes (especially small fish) have very similar food habitats (Hubbs and others 1978). If non-native species are added to the aquatic ecosystems, greater competition or overlap among species is possible. These non-native species may be able to acquire resources with greater efficiency than native species (USFWS 1984). Suckermouth catfishes (*Loricariidae*) are a non-native fish species that has become established in the waters of Texas including the Comal and San Marcos rivers (Howells 2005). In particular, suckermouth catfishes prefer to feed on periphyton and algae (Hoover and others 2006). The fountain darter lays eggs on algae and is believed to be threatened by the loss of spawning habitat and possibly egg predation. There is some concern that excessive numbers of suckermouth catfishes could cause direct (potential displacement) and indirect effects (disruption of food supply) to the fountain darter in the Comal and San Marcos rivers.

A non-native gastropod (giant ramshorn snail [*Marisa cornuarietis*]) also poses a threat to the Comal Springs ecosystem. The giant ramshorn snail, a species in the aquarium trade, was first discovered in Landa Lake in 1984 (McKinney and Sharp 1995). This snail grazes on aquatic plants and in the 1990s played a major role in reducing plant biomass in Landa Lake. This snail prefers clear streams and pools with temperatures of at least 66° F (19° C). When exposed to lower temperatures, the snails withdraw into their shells and only survive for short periods. The warmest temperature that the giant ramshorn snail can withstand is 102° F (39° C). Although the population has diminished since the mid-1990s, the potential for future alteration of plant communities in these two ecosystems remains and could affect endangered species (McKinney and Sharp 1995, BIO-WEST 2007c). The strong preference of fountain darters for aquatic vegetation highlights the concern posed by the grazing activities of the giant ramshorn snail (BIO-WEST 2004a). Regardless of present numbers, this species needs to be monitored closely to assure that it does not significantly reduce the available fountain darter habitat.

Water quality encompasses a range of variables that can potentially impact fountain darters and other aquatic life if altered too far from the historic range to which the stream inhabitants have become accustomed. Most potential water quality problems are linked to nonpoint source pollution such as fertilizer runoff and chemicals washed in from adjacent streets; however, spills and leaks from industrial and municipal infrastructure along the heavily developed shorelines of the Comal River also present hazards. The potential for accidents and nonpoint source pollution to affect the organisms in the Comal River may be exacerbated during below average flows since chemicals and nutrients would be less diluted when a lower volume of water is present.

Recreational pressure is another concern regarding the protection of fountain darter habitat. Qualitative observations of increasing recreational activity have been noted for the Comal Springs system. However, on the Comal Springs system, the bulk of the recreational activity is fairly isolated to the New Channel, portions of the Old Channel and below the confluence of the Old and New channels. Being at the downstream extent of the Comal River, these areas support the lowest quality habitat for fountain darters and thus, recreation, as long as it does not increase in the higher quality habitat, is not nearly the concern as for the San Marcos River.

- Comal Springs riffle beetle (*Heterelmis comalensis*)

Comal Springs riffle beetles (*Heterelmis comalensis*) are found in areas where springflow is evident around Landa Lake in the Comal River (Figure 3). This includes spring runs 1, 2, 3, and 6 (Bosse and others 1988, Bowles and others 2002, Gibson and others 2008) and spring openings associated with shoreline habitat, upwelling areas surrounding Pecan Island, and deeper water within the lake (BIO-WEST 2002c, Gibson and others 2008). Bowles and others (2002) suggest that the primary requirements for Comal Springs riffle beetles relate to high-quality springflow and maintenance of physical habitat, and BIO-WEST (2004a–2010a) has documented the affinity for clear flowing water either horizontally or via upwelling.

One of the primary flow-related questions is associated with the survival of the species during the drought of the 1950s. No information is available to indicate how the species survived this period of prolonged drought and approximately five months of zero flow. However, recent discoveries of individuals in the lake suggest that individuals were likely in areas that maintained surface water during that period. Hypotheses regarding their survival include the persistence of a few individuals in Landa Lake and subsequent redistribution to spring run habitats, a localized retreat into the spring heads or hyporheos (between particles of the stream bottom substrate), or aestivation carried out in a specific life stage (Bowles and others 2002, BIO-WEST 2002d).

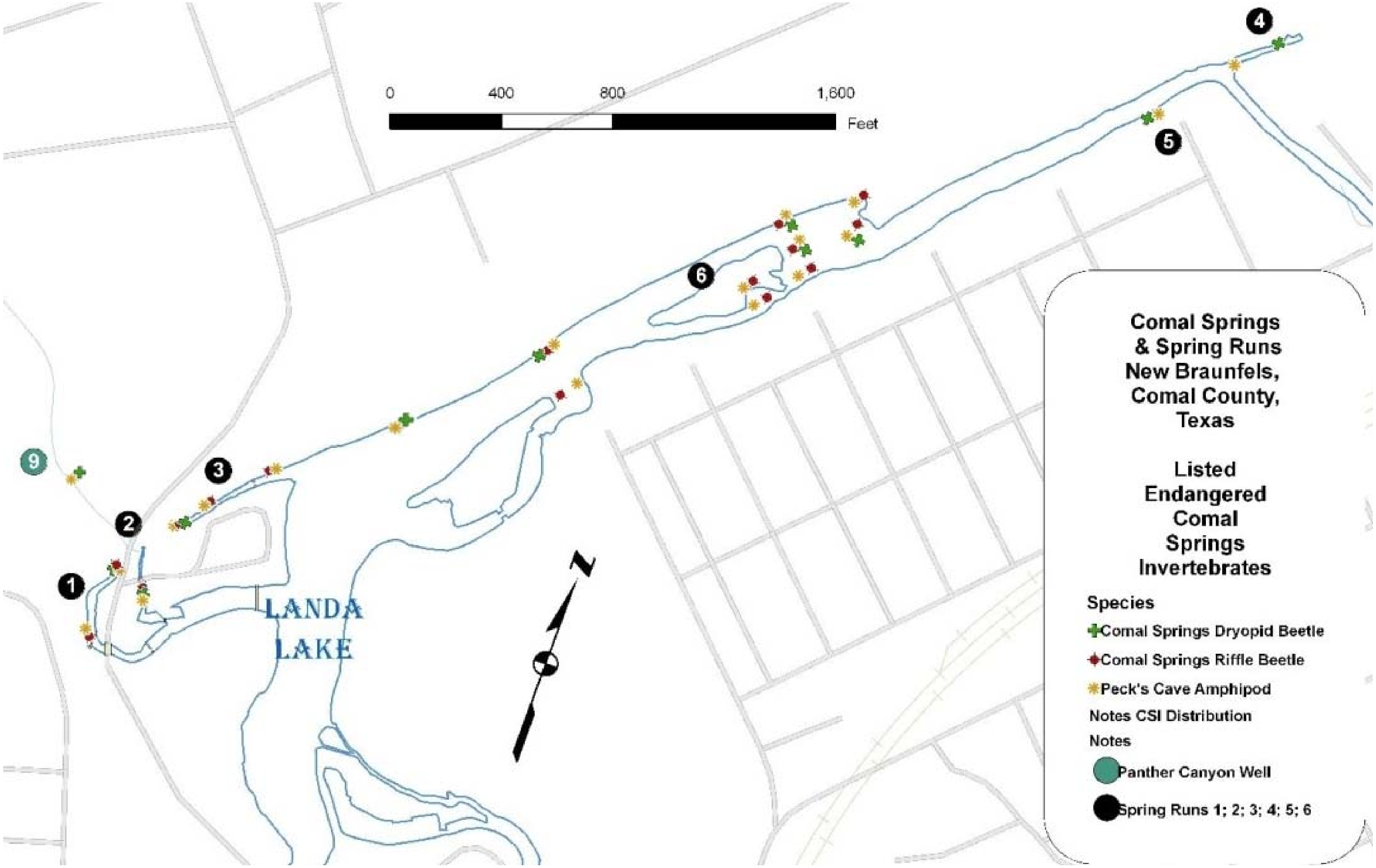


Figure 3: Collection locations of Comal Springs threatened and endangered invertebrates during the Edwards Aquifer Authority variable flow study.

One of the hypotheses, the use of the hyporheos during drought conditions, was tested under laboratory conditions. The findings suggest that Comal Springs riffle beetles associate strongly with springflow and move down into the substrate in response to upwelling (BIO-WEST 2002d). The study showed Comal Springs riffle beetle response to a shift in springflow direction and intensity (that is, individuals tended to move downward toward the source of water flow). This would lend credence to the hypothesis that the species retreats into spring heads during drought and possibly at other times. Although no published document has indicated that members of the genus *Heterelmis* use the hyporheos at times other than during drought, Poole and Stewart (1976) found that members of another riffle beetle genus, *Stenelmis*, were the most prevalent insects recovered from deeper strata in the Brazos River, Texas. This occurred despite the fact that no springs allowed for water circulation (that is, replenishment of oxygen, removal of waste products, etc.). In the spring-fed conditions within the range of the Comal Springs riffle beetle, factors such as low dissolved oxygen that typically limit vertical stratification in the hyporheos would be less prohibitive. This behavior in a similar taxon and research suggesting movement toward the source of water flow (downward) raises uncertainty about the proportion of the population that may be found below the upper layer of rocks that have been primarily sampled for the species.

To evaluate the surface flow or wetted area in the spring runs, Hardy (2009) modeled the three main spring runs of Landa Lake. The potentially suitable habitat for the Comal Springs riffle beetle was restricted to the main spring runs in water depths ranging from 0.02 to 2.0 feet and velocities of up to 2.0 feet per second. The simulated model runs for the surface area in the spring runs is presented in Figure 4.

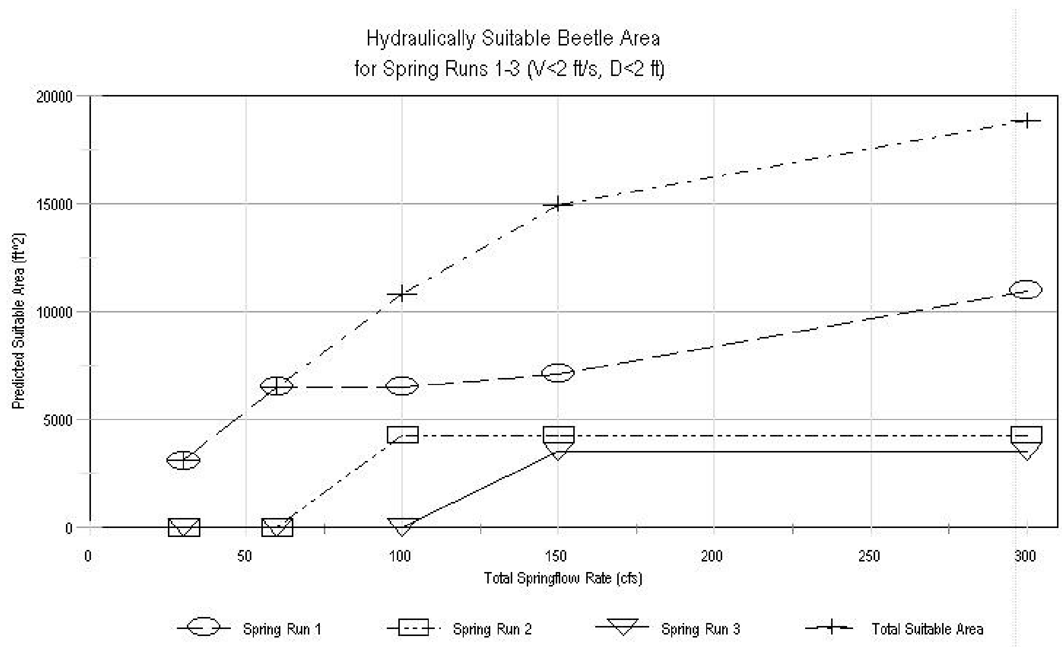


Figure 4: Simulated Comal Springs riffle beetle surface habitat in main spring runs at Comal Springs based on depth and velocity criteria (Hardy 2009).

Figure 4 shows approximately a 30 percent reduction in Comal Springs riffle beetle surface habitat within Spring Run 1 from 300 cubic feet per second to 150 cubic feet per second total discharge with no reduction in surface habitat for spring runs 2 or 3 at the same flow reduction. There is only a slight reduction predicted in surface habitat in Spring Run 1 going from 150 cubic feet per second to 100 cubic feet per second or 60 cubic feet per second total discharge. There is no reduction in surface habitat predicted at Spring Run 2 at 100 cubic feet per second. However, elimination of surface habitat is predicted at 100 cubic feet per second at Spring Run 3 and 60 cubic feet per second for Spring Run 2. Overall, there is approximately a 70 percent predicted reduction in Comal Springs riffle beetle surface habitat within Spring Run 1 from 300 cubic feet per second to 30 cubic feet per second total discharge. There is no surface habitat predicted for spring runs 2 or 3 at 30 cubic feet per second total discharge.

Although the modeling of surface habitat addresses changing conditions within the three main spring runs, it is important to reiterate that approximately 50 percent of Comal Springs riffle beetle habitat exists within Landa Lake (Figure 3) and was not considered in this modeling exercise. Additionally, the importance of subsurface habitat was not considered in this modeling exercise. Because specific springflow requirements cannot be accurately defined with these stated limitations in modeling, conservative management dictates that historic conditions should not be approached or exceeded. Bowles and others (2002) was unable to determine the appropriateness of current take and jeopardy limits set by the U.S. Fish and Wildlife Service but suggested that the springs should not be allowed to stop flowing for extended periods or become permanently dry. Hardy (2009) recommends that, “the most conservative approach to long term protection of this species would be to maintain surface flows in the various spring runs of Landa Lake”. Additional research is needed to assess the extent of population-level effects under low flows and to identify potential mechanisms for coping with drought that may have contributed to survival during the drought of record. However, until any such mechanisms are identified, it is assumed that conditions experienced in the drought of record were harmful to the species and exposing the population to zero flow for any longer than previously experienced would incur a high probability of detrimental impacts. This is supported by Gonzales (2008) who suggests a divergence in genetic diversity between the spring runs and Landa Lake populations of Comal Springs riffle beetles, potentially related to low flow extremes. It is also recognized that hydrological conditions experienced since the drought of the 1950s did not cause extirpation of the species as they continue to exist in the springs (although the species was not described until after the 1950s, it is assumed that it was present before or during the 1950s).

- Comal Springs dryopid beetle (*Stygoparnus comalensis*)

Very little information is available for the Comal Springs dryopid beetle (*Stygoparnus comalensis*), except that it is a subterranean, aquatic (stygobiotic) species that has been collected primarily from spring runs in the Comal Springs ecosystem and Fern Bank Spring in Hays County (Barr and Spangler 1992, Gibson and others 2008). Figure 3 shows the collection locations for the beetle during the Edwards Aquifer Authority variable flow study. The subterranean nature and restricted range of the species (to the headwaters of the springs and spring upwelling areas) suggests that it does not require substantial surface discharge from springs to survive. Therefore, it is presumed that springflow (of sufficient water quality) that continually covers the spring orifice should prevent harm to the population.

- Peck's Cave Amphipod (*Stygobromus pecki*)

As with the Comal Springs dryopid beetle, very little is known of the habitat requirements of Peck's Cave amphipod (*Stygobromus pecki*). The species has been found in the spring orifices and upwelling areas throughout Comal Springs, and the Panther Canyon well (Figure 3). This species is often found in large numbers associated with the major spring runs at Comal (BIO-WEST 2004a–2010a). Assumptions regarding the species' requirements include sufficient springflow and water quality. In order to meet these assumptions, it is presumed that spring orifices should remain covered with flowing water to prevent harm to the species.

<u>Historical flows at Comal Springs</u>

To put the observed variable flow data from the past nine years and predicted model results in perspective and following the concept of the natural flow paradigm, we conducted an evaluation of the historical hydrology. The average discharge at Comal Springs during the period of record from 1927 to 2009 was approximately 291 cubic feet per second. The minimum recorded flow was zero when the springs stopped flowing for 144 consecutive days in 1956. This extreme flow condition, coupled with the likelihood that this event led to the extirpation of the fountain darter, is considered beyond the point of severe risk to the threatened and endangered species. Although all other endangered species were assumed to persist through this period, there is no evidence as to the state of health of any of these populations immediately following that event which provides an unknown relative to whether they would persist if those conditions were repeated.

Another historic period that is biologically meaningful for the Comal Springs system is the period of time since the fountain darter has been re-introduced into Comal Springs (post-1975). Sustained current populations (BIO-WEST 2002a–2010a) suggest that this period has been favorable for the fountain darter. It is important to note that spring discharge in the Comal Springs system in 1984 went below 60 cubic feet per second for over 100 consecutive days and below 40 cubic feet per second for over 40 consecutive days (dropping all the way down to 26 cubic feet per second). Since 1975, diminished flows at Comal Springs have occurred in 1984 (26 cubic feet per second), 1989 (62 cubic feet per second), 1990 (46 cubic feet per second), 1996 (83 cubic feet per second), and 2000 (138 cubic feet per second) with continued survival of the fountain darter, Comal Springs riffle beetle, Comal Springs dryopid beetle, and Peck's Cave amphipod.

<u>Comal Springs flow regime recommendations</u>

Figure 5 provides an overview of the information used to develop the flow regime recommendations for the Comal Springs system. To develop an ecologically protective flow regime, a balancing of species specific requirements was conducted where results did not align identically. In instances where there were competing species specific requirements, the higher flow requirement was conservatively chosen in each case following an analysis and understanding that this recommendation would not negatively impact the other species or overall ecosystem integrity.

Long-term average	Minimum 6-month average	Minimum 1-month average
Edwards Aquifer Authority Variable Flow Study (BIO-WEST 2002a-2010a) - Twenty-four comprehensive sampling events have been conducted on the Comal Springs system since 2000 over a total discharge range of 224 cfs to 446 cfs. Total Comal Springs system discharge greater than 225 cfs has been shown to provide high quality habitat throughout the range for the species present in this system. ***Hardy and others (2000)*** - No discernable change in modeled fountain darter habitat from 300 to 150 cfs total discharge. - Temperature conditions are suitable for fountain darter reproduction within its entire range at 150 cfs. ***Hardy (2009)*** - Approximately a 30 percent reduction in Comal Springs riffle beetle surface habitat within Spring Run 1 from 300 cfs to 150 cfs total discharge. - No reduction in Comal Springs riffle beetle surface habitat for Spring runs 2 or 3 at same flow reduction. ***Historical Hydrology*** - Average total discharge from 1927–2009 is 291 cfs. cfs = cubic feet per second	***Edwards Aquifer Authority Variable Flow Study (BIO-WEST 2002a-2010a)*** - Three critical period full monitoring events have been conducted since 2000 ranging in total discharge from 138 to 175 cfs. - Habitat reduction and subsequent reduction in fountain darter presence is noted in the Upper Spring Run reach at approximately 150 cfs when flow from Spring Run 5 ceases surface flow over the concrete structure. ***Hardy and others (2000)*** - Available fountain darter habitat reduced to approximately 90 and 75 percent of maximum available habitat at 100 and 60 cfs, respectively. - 77°F shown to cause reduced larval survival for fountain darters. At 60 cfs, this temperature is predicted to be exceeded in approximately 50 percent of the Upper Spring Run reach, 10 percent of the Old Channel, and 10 percent of the New Channel. At 60 cfs, Landa Lake below Spring Island is not predicted to be affected. ***Hardy (2009)*** - Only a slight reduction predicted in Comal Springs riffle beetle surface habitat in Spring Run 1 from 150 cfs to 100 cfs or 60 cfs total discharge. - No reduction at Spring run 2 predicted at 100 cfs. However elimination of surface habitat predicted at 100 cfs at Spring Run 3 and 60 cfs for Spring Run 2. ***Historical Hydrology*** - Minimum six month average discharge was 4 cfs from June to November 1956. - During 1984 total discharge went below 60 cfs for 103 consecutive days.	***Edwards Aquifer Authority Variable Flow Study (BIO-WEST 2002d, McDonald and others 2007)*** - Comal Springs riffle beetle laboratory studies suggest that the beetle has a strong affinity for upwelling flow and will retreat into artificial substrate during periods of low discharge. - Laboratory study suggests trematode gill parasite did not have a significant impact on fountain darter reproduction. ***Hardy and others (2000)*** - Available fountain darter habitat reduced to approximately 60 percent of maximum available habitat at 30 cfs. - 77°F shown to cause reduced larval survival for fountain darters. At 30 cfs, this temperature is predicted to be exceeded in approximately 100 percent of the Upper Spring Run reach, 40 percent of the Old Channel, and 60 percent of the New Channel. At 30 cfs, Landa Lake below Spring Island is not predicted to be affected. - Critical Thermal Maximum of 94.6°F established in Brandt and others 1993. The model suggests that this temperature would not be exceeded anywhere in the Comal Springs system at 30 cfs. ***Hardy (2009)*** - Approximately a 70 percent predicted reduction in Comal Springs riffle beetle surface habitat within Spring Run 1 from 300 cfs to 30 cfs total discharge. - No Comal Springs riffle beetle surface habitat predicted for Spring runs 2 or 3 at 30 cfs total discharge. ***Gonzales (2008)*** - Genetic differences of Comal Springs riffle beetle in spring runs versus Landa Lake suggest divergent populations and a bottleneck in the past. ***Historical Hydrology*** - Minimum one month average discharge was 0 cfs from July to October 1956. - During 1984 total discharge was below 40 cfs for 41 consecutive days dropping to a low of 26 cfs.

Figure 5: Overview of results used to inform flow regime recommendation on the Comal Springs system.

Based on the review of the best available science discussed throughout this report and summarized in Figure 5, we developed recommendations for the Comal Springs Flow Regime as presented in Table 2.

With the assumptions noted, it is our determination that maintaining all components of the proposed flow regime would meet the goal of long term survival of the threatened and endangered species of the Comal Springs system in the wild.

A long-term average value flow of 225 cubic feet per second is supported by long-term monitoring data and modeling results. At these total discharge levels, populations of each of the threatened and endangered species are anticipated to maintain or increase their respective populations. The most important aspect of maintaining the long-term average component of the flow regime is that the system would not be able to have repeated 6-month or 1-month events also prescribed in the flow regime. As such, the lower flow criteria were developed with the understanding that if they should occur, they would only be experienced a few times.

A minimum 6-month average flow of 75 cubic feet per second provides a condition that is sub-optimal for both the fountain darter and the Comal Springs riffle beetle. Water temperatures greater than those preferred for fountain darter larval survival would be exceeded throughout most of the Upper Spring Run reach and lower portions of the New and Old channels. This would have the potential to limit reproductive success within

Table 2: Comal Springs flow regime recommendations.

Comal Springs flow regime recommendation*		
Criteria	**Flow (cfs)**	**Notes**
Long-term average flow	225	
Minimum 6-month average	75	
Minimum 1-month average	30	No flows below 5 cfs

cfs = cubic feet per second

*Assumptions:

- Invasive species remain at current levels, both as to number of species and numbers of individuals/coverage.
- Gill parasite levels do not increase.
- Ramshorn snail populations do not increase.
- Amount of sediment in the river does not increase.
- Recreation remains at current levels (that is, no new tube/canoe/kayak rental facilities, no new water parks)
- Current in-channel structures remain unchanged.
- No additional mitigation activities beyond those currently in practice.

these portions of the system. However, at 75 cubic feet per second, the entirety of Landa Lake and upper portions of the Old and New channels would remain suitable to fountain darter reproduction. As fountain darter have been documented to reproduce year round in high quality habitat such as Landa Lake, a reduction in fountain darter reproduction is not anticipated to drive the population to a point from which it could not quickly rebound. Additionally, surface habitat for the Comal Springs riffle beetle is reduced in Spring Run 1 and predicted to be lost in Spring runs 2 and 3. It needs to be reiterated that although surface habitat is reduced for the riffle beetle in the spring runs, surface habitat at this discharge still exists at springs along the western shoreline of Landa Lake and spring upwelling areas near Spring Island and within the deeper portions of Landa Lake. Additionally, surface habitat is still predicted to be available at Spring Run 1 and subsurface habitat is still available at all spring runs.

A minimum 1-month average flow of 30 cubic feet per second is the lower threshold that we recommend the system not fall below with the current set of assumptions in place. At these levels, larger portions of fountain darter habitat relative to reproductive success are reduced in quality because of elevated water temperatures. However, even at 30 cubic feet per second, the majority of Landa Lake maintains suitable water temperatures for fountain darter reproduction. Additionally, it is not predicted that at 30 cubic feet per second any areas of fountain darter habitat exceed or even approach lethal temperatures for fountain darter survival. At 30 cubic feet per second, surface habitat for the riffle beetle is reduced nearly 70 percent in Spring Run 1 with no available surface habitat predicted in Spring runs 2 or 3. The possible genetic bottleneck in the Comal Springs riffle beetle spring run population suggested (Gonzales 2008) to occur during the 1950s drought makes going below this minimum threshold undesirable. The same understanding of available surface habitat at Spring Run 1, Spring Island, and Landa Lake, and subsurface habitat within the spring runs as described above for the minimum 6-month average flow applies at 30 cubic feet per second for the riffle beetle.

We reiterate earlier discussions in this report that emphasize that the flow regime recommendations for Comal Springs are based on the best available science and professional judgment at this time. We understand that these threatened and endangered species in the Comal Spring System can withstand short time periods of habitat loss and even some direct impact to the species themselves without resulting in long-term harm to the overall population. With that said, several unknowns still exist. One of the questions that remains is: What frequency or duration of these events could be tolerated by these species without long-term consequences? In the absence of that answer we have elected to recommend flows that are higher than the historically observed low flow statistics at Comal Springs because of the extirpation of the fountain darter following the 1950s drought. Although the remaining endangered species all presumably survived the 1950s drought, the condition of their populations prior to that event is unknown, and a possible genetic bottleneck is suggested to have occurred within the spring run population of Comal Springs riffle beetle.

A second major factor not incorporated into the habitat modeling results is the potential change to aquatic vegetation as flows decrease. The model assumes that the aquatic vegetation community will remain the same, which is certainly a false assumption to some unknown degree. Concern has also been raised by U.S. Fish and Wildlife Service personnel that major die-offs and decomposition of aquatic vegetation during periods of low-flow may cause significant reductions in dissolved oxygen available for the fountain darter. The reduction in aquatic vegetation could also cause crowding or clumping of darters in remaining suitable habitat which could possibly make them more vulnerable to predation or increased competition (native and non-native). These are some of the factors associated with the professional judgment component of the review of model results that were considered by the Expert Science Subcommittee during deliberations. An additional factor in the Comal Springs system is the continued presence of an Asian trematode, *Centrocestus formosanus*. Should moderate flow exist for several years without any flash floods followed by low flows due to drought conditions, it is anticipated that cercarial abundance may increase to a more severe level (Thomas Brandt, personal communication).

All the unknowns logically lead one to a conservative mindset in the setting of flow-related requirements. However, we made a conscious decision not to incorporate a margin of safety into the proposed recommendations. It was our interpretation of the legislative charge that the subcommittee should evaluate the best available science objectively, clearly state the assumptions associated with the recommendations, and acknowledge the need for further study where appropriate. For instance, if it is later revealed that significant impacts are not captured in the model results or efforts to control the parasite or its host are not in place or successful in the future, then one needs to be cautious with strict implementation of the proposed flow recommendations. However, should information come forward that these species are able to aggregate in areas of suitable habitat more frequently or for longer durations than currently thought without significant consequence, or mitigation activities are in place that could be effective in providing additional levels of protection, then the proposed flow regime recommendations for the Comal Springs system would also need to be revisited. One thing is clear, long-term monitoring of this system is essential, and further study and research specifically during critical low flow periods (or simulated critical low-flows) are needed to accurately determine the potential impacts to the species at Comal Springs.

<u>San Marcos Springs analysis and assumptions</u>

- Fountain darter (*Etheostoma fonticola*)

Fountain darters were first collected in the San Marcos River in 1884 from immediately below the confluence with the Blanco River. Fountain darters have been found in the San Marcos River intermittently between downstream of Cumming's Dam and Martindale. The present distribution of fountain darters in the San Marcos River is from Spring Lake to an area between the San Marcos wastewater treatment plant outfall and the confluence with the Blanco River.

Biological monitoring for fountain darters conducted over the past nine years (BIO-WEST 2002b - 2010b) has focused on three main reaches of the San Marcos Springs system: Hotel Reach (Spring Lake), City Park, and Interstate 35 (Figure 6). Data collected via the Edwards Aquifer Authority variable flow study over the past nine years suggest that the highest quality fountain darter habitat is located within Spring Lake.

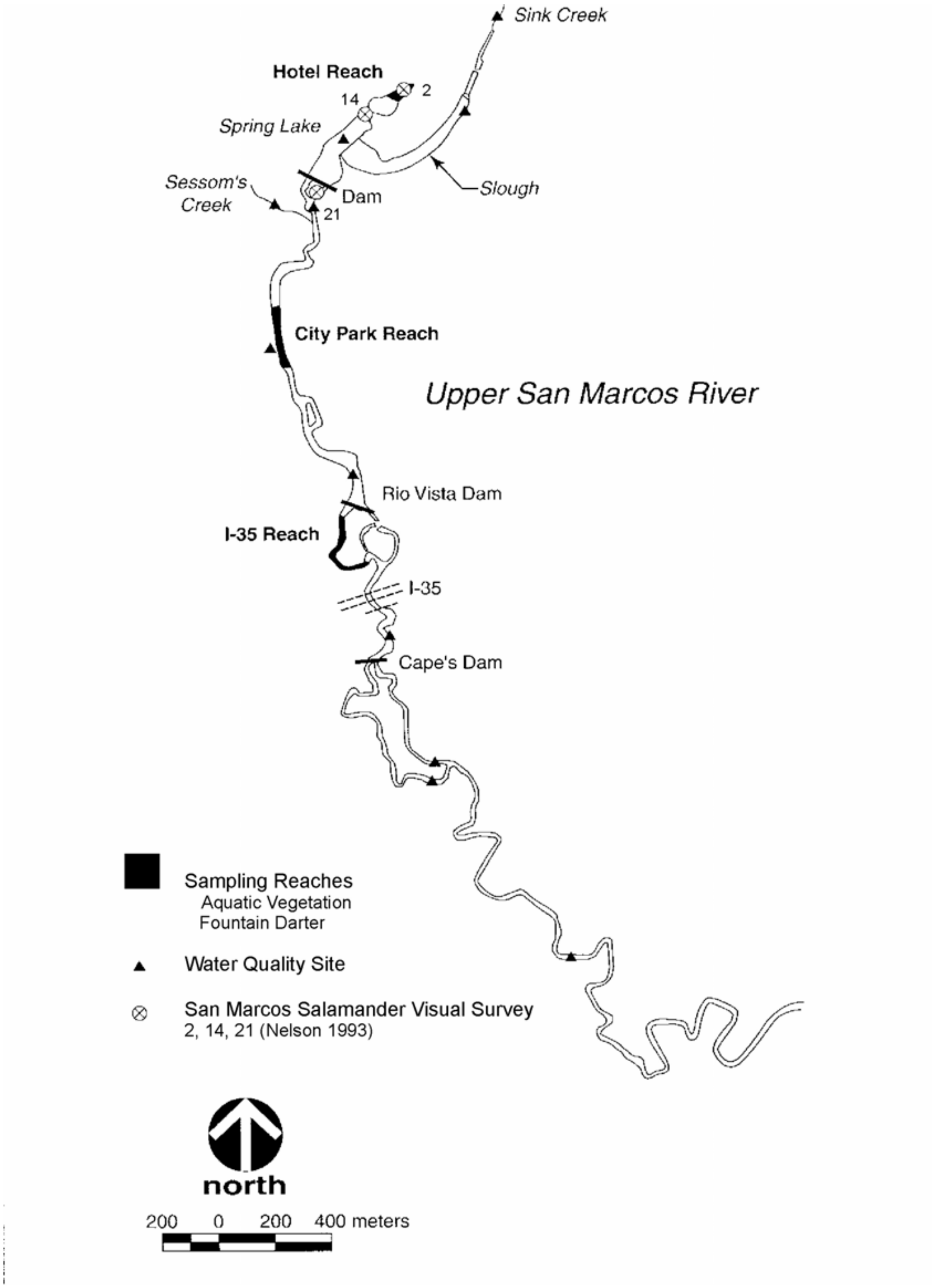


Figure 6: San Marcos River water quality and biological sampling areas for Edwards Aquifer Authority variable flow study (BIO-WEST 2009b).

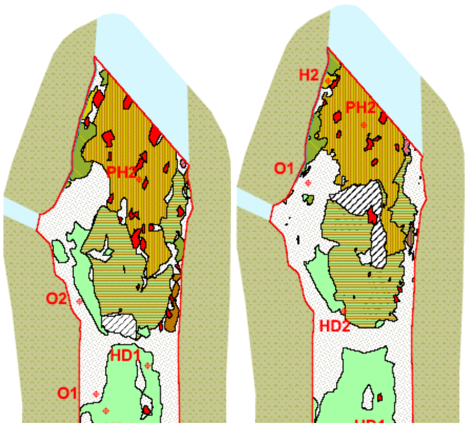
Spring Lake maintains a diverse aquatic vegetation community, supports year round reproduction of fountain darters, and exhibits exceptional water quality conditions. These factors contribute to the continuance of large populations of fountain darters within Spring Lake. The City Park and Interstate 35 reaches both maintain more variable habitat conditions for fountain darters relative to spring discharge (BIO-WEST 2002b–2010b). These reaches typically support seasonal fountain darter reproduction peaking during the spring. In comparison to habitat in Spring Lake or Landa Lake of the Comal Springs system, the habitat in these reaches is of lesser quality to fountain darters due to swifter currents, vegetation types, and recreational activities.

Over the past nine years of monitoring (BIO-WEST 2002b–2010b), total San Marcos Springs System discharge greater than 125 cubic feet per second has been shown to provide high quality fountain darter habitat throughout its range, excluding periods of high flow pulses. Indirect impacts associated with recreational activities in City Park occur each year regardless of flow condition but are magnified during flows less than 100 cubic feet per second as discussed below. Considerable habitat alteration has occurred several times over the years as a result of high flow pulses (heavy localized rain events) scouring out extensive areas of aquatic vegetation. These time periods are generally short-lived (hours to days) and the aquatic vegetation typically recovered and/or expanded in one to six months. BIO-WEST (2007c) has concluded that these represent flow events that have direct impacts on fountain darter habitat, but only on a temporary time scale.

During the nine years of monitoring at San Marcos Springs, it appears that the combination of sedimentation, low water levels, and intense recreation cause impacts to fountain darter habitat as total discharge declines to 110 cubic feet per second in the system. At this total discharge level, conditions within Spring Lake remain relatively unchanged; however, conditions within Sewell Park and City Park start showing considerable reductions in aquatic vegetation. Figure 7 shows the difference in vegetation impact in the City Park Reach between spring (April) and fall (October) during three flow conditions (A. 2005 [above average year—greater than 200 cubic feet per second], B. 2006 [below average year—near 110 cubic feet per second], and C. 2009 [below average year—below 100 cubic feet per second]). The colored polygons represent different types of aquatic vegetation within the upper portion of the City Park reach (for specific vegetation types and coverage, see BIO-WEST 2006b, 2007b, and 2010b). It is evident that even during higher than average flow conditions, recreation impacts occur to the central portion of the City Park reach (footpath across the river in the lower portion of each figure; Figure 7). However, the impacts remain relatively minor during 2006 even at much lower than average flow conditions. The effects of recreation are clearly magnified in this high access area when flow conditions go below 100 cubic feet per second total discharge (Figure 7).

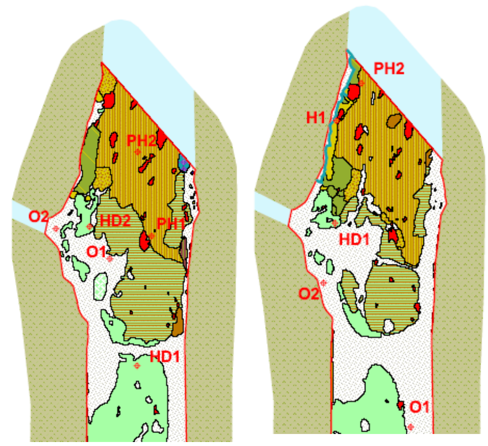
Table 3 shows the total aquatic vegetation area for the full City Park reach from these years and the differences recorded between spring and fall . Additionally, Table 3 shows the total aquatic vegetation area and seasonal differences for the Interstate 35 reach for the same years.

A.



Spring 2005 Fall 2005

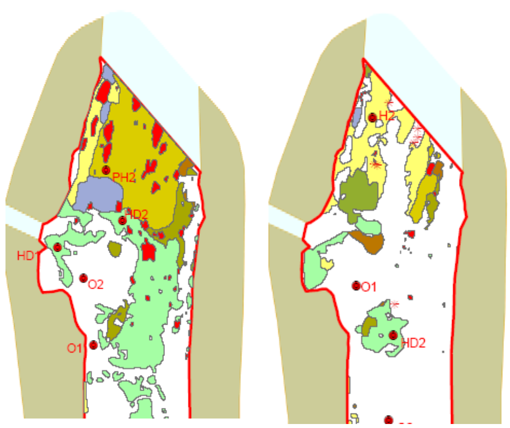
B.



Spring 2006 Fall 2006

	2005	**2006**	**2009**
Average Flow 6 months prior to spring	323 cfs	140 cfs	99 cfs
Average Flow between spring and fall	228 cfs	107 cfs	94 cfs

C.



Spring 2009 Fall 2009

San Marcos River – City Park Reach Aquatic Vegetation Maps

Figure 7: Aquatic vegetation maps for spring (April) and fall (October) (A) 2005, (B) 2006, and (C) 2009. Average flows for the San Marcos River for the six months preceding condition and between mapping efforts per year also shown (BIO-WEST 2006b, 2007b, 2010b) (cfs = cubic feet per second).

Table 3: Total aquatic vegetation area within City Park and Interstate 35 reaches during different flow conditions over time.

Reach	Total aquatic vegetation (m^2)		% Decline
	Spring (April)	Fall (October)	
City Park			
2005	4298	4319	0
2006	4620	4171	10
2009	4308	2690	38
Interstate 35			
2005	525	612	-17
2006	883	925	-5
2009	759	739	3

m^2 = square meters

Table 3 highlights the level of recreational impact in high access areas at lower flow conditions as the reduction in the City Park reach between spring and fall 2009 was 38 percent, while the total reduction in aquatic vegetation within the Interstate 35 reach during these same low flow conditions was only 3 percent. The greater amounts of aquatic vegetation in the Interstate 35 reach during lower flow conditions and in the fall versus spring (again, typically lower flow conditions in fall) are a result of reduced velocities throughout this reach. Higher velocities do not allow for establishment of large amounts of aquatic vegetation within the Interstate 35 reach at even long term historical average conditions. This highlights the importance of a flow regime and how maintaining variable flow benefits certain reaches at certain times in contrast with other segments of the river. Saunders and others (2000) make the same conclusion in their instream flow recommendation report for the San Marcos River (described below).

Moving beyond monitoring data into an evaluation of modeling results, the same habitat criteria employed in the Comal Springs ecosystem can be used to evaluate the suitable habitat available to fountain darters in the San Marcos Springs ecosystem. However, for the San Marcos River there have been two efforts for evaluation conducted by the U.S. Fish and Wildlife Service (Bartsch and others 2000) and Texas Parks and Wildlife Department (Saunders and others 2000), respectively. Rather than having the temperature data, vegetation composition, and wetted perimeter information combined into a single estimate of total usable fountain darter area as in Bartsch and others (2000), Saunders and others (2000) conducted a study that examined each component separately for the San Marcos Springs system. Again, only those primary conditions for suitable habitat are discussed; other potential influences may alter these estimations.

Temperature remains a variable of primary importance because individuals near the confluence of the Blanco River periodically experience temperatures that reach or exceed 77º F (25º C). The water temperature is typically in the range of 69.8–73.4º F (21.0–23.0º C) near the springs under historical average flows; the range broadens at the downstream edge of the fountain darter range (the confluence with the Blanco River). Groeger and others (1997) observed a range of approximately 68.0–75.2ºF (20.0–24.0º C) just upstream of the confluence with the Blanco (4.8 kilometers downstream of headwaters of the San Marcos) during 1993–1994.

Saunders and others (2000) modeled water temperature from Spring Lake Dam down to the confluence with the Blanco River using the U.S. Fish and Wildlife Service's Stream Network Temperature Model (SNTEMP) developed by Theurer and others (1984). The model was applied to two flow scenarios: the historic mean and historic minimum for each month. This model provides information on daily mean and maximum temperatures for each month, and the two scenarios allow for a comparison between a typical year and the "worst case" scenario as derived from the recent historical record. The results indicate that the mean daily average should have exceeded the thermal maximum of 80.0º F (26.7º C) only under the historic minimum scenario and only at the downstream periphery of the fountain darter's range. Under historical average conditions, the more conservative mean daily threshold of 77.0º F (25.0º C) should not have been exceeded in the range of the fountain darter (Table 4). The study also examined the potential effects of elevated air temperatures on the model and found a slight increase in the amount of time during which water temperature would be at or above the threshold values. The investigators determined however, that "the model was fairly insensitive to changes in air temperature" (Saunders and others 2000).

Table 4: Number of months in which threshold water temperatures (77° F and 80° F) are exceeded in the San Marcos River as predicted by a SNTEMP model under normal (mean) and minimum springflow scenarios.

		Mean Air Temperature		Elevated Air Temperature	
	Station [a]	77º F [b]	80º F [b]	77º F [b]	80º F [b]
Normal Springflow	1	-	-	1	-
	3	-	-	5	-
	4	-	-	5	-
	5	-	-	5	-
Minimum Springflow	1	-	-	1	-
	3	2	-	5	4
	4	3	-	5	4
	5	4	2	5	5

Table created from data in Saunders and others (2000).
[a] Stations of increasing number are found further downstream.

[b] (77 º F = 25 º C; 80 º F = 26.7 º C.)

Saunders and others (2000) determined values of weighted usable area for several of the dominant vegetation types in the San Marcos River based on their importance in the ecosystem rather than to fountain darters. There were two components used in calculating weighted usable area for vegetation. First, habitat suitability criteria for each species were determined for both the main channel and natural channel (referring to the divergence that occurs downstream of Cape's Dam). These suitability criteria were then combined with hydraulic model output to determine weighted usable area estimates. The vegetation species included in this calculation were wild-celery (*Vallisneria americana*), delta arrow-head (*Sagittaria platyphylla*), Illinois pondweed (*Potamogeton illinoensis*), water stargrass (*Heteranthera liebmannii*), and Texas wild-rice (*Zizania texana*). Although information is lacking on the suitability of water stargrass as fountain darter habitat, the other species all provide fountain darter habitat at varying degrees (Schenck and Whiteside 1976, Bartsch and others 2000). The loss of habitat for these aquatic plant species, resulting in diminished areal coverage, may have indirect impacts on the fountain darter population.

The results of the weighted usable area calculations at various levels of discharge from 50 to 140 cubic feet per second can be found in Table 5. The modeling results indicate that wild-celery is minimally impacted by decreases in discharge and might benefit from flows down to 80 cubic feet per second in most of its range. When discharge approaches the historic minimum, the models show that weighted usable area for this species remains above 85 percent. According to the model, delta arrow-head is more significantly impacted in the upper reach with a steady decline in usable habitat (to just under 63 percent of the usable habitat available under maximum conditions) when flow is 50 cubic feet per second. As shown in the model, the usable area in the middle section remains highly resistant to decreases in flow, while in the lower reach usable area is maximized at 100 cubic feet per second and decreases at 50 cubic feet per second.

According to the model, Illinois pondweed and water stargrass have similar results to changes in discharge with usable habitat declining steadily as flows drop below 140 cubic feet per second in all reaches. Each declines to a low of 55 percent of the usable habitat under maximum conditions in the upper reach. The importance of Texas wild-rice to fountain darters is limited according to Schenck and Whiteside (1976), and little other information is available regarding the interaction between the two species; consequently, the results for Texas wild-rice are discussed separately and in more detail later in this report.

Information on wetted width is also presented in Saunders and others (2000). The information is presented by mesohabitat type: pools, runs, and riffles (Table 6). According to predictions, run habitat is lost in both the main and natural channels as flow decreases from 140 cubic feet per second to 50 cubic feet per second. Pools, another potential fountain darter habitat (though substantially less common in the system), had little change in wetted width as discharge decreased; virtually all of the habitat remained in the natural channel, and less than 5 percent was lost in the main channel. Riffles, also uncommon in this run-dominated system, experienced the greatest decline in wetted width as flow decreased, but they remained above 75 percent of normalized wetted width at 50 cubic feet per second.

Table 5: The weighted usable area (WUA)[a] for five dominant aquatic plant species in the San Marcos River.

VEGETATION TARGET SPECIES	Springflow (cfs)	Total % WUA in Segment 1	% of maximum	Total % WUA in Segment 2	% of maximum	Total % WUA in Segment 3	% of maximum
Wild-celery *Vallisneria americana*	140	33.0	75.0	20.0	100.0	33.0	89.2
	120	34.0	77.3	18.5	92.5	34.0	91.9
	100	39.5	89.8	18.0	90.0	35.5	95.9
	80	44.0	100.0	18.0	90.0	37.0	100.0
	60	41.0	93.2	17.0	85.0	34.0	91.9
	50	41.0	93.2	17.0	85.0	32.0	86.5
Delta arrow-head *Sagittaria platyphylla*	140	33.0	98.5	46.5	98.9	56.0	94.9
	120	31.0	92.5	46.0	97.9	53.0	89.8
	100	33.5	100.0	45.0	95.7	49.0	83.1
	80	31.5	94.0	45.0	95.7	47.0	79.7
	60	28.0	83.6	44.0	93.6	39.5	66.9
	50	26.0	77.6	43.0	91.5	37.0	62.7
Illinois pondweed *Potamogeton illinoensis*	140	61.0	96.8	53.0	98.1	72.5	94.2
	120	59.0	93.7	52.0	96.3	68.0	88.3
	100	56.0	88.9	49.0	90.7	61.0	79.2
	80	52.0	82.5	48.5	89.8	57.0	74.0
	60	45.5	72.2	47.5	88.0	48.5	63.0
	50	41.0	65.1	46.5	86.1	42.5	55.2
Water stargrass *Heteranthera liebmannii*	140	52.0	97.2	27.0	87.1	32.0	91.4
	120	51.0	95.3	25.0	80.6	30.0	85.7
	100	46.0	86.0	24.0	77.4	28.0	80.0
	80	41.0	76.6	21.5	69.4	25.0	71.4
	60	34.5	64.5	20.5	66.1	22.5	64.3
	50	32.0	59.8	19.5	62.9	19.5	55.7
Texas wild-rice *Zizania texana*	140	63.0	96.2	37.0	94.9	49.0	99.0
	120	64.0	97.7	36.5	93.6	49.5	100.0
	100	65.0	99.2	35.0	89.7	48.5	98.0
	80	65.5	100.0	35.0	89.7	46.0	92.9
	60	63.0	96.2	31.5	80.8	41.0	82.8
	50	63.5	96.9	31.0	79.5	39.0	78.8

Table created from data in Saunders and others (2000).

[a] The WUA is calculated as a percent of the total area in the segment and as a percent of usable area in that segment under optimal conditions. The percent of maximum is calculated by dividing the WUA per flow by the highest amount of WUA for that respective species and segment over the range of modeled flows. Segments are those defined by Saunders and others (2000) for the Upper San Marcos River: Segment 3 extends from Spring Lake Dam to Rio Vista Dam, Segment 2 extends from Rio Vista Dam to Millrace headgate downstream of the state fish hatchery outfall, and Segment 1 extends from the Millrace headgate to Cummings Dam.

Table 6: Normalized wetted width in pool, run, and riffle mesohabitats relative to discharge in the upper San Marcos River.

		Normalized Wetted Width			
Mesohabitats	Springflow (cfs)	Main Channel	% Loss	Natural Channel	% Loss
	140	99.5	0.5	100.0	0.0
	120	98.5	1.5	100.0	0.0
Pool	100	98.0	2.0	100.0	0.0
	80	97.0	3.0	100.0	0.0
	60	96.0	4.0	100.0	0.0
	50	95.5	4.5	100.0	0.0
	140	99.5	0.5	100.0	0.0
	120	98.5	1.5	99.0	1.0
Run	100	98.0	2.0	98.0	2.0
	80	95.0	5.0	96.5	3.5
	60	91.5	8.5	95.5	4.5
	50	89.0	11.0	94.0	6.0
	140	99.5	0.5	100.0	0.0
	120	99.0	1.0	99.5	0.5
Riffle	100	99.0	1.0	99.5	0.5
	80	90.0	10.0	99.0	1.0
	60	80.0	20.0	99.0	1.0
	50	76.0	24.0	98.5	1.5

Modified from Saunders and others (2000) to include calculated % loss.

The Hardy (2009) study results summarize both the original work (Bartsch and others 2000) conducted on habitat availability modeling for the fountain darter in the San Marcos River using 1997 channel geometries and the updated 2001 channel geometries. Both of these scenarios were modeled using the original habitat suitability criteria for fountain darters (Bartsch and others 2000). The 2009 model update used the 2001 channel geometries but utilized the updated habitat suitability criteria that were established following a detailed examination and analysis of existing data conducted by Dr. Tim Bonner of Texas State University.

The temperature modeling (Figure 8) shows that at 80 cubic feet per second total discharge, all areas of the San Marcos River are suitable for fountain darter reproduction. At 60 cubic feet per second, portions of the lower-most reaches slightly exceed the 77° F value. Temperature from Spring Lake to Rio Vista Dam supports fountain darter reproduction down to the lowest flow rate (30 cubic feet per second) modeled.

The relationships between available simulated habitat (weighted usable area) for fountain darters versus flow in the San Marcos River are shown in Figure 9. Figure 9 demonstrates that the measured channel changes between 1997 and 2001 resulted in a scaling of the predicted fountain darter habitat magnitude rather than a considerable change in the overall shape of the weighted usable area to discharge relationship (Hardy 2009). Again, it important to point out that these two scenarios do not incorporate revisions to the fountain darter habitat suitability functions. The Hardy (2009) results based on the 2001 channel geometries and updated fountain darter habitat suitability

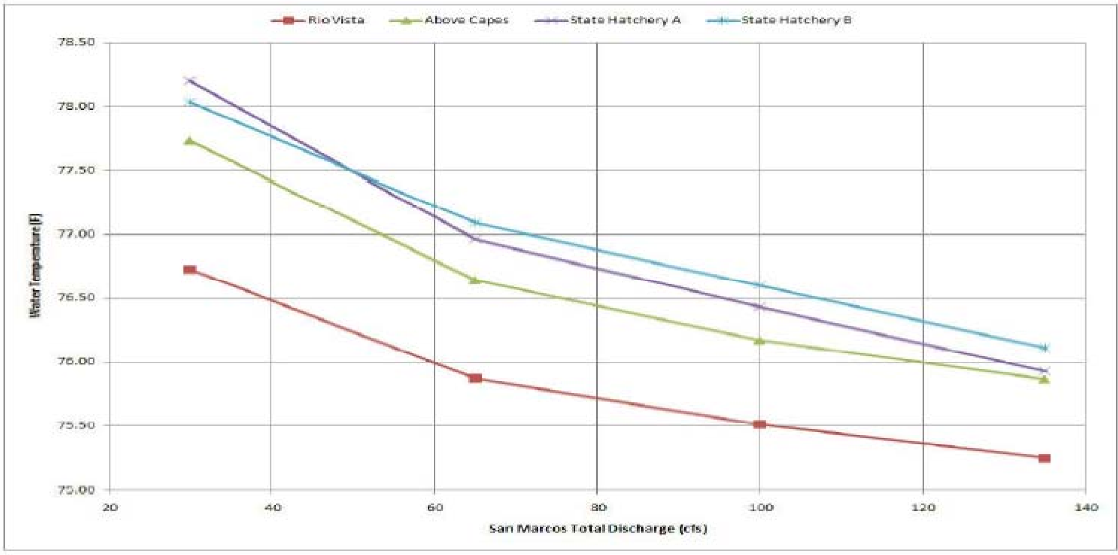


Figure 8: Relationship between total San Marcos River discharge (cubic feet per second [cfs]) and reach level maximum daily temperature (°F) (Hardy 2009).

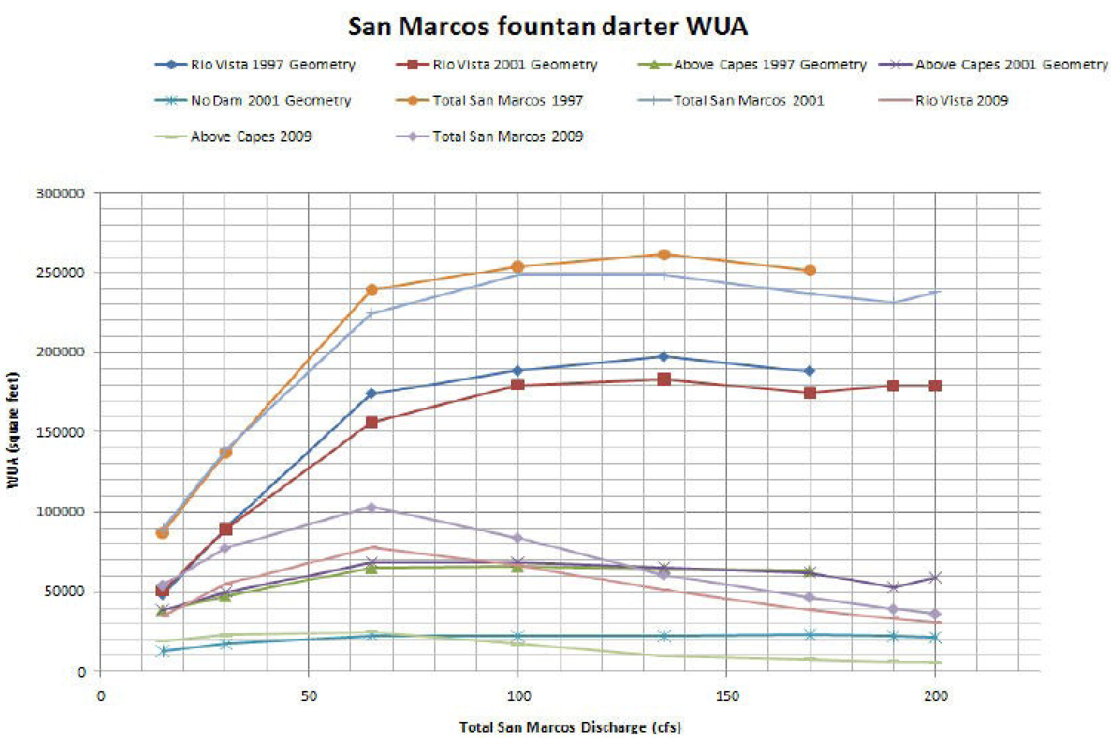


Figure 9: Simulated fountain darter available habitat in sections of the San Marcos River (Hardy 2009) (cfs = cubic feet per second; WUA = weighted usable area).

functions not only changed the magnitude of weighted usable area versus discharge but shifted the flow rate at which the maximum habitat values were predicted. As expected, this compares well with actual field data collected over the past nine years, in that areas of lesser flow tend to support more aquatic vegetation growth and higher utilization of fountain darters. This trend can only be supported down to some point as lowering flows subsequently cause the reduction in wetted area which in turn reduces the overall amount of available habitat for the fountain darter. When considering the total San Marcos River in 2009 (Figure 9), the maximum amount of available habitat predicted for the fountain darter occurs at 65 cubic feet per second. As flow declines to 30 cubic feet per second, approximately 75 percent of the maximum available habitat remains. As flow declines to 15 cubic feet per second, approximately 50 percent of the available habitat suitable for the fountain darter is predicted.

Overall, the species specific results of the Bartsch and others (2000) and Hardy (2009) modeling (both temperature and habitat) related to the fountain darter are similar to the ecosystem approach applied by Saunders and others (2000).

As discussed in the Comal Springs section, parasites, the presence of exotic species (primarily suckermouth catfishes and ramshorn snails), water quality degradation, and recreation all have consequences on the fountain darter populations. As in the Comal Springs system, the gill parasite (*Centrocestus formosanus*) is a potential threat that needs careful attention and study. Thomas Brandt (U.S. Fish and Wildlife Service, personal communication, 2009) speculates the parasite became well established, with 100 percent of collected fish infected with an average of 100 cysts per fish in the San Marcos River near Interstate 35, in 2009. Suckermouth catfishes are abundant in the San Marcos River and successfully reproducing (BIO-WEST 2007c). Ramshorn snails have been present in the San Marcos Springs system but at low levels since the inception of the Edwards Aquifer Authority variable flow study in fall 2000. Regardless of present numbers, this species needs to be monitored closely to assure that it does not significantly reduce the available fountain darter habitat.

As discussed in the Comal Springs section, water quality encompasses a range of variables that can potentially impact fountain darters and other aquatic life if altered too far from the historic range to which the stream inhabitants have become accustomed. Particularly on the San Marcos River, recreational activities have the potential to affect fountain darter populations directly (for example, trampling and displacing individuals) in addition to decreasing areal coverage of suitable habitat (various species of aquatic vegetation). These effects have been documented to be intensified during periods of lower spring discharge (BIO-WEST 2007c).

One additional factor for the San Marcos Springs system relevant to fountain darters and Texas wild-rice is increased sedimentation. Over the past decade, the upper San Marcos River has filled in considerably from just below Spring Lake Dam (near the mouth of Sessom Creek) to the reconstructed Rio Vista Dam. This statement is not based on a sediment transport study or model (as this type of effort has not been conducted to date) but rather on 20 years of visual observations and actually being in the river on a regular basis (Jackie Poole, personal communication; Ed Oborny, personal communication). The build-up of sediment in this stretch directly dictates the depth of water and substrate composition. Water depth and substrate are important components to maintaining the proper aquatic vegetation for fountain darter habitat as well as suitable conditions for Texas wild-rice. Sedimentation relative to Texas wild-rice distribution has been studied (Griffin 2006). Griffin (2006) states that the sediment input to this upper reach derives from Sink Creek, Sessom Creek, and through overland flow. Griffin (2006) discusses the effectiveness of the five flood detention dams that have been built on tributary creeks draining into the San Marcos River and explains how reducing the frequency of higher flows has reduced the ability of the river to flush out the accumulated bed sediment (Griffin 2006).

- Texas wild-rice (*Zizania texana*)

Texas wild-rice was first collected in the San Marcos River in 1892. When the species was originally described in1933, it was reported to be abundant in the San Marcos River, including Spring Lake and its irrigation waterways (Silveus 1933). Beaty (1975) reported coverage of 240 square meters (2,580 square feet), but he did not provide distribution within the river or survey methodology. By 1967, only one plant remained in Spring Lake, no plants were found in the uppermost 0.8 kilometers (0.5 miles) of the San Marcos River, only scattered plants in the lower 2.4 kilometers (1.5 miles), and none below that (Emery 1967). In 1976, Emery began monitoring the coverage of Texas wild-rice within the San Marcos River on a regular basis (Table 7).

Currently, Texas wild-rice occurs in the upper 2.4 kilometers of the San Marcos River, above the confluence with the Blanco River. Texas wild-rice is generally found in high to moderate current velocities (0.4 to 3.3 feet per second [0.12 to 1.0 meters per second]) at shallow water depths (0.76 to 3.3 feet [0.23 to 1 meters]) on coarse and sandy substrates (Poole and Bowles 1999; Saunders and others 2000). Texas wild-rice is also frequently found in areas with dense growth of other aquatic macrophytes, including the native species *Potamogeton illinoensis, Vallisneria americana, Cabomba caroliniana, Ludwigia repens*, and the non-native species *Hygrophila polysperma, Hydrilla verticillata and Egeria densa* (Poole and Bowles 1999). Power (1996a) also found that substrate composition and current velocity affect plant biomass and stem density and argued that the decline in the population can be partially attributed to changes in habitat that have occurred through urbanization and impoundment. Since Texas wild-rice prefers shallow areas, significant reductions in streamflow could expose many plants to less than optimal depths, either reducing plant growth or desiccating and killing plants. Texas wild-rice will perish in moist soil or even less than a few inches of water (Vaughan 1986). Texas wild-rice seeds have a significantly better germination rate when grown in inundated soils versus moist, but not inundated, soil (Alexander 2008). Herbivory is a potential problem for Texas wild-rice; decreased flows leave the plants more susceptible to waterfowl, introduced nutria, and ramshorn snails (Rose and Power 1992). Lower flows also increase the likelihood of vegetation mats forming on top of Texas wild-rice plants. Vegetation mats interfere with culm emergence, block sunlight and interfere with photosynthesis, and slow current velocity (Power 1996b). Another concern is competition with exotics, which may gain a competitive advantage when conditions are sub-optimal for Texas wild-rice. Figure 10 depicts the mapping segments for Texas wild-rice employed by

Table 7: Annual coverage (square meters [m^2)]) of Texas wild-rice broken down by river segment (see Figure 10) (1976 and 1978 data from Emery; 1983-1986 from Vaughan; 1989-2009 from Texas Parks and Wildlife Department).

SEGMENT YEAR	1976	1978	1983	1984	1985	1986	1989	1990	1991	1992	1993	1994	1995
A	0.00	0.00	0.00	0.00	0.00	0.00	23.10	77.63	83.39	34.23	38.66	34.43	35.93
B	0.00	0.00	0.00	0.00	0.00	0.00	76.73	162.44	237.80	207.72	267.35	417.17	513.07
C	554.00	463.50	251.00	228.00	217.00	209.00	326.83	477.94	392.02	449.23	540.70	442.62	514.34
D	0	0	0	0	0	0	0	0	0	0	0	0	0
E	55.00	26.00	29.00	27.00	19.00	19.00	81.33	72.40	109.81	71.86	77.05	62.85	81.16
F	164.00	no data	119.00	83.00	103.00	92.50	276.57	241.90	271.42	380.08	429.44	270.49	276.28
G	68.00	33.00	37.00	8.00	8.00	7.50	18.58	18.83	12.88	12.65	20.25	17.64	14.74
H	0.50	0.00	0.00	0.00	0.00	0.00	11.40	11.82	8.66	9.74	1.32	3.73	5.03
I	9.00	no data	4.00	3.00	4.50	4.00	12.86	5.55	1.40	0.21	0.32	0.17	0.11
X	0.00	0.00	0.00	0.00	0.00	0.00	1.04	0.00	0.00	0.00	0.00	0.00	0.00
J	49.00	no data	46.00	28.00	68.00	55.00	95.03	120.46	117.01	117.39	96.57	76.22	46.58
K	233.50	no data	55.00	15.00	69.50	67.00	77.14	191.02	171.52	122.56	136.21	129.50	136.24
L	0.00	0.00	0.00	0.00	0.00	0.00	2.84	0.43	0.29	0.33	0.52	1.52	0.52
M	0.00	0.00	0.00	0.00	0.00	0.00	0.52	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	1132.50	522.50	541.00	412.00	489.00	454.00	1003.97	1380.42	1406.20	1406.00	1608.39	1456.34	1624.00

Table 7: Continued.

SEGMENT YEAR	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
A	31.70	48.99	57.43	75.77	77.58	104.41	141.58	256.35	285.63	325.72	410.47	361.15	354.07	327.24
B	555.06	519.68	766.48	661.81	745.09	991.22	1034.99	1312.01	1799.6	2299.5	2332.1	2529.3	2341.5	2299.4
C	459.95	416.09	422.61	493.08	553.34	399.16	425.74	716.91	655.57	830.9	735	726.55	668.7	710.44
D	0	0	0	0	0	0	0.00	4.51	7.22	12.19	8.42	8.69	14.95	7.71
E	72.83	76.34	67.75	38.67	24.25	19.98	11.80	19.66	21.15	6.13	5.05	6.08	2.94	1.49
F	275.97	335.40	327.62	339.49	350.52	359.42	286.41	429.13	460.16	426.07	550.99	539.37	425.39	386.8
G	10.64	11.98	20.80	23.26	20.85	4.78	6.69	9.69	12.08	16.8	18.23	16.95	24.3	13.75
H	4.35	2.43	2.84	2.92	3.67	0.98	0.90	12.59	20.36	25.54	15.88	20.2	16.58	28.67
I	0.064	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0
X	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0
J	36.96	36.99	48.82	7.33	6.22	6.70	3.00	5.36	0	7.27	6.39	5.94	3.58	0.61
K	202.60	134.39	234.94	2.55	9.56	8.97	5.14	9.83	127.85	37.38	71.9	57.36	53.53	46.91
L	1.95	1.87	0.00	0.00	0.00	0.00	0.00	0.00	0	5.21	6.74	5.84	4.2	5.28
M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0	0
	1652.07	1584.16	1949.29	1644.88	1791.08	1895.62	1916.3	2776.04	3389.57	3992.7	4161.1	4277.5	3909.7	3828.3

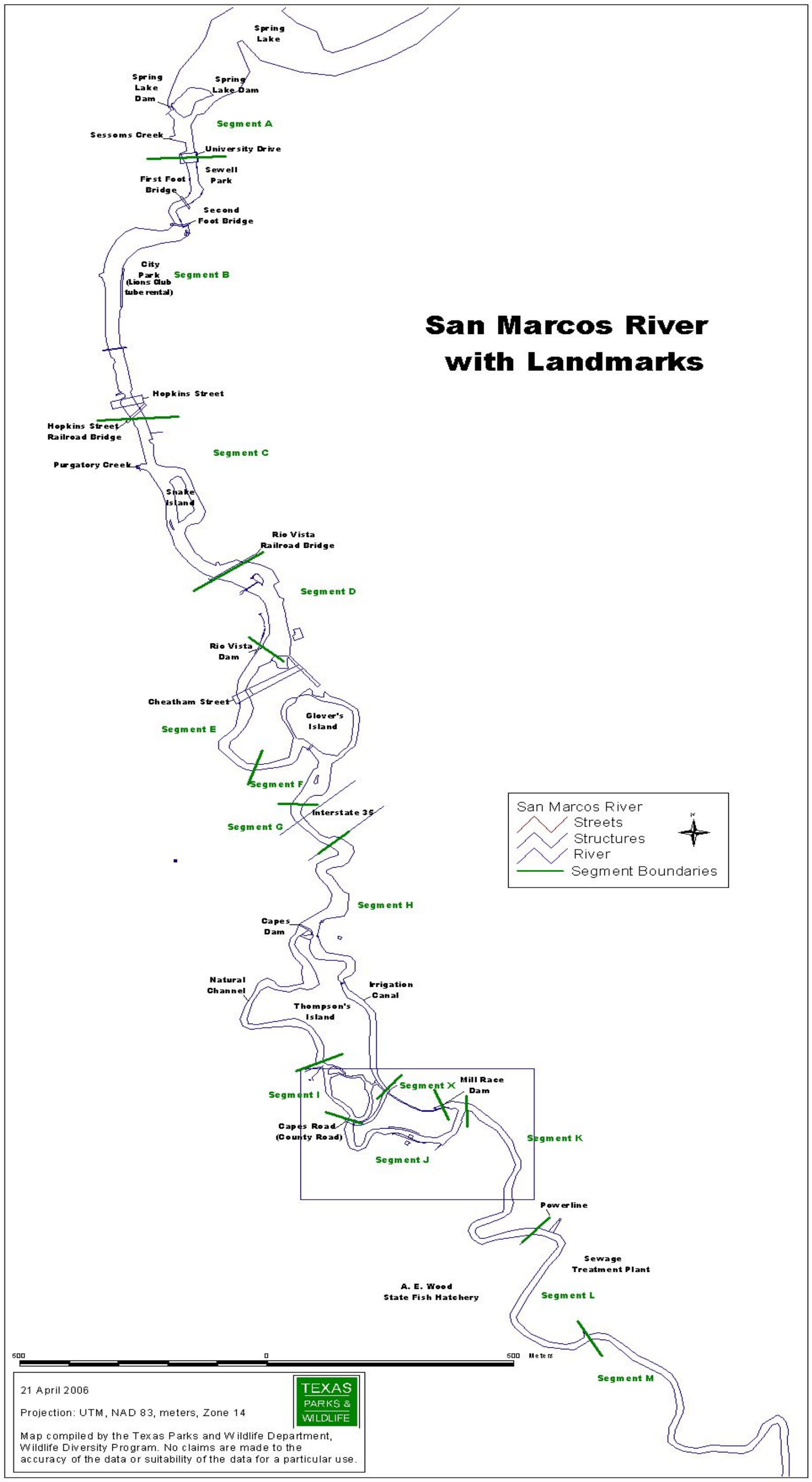


Figure 10: Texas wild-rice mapping segments used by Texas Parks and Wildlife Department for annual monitoring (Texas Parks and Wildlife Department unpublished data)

Texas Parks and Wildlife Department for their annual monitoring. Figure 11 represents the mapping sections used by the Edwards Aquifer Authority variable flow study of Texas wild-rice in the upper San Marcos River. Figure 12 depicts the total Texas wild-rice coverage in the San Marcos River as mapped annually in the summer by Texas Parks and Wildlife Department and for the Edwards Aquifer Authority variable flow study.

The variation between the Texas Parks and Wildlife Department values and the Edwards Aquifer Authority variable flow study results in Figures 12 and 13 and Table 7 may be due to slight differences in mapping techniques and procedures and/or timing of summer monitoring. Texas wild-rice rarely grows as a single-stemmed individual; normally, plants are composed of dozens or hundreds of rooted stems that may represent more than one genetic individual (Richards and others 2007). In the methodology employed by Texas Parks and Wildlife Department, plants that are in physical contact are grouped into stands. The stand location is measured from the stand's upstream-most end to a surveyed monument on the bank using a distance and bearing. The full extent of the stand's length and width are measured, and an aerial percent cover of Texas wild-rice within the length-width rectangle is estimated to provide aerial coverage. For the Edwards Aquifer Authority variable flow study, real-time GPS is used to map the perimeter of stands while kayaking or walking around the stands being measured. Stands smaller than 1 square meter are represented by a point without any associated aerial cover. However, despite the fact that there are many small plants, this probably represents less than 10 square meters of aerial coverage. For both efforts, annual mapping is done in the summer, usually in the month of July. The important aspect is not the slight differences in results but the consistency within sample methodology, with both methods providing a valuable double check for the other.

While it is true that Texas wild-rice coverage in the San Marcos River has more or less quadrupled in 20 years, if coverage is viewed on a segment-by-segment basis, a somewhat different picture emerges. Table 7 shows the annual coverage of Texas wild-rice broken down by Texas Parks and Wildlife Department river segment (Figure 10) from the earliest data collected by Emery in 1976 and 1978, Vaughan in 1983–1986, and Texas Parks and Wildlife Department (1989–2009) and Figure 13 shows the Edwards Aquifer Authority variable flow study total Texas wild-rice coverage per study section. Neither Emery nor Vaughan recorded Texas wild-rice in the uppermost segments (A and B) of the river. Until Texas wild-rice was listed as an endangered species, Texas State University and the City of San Marcos regularly dredged the bottom of the river in Sewell and City parks. Although Texas wild-rice was seen in Sewell Park in 1984 (Jackie Poole, personal observation), it is not known why Vaughan did not record it. The river segment that increased most in coverage is Segment B where the dredging occurred. Whether Texas wild-rice reestablished itself from seeds, surviving shoots and root balls, or from plantings is lost to history. However, Texas wild-rice made an impressive recovery in this segment of the river, going from 76.73 square meters in 1989 to a high of over 2,500 square meters in 2007, but much suitable habitat was available and unoccupied. In contrast, Segment K in the lower part of the San Marcos River had almost the same coverage in 1989 as Segment B and had increased (despite a few dips) in coverage until the 1998 flood when almost all the plants were destroyed. Although coverage shows a dramatic increase in this segment in 2004, this was due to U.S. Fish and Wildlife Service transplants that as the subsequent data shows did not fare well.

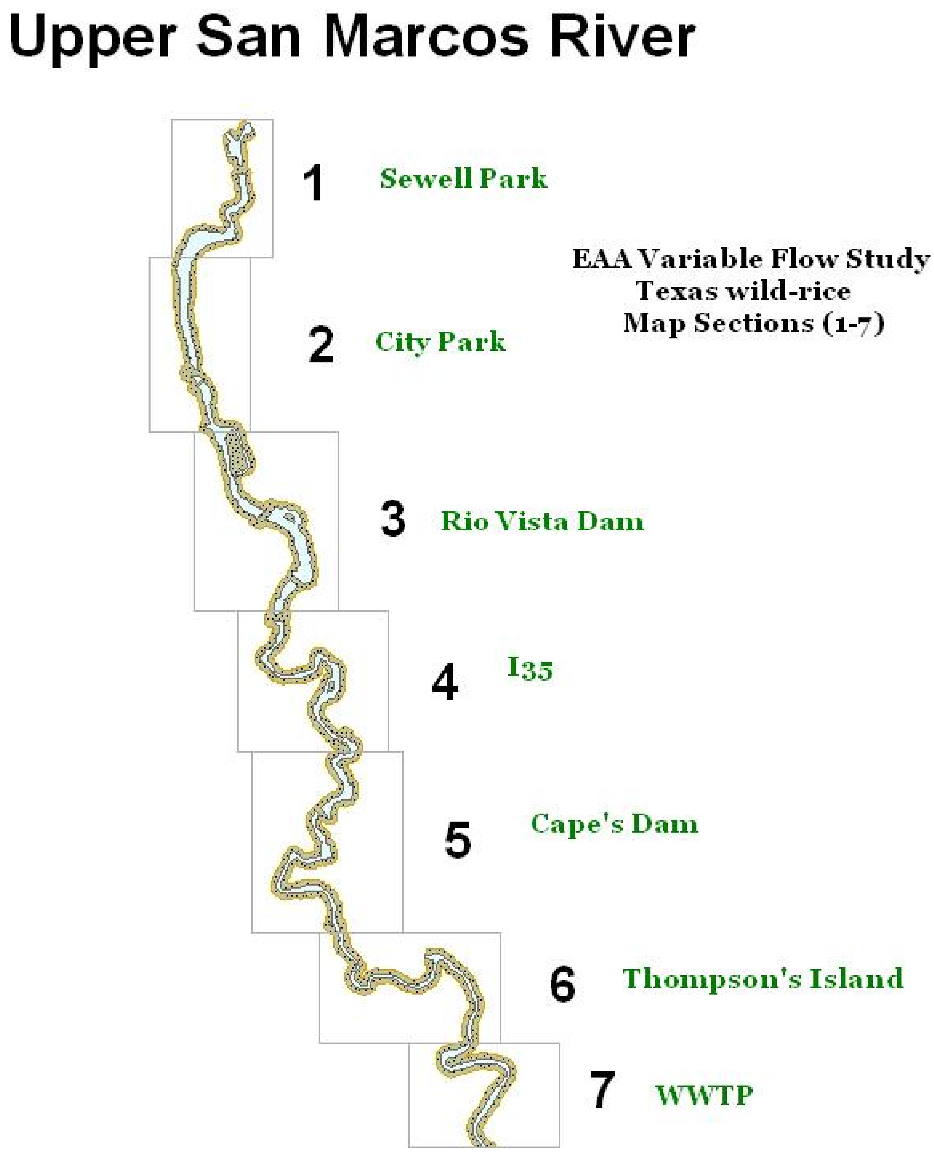


Figure 11: Texas wild-rice mapping sections for the Edwards Aquifer Authority variable flow study (BIO-WEST 2009b)

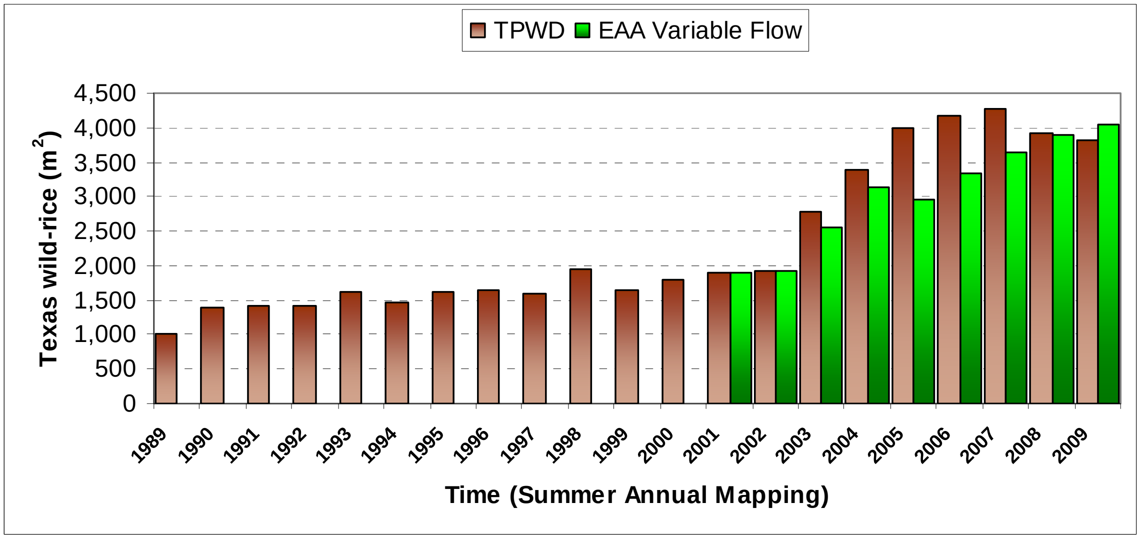


Figure 12: Total Texas wild-rice coverage (square meters [m^2]) on an annual basis as reported by Texas Parks and Wildlife Department and the Edwards Aquifer Authority variable flow study (only summer annual mapping results presented).

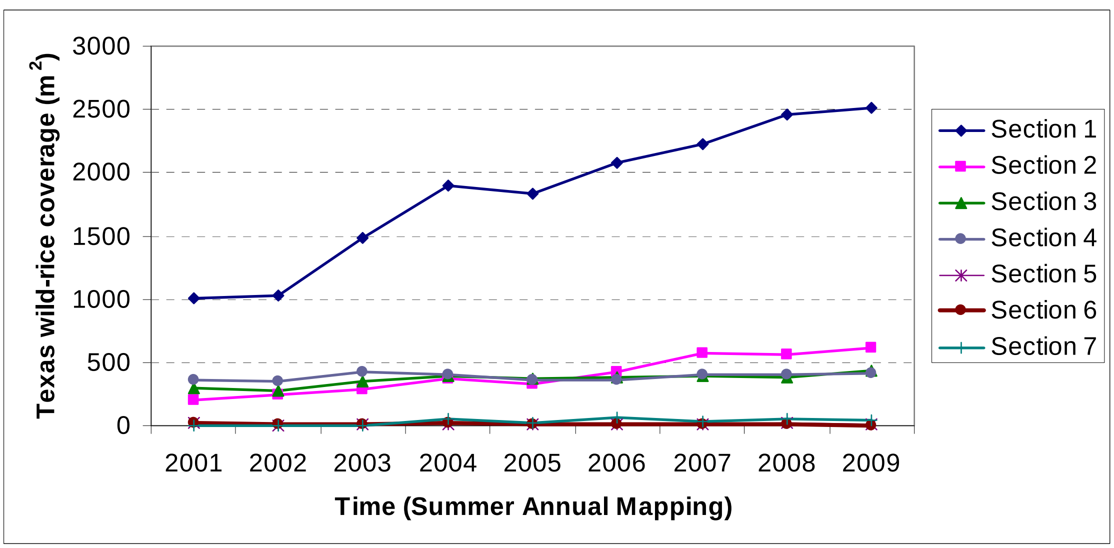


Figure 13: Total Texas wild-rice coverage (square meters [m^2]) per the Edwards Aquifer Authority variable flow study section (Figure 11) measured on an annual basis.

Other segments such as J and E have decreased as well with the Segment J decrease due to the 1998 flood and the Segment E decrease due to increased recreation below Rio Vista Dam. Thus, while coverage has increased in some areas, the overall range of Texas wild-rice has decreased—a troubling sign for a species with an already limited range. It should also be pointed out that increases in some segments of the river have been a result of human intervention via planting (Spring Lake; segments A, F, and K), seeding (Segment A), and appropriate management (that is, temporary removal of vegetation mats covering Texas wild-rice in the Sewell Park section of Segment B).

It should be pointed out that the annual summer monitoring data (Figure 12, Table 7) shows that during the low-flow conditions experienced during 2006, Texas wild-rice overall coverage as measured during the summer annual mapping (both Texas Parks and Wildlife Department and Edwards Aquifer Authority in 2006) actually increased compared to summertime results from 2005. While similar trends were exhibited in most sections or segments when viewed on that basis (Figure 13, Table 7), some sections (3, 4, and 6) or segments (C, D, H, and J) remained more or less stable or decreased. During the more extended low-flow conditions of 2009, Texas wild-rice overall coverage results were mixed, with Edwards Aquifer Authority showing a slight increase in coverage and Texas Parks and Wildlife Department showing a slight decrease. Coverage decreased in most of the Texas Parks and Wildlife Department segments, although coverage increased in segments C, H, and L. In the Edwards Aquifer Authority sections, coverage increased in all sections except where coverage remained stable in sections 6 and 7. However, during 2006 and 2009, it was very evident that lower water conditions affected Texas wild-rice stands during summer time conditions. In these years, annual measurements did not capture the entire picture of changing conditions in the wild. Therefore, Edwards Aquifer Authority conducted additional mapping of the whole river in early October in each of these years to quantify that impact. The average discharge from April through September 2006 and 2009 were approximately 107 cubic feet per second and 94 cubic feet per second, respectively.

—Summer (July)/fall (October) 2006

When the October 2006 mapping for Texas wild-rice was conducted, the average springflow in the previous six months was approximately 107 cubic feet per second. Springflow the six months prior to April 2006 was approximately 140 cubic feet per second which shows that for over a year the springflow conditions were below average and steadily decreasing. As discharge continued to decline to the lowest levels recorded in the previous 10 years, areas that were previously very shallow became exposed. As dry land became more prevalent, Texas wild-rice stands became fragmented and plants died. Other aquatic vegetation and in some cases terrestrial grasses began to replace habitat that had previously been dominated by Texas wild-rice. The shallow water also made it possible for more people to walk in these shallow areas creating paths and further fragmenting large Texas wild-rice stands. Low flows in combination with lack of flushing flow events also led to large, thick vegetation mats covering considerable areas of Texas wild-rice. The mats were especially prevalent in shallow areas, such as Sewell Park, where many Texas wild-rice plants either had submergent leaves close to the water's surface due to low flows or emergent blades that caught floating vegetation and trash coming from upstream and the surrounding area. These floating vegetation mats can prohibit photosynthesis as evidenced by discoloring of leaves when these mats are cleared off. In addition, as vegetation floats over the Texas wild-rice, it can pull out or shred the leaves (Power 1996b).

Figure 14 provides photographs of conditions in Sewell Park in September 2006. The photographs show the healthy stands in the deeper portion on river left (left) and the poor health of the stands intertwined with the emergent vegetation along the river right (right). The greatest impacts observed during 2006 were the indirect effects of the lower discharge conditions on Texas wild-rice. The most prominent indirect effects were from extensive sedimentation that has occurred over the past decade and increased recreation in these shallow areas. For example, in the upper end of Sewell Park, "paths" developed in the shallow areas where Texas wild-rice was located as it was easier for people to wade in these areas during lower discharge conditions. People were observed walking in these areas and parking their kayaks/tubes/inflatable floats on top of plants, leading to plants being pulled out or trampled.

Figure 14: Texas wild-rice in Sewell Park, September 2006.

The greatest single impact was observed in the eastern spillway below Spring Lake Dam where a 73 percent decrease in total Texas wild-rice area was observed in October 2006 (Figure 15). Upon visual observation during a field investigation, it was evident that large patches of Texas wild-rice had been physically pulled out with only solitary leaves and root-mats to indicate where these plants had been.

Further evidence of manipulation of the river by people was present immediately downstream of Spring Lake Dam. Artificially created walls of rocks emerging from the water column served to further channelize this area, blocking flow to several Texas wild-rice plants and perhaps disturbing San Marcos salamanders.

To put the Spring Lake Dam physical disturbance into perspective, the overall coverage of Texas wild-rice in the San Marcos River, according to the Edwards Aquifer Authority variable flow study, increased by 50 square meters from July 2005 to October 2006. Texas Parks and Wildlife Department data also shows a similar small increase in total coverage between 2005 and 2006 as well as an increase in Segment A of 26 percent (Texas Parks and Wildlife Department 2006 data was gathered in June before the

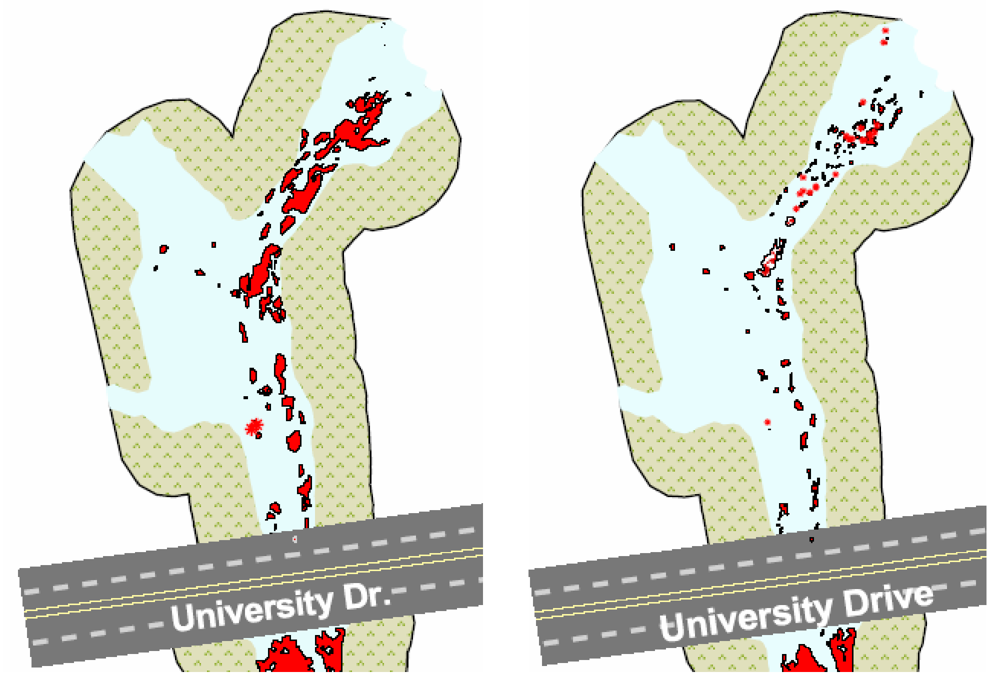


Figure 15: Texas wild-rice aerial coverage (July 2006, left; October 2006, right).

recreational damage in September). From July 2006 to October 2006, the overall (river wide) Texas wild-rice coverage declined by 335.3 square meters or approximately 10 percent. Subtracting the 234 square meters that was clearly human-related disturbance, this leaves an overall 2006 decline (101 square meters—approximately 3 percent) that might be directly attributable to lower discharges or other causes.

—Summer (July)/fall (October) 2009

When the October 2009 mapping for Texas wild-rice was conducted, the average springflow since that preceding spring (April) was approximately 94 cubic feet per second. During 2008-2009, the lowest 6-month average was approximately 91 cubic feet per second; the lowest 12-month average was approximately 96 cubic feet per second; and the lowest l6-month average was approximately 103 cubic feet per second. This highlights the extended nature of the drought in 2008 and 2009. Table 8 shows the decline in Texas wild-rice that accompanied lower than average flow conditions in the San Marcos River from July to October of 2006 and 2009.

Figure 16 provides photographs of conditions in Sewell Park in August 2009. The photographs show the shallow water and stands of Texas wild-rice along the river left (left) and the emergent vegetation and almost non-existent Texas wild-rice stands along the river right (right).

Although summer-to-summer annual Edwards Aquifer Authority variable flow study coverage of Texas wild-rice increased from July 2005 through June 2009 (Texas Parks and Wildlife Department annual coverage decreased almost 11 percent from 2007 to

Table 8: Total coverage and percentage decline of Texas wild-rice in the San Marcos River during 2006 and 2009 (BIO-WEST 2007b, BIO-WEST 2010b).

Year	Total Texas wild-rice (m^2)		% Decline
	Summer (July)	Fall (October)	
2006 Total	3,335	3,000	10
2006 (not including physical uprooting in Spring Lake Dam Reach)	3,335	3,234	3
2009 Total	4,034	3,350	17

Figure 16: Texas wild-rice in Sewell Park, August 2009.

2009), impacts during 2006 and 2009 did occur. Including the 234 square meter area below Spring Lake Dam which was documented to be direct physical disturbance, there was a 10 percent decrease in Texas wild-rice from July to October 2006. The impacts observed in 2009 were much greater, with an overall 17 percent decrease from July to October. Table 9 highlights the declines or increases in each of the Edwards Aquifer Authority variable flow study sections, again demonstrating that 2009 was more severe than 2006. According to the Edwards Aquifer Authority data, only Section 1 (Sewell Park section) exhibited declines during 2006 (total area of Texas wild-rice decreased 384.1 square meters, an 18 percent decrease in coverage from July to October 2006 [Table 9]). Texas Parks and Wildlife Department also showed a 12 percent decrease in aerial coverage in Segment A between 2006 and 2007. However, as discussed previously, much of this decrease occurred just below Spring Lake Dam where a large area of Texas

Table 9: Total Texas wild-rice coverage (square meters [m^2]) for each Edwards Aquifer Authority variable flow study section during summer and fall 2006 and 2009.

Year / Section	Total Texas wild-rice (m^2)		% Decline		
	July	September			
2006					
Section 1	2,080	1,695	18		
Section 2	429	431	-1		
Section 3	386	386	0		
Section 4	357	400	-12		
Section 5	9	10	-10		
Section 6	10	11	-10		
Section 7	66	67	-2		
2009	June/July	October		Decrease (m^2)	% of overall TWR decreased
Section 1	2,517	2,071	18	446	65
Section 2	610	522	14	88	13
Section 3	433	363	16	71	10
Section 4	413	341	17	72	11
Section 5	14	10	25	3	<1
Section 6	2	3	-45	-1	0
Section 7	46	42	10	5	1

wild-rice was manually removed by recreationists in early September. The majority of this decline was the physical disturbance below Spring Lake Dam followed by the river right portion of Sewell Park that became exposed causing fragmentation of stands. However, Texas Parks and Wildlife Department segment data from 2006 to 2007 also showed declines in segments C (1 percent), F (2 percent), G (7 percent), J (12 percent), K (20 percent), and L (3 percent).

During 2009, each of the sections (with the exception of Section 6) exhibited declines in coverage of Texas wild-rice from July to October (Table 9). This overall reduction can be translated as the entire river was experiencing low enough flow conditions to leave Texas wild-rice stands exposed or in extremely shallow water. As in 2006, the greatest decrease in area (446 square meters) was in Section 1 which represented 65 percent of the Texas wild-rice lost during this period. This data clearly illustrates that as flows approach 100 cubic feet per second, total discharge impacts to Texas wild-rice become more pronounced. As total discharge declines to 90 cubic feet per second, impacts are magnified in that Texas wild-rice stands in shallow water become exposed and stranded. Texas Parks and Wildlife Department 2009 monitoring data (Jackie Poole, unpublished data) revealed 99 Texas wild-rice stands (15 percent of the total stands) at less than optimal depths, with 56 Texas wild-rice stands (almost 9 percent of the total stands) in water less than 6 inches deep, and some stranded. Many such plants were moved to deeper water, but lack of personnel meant that not all stranded plants would be rescued. Additional losses occurred throughout the river at these flows, but again were magnified within areas that encounter high recreation pressure.

The durational component experienced in 2009 must also be considered in this evaluation. In 2006, the lower flow conditions were only experienced for approximately three months, whereas in 2009 the low flow conditions were experienced for greater than one year. The potential magnification of effects by extended durations of low flow was a key factor in our determination to have a minimum 6-month criterion within the recommended flow regime.

As flows have not been observed at levels nearer to historical minimums, modeling efforts have been conducted to evaluate the potential for impacts to Texas wild-rice at lower flow conditions. An evaluation of the Saunders and others (2000) report shows that approximately 10 percent and 20 percent of weighted usable area would be lost when springflow drops from 140 cubic feet per second to 80 cubic feet per second and 50 cubic feet per second, respectively (Table 10). For these estimates, the weighted usable area approach was described in Saunders and others (2000) and summarized below.

The Saunders and others (2000) approach includes combining habitat suitability (only depth, substrate, and velocity for Texas wild-rice were included) and hydraulic modeling components to determine weighted usable area. In the lower San Marcos River (Segment 1—millrace headgate to Cumming’s Dam), weighted usable area for Texas wild-rice was lowest above 140 cubic feet per second and increased slightly as discharge decreased from 140 to 80 cubic feet per second, but weighted usable area did not fall below 96 percent of optimal conditions as discharge declined to 50 cubic feet per second. Unfortunately, most of the Texas wild-rice in this segment was lost in the 1998 flood (two years after the Saunders and others data was taken). Despite at least two attempts to reintroduce Texas wild-rice to this area, coverage remains extremely low. In the farthest upstream portion (Segment 3—Spring Lake Dam to Rio Vista Dam), the most weighted usable area is available around 120 cubic feet per second; this drops to around 78.8 percent of that number at 50 cubic feet per second. Segment 2 (Rio Vista Dam to millrace headgate) is similar to Segment 1, and weighted usable area declines steadily from 140 cubic feet per second to 79.5 percent of optimal conditions at 50 cubic feet per second.

Table 10: Weighted usable area (WUA) simulated for Texas wild-rice in the San Marcos River (Saunders and others 2000). Segment 3 extends from Spring Lake Dam to Rio Vista Dam, Segment 2 extends from Rio Vista Dam to Millrace headgate downstream of the fish hatchery outfall, and Segment 1 extends from the Millrace headgate to Cumming's Dam (see Saunders and others 2000) (cfs = cubic feet per second).

VEGETATION TARGET SPECIES	Springflow (cfs)	Total % WUA in Segment 1	% of maximum	Total % WUA in Segment 2	% of maximum	Total % WUA in Segment 3	% of maximum
Texas wild-rice *Zizania texana*	140	63.0	96.2	37.0	94.9	49.0	99.0
	120	64.0	97.7	36.5	93.6	49.5	100.0
	100	65.0	99.2	35.0	89.7	48.5	98.0
	80	65.5	100.0	35.0	89.7	46.0	92.9
	60	63.0	96.2	31.5	80.8	41.0	82.8
	50	63.5	96.9	31.0	79.5	39.0	78.8

An additional modeling effort to evaluate Texas wild-rice was conducted by Bartsch and others (2000) and recently revised by Hardy (2009). Figure 17 shows the simulated Texas wild-rice available habitat in the San Marcos River based on 1997 channel geometries, 2001 channel geometries, and geometries based on assumed removal of Cape's Dam.

Regarding Figure 17, Hardy (2009) states that "The results suggest that Texas wild-rice habitat availability is maximized in both these sections of the San Marcos River as flow rates increase above approximately 100 cubic feet per second." The results also suggest that rapid decreases in suitable area occur below the 65 cubic feet per second simulated flow. At 65 cubic feet per second, approximately 75 percent of maximum habitat is maintained and drops to approximately 50 percent at 30 cubic feet per second. Loss in available habitat occurs rapidly as flows drop below 30 cubic feet per second." Hardy (2009) summarizes the technical team's review of the model results as follows: "As part of the technical team evaluation, the spatial distribution of predicted cell suitabilities were examined on a computational cell by cell basis and compared to actual wild rice distributions based on 1989 to 2008 monitoring data at each simulated discharge. Observed versus use frequency distributions at flow above 60 cubic feet per second are very similar to that reported above for 60 cubic feet per second while the results for 30 cubic feet per second are indicative of the results at simulated flow lower than 30 cubic feet per second. This appears to be a systematic bias in the modeling results at lower flows that should be examined in more detail with the revised modeling currently underway."

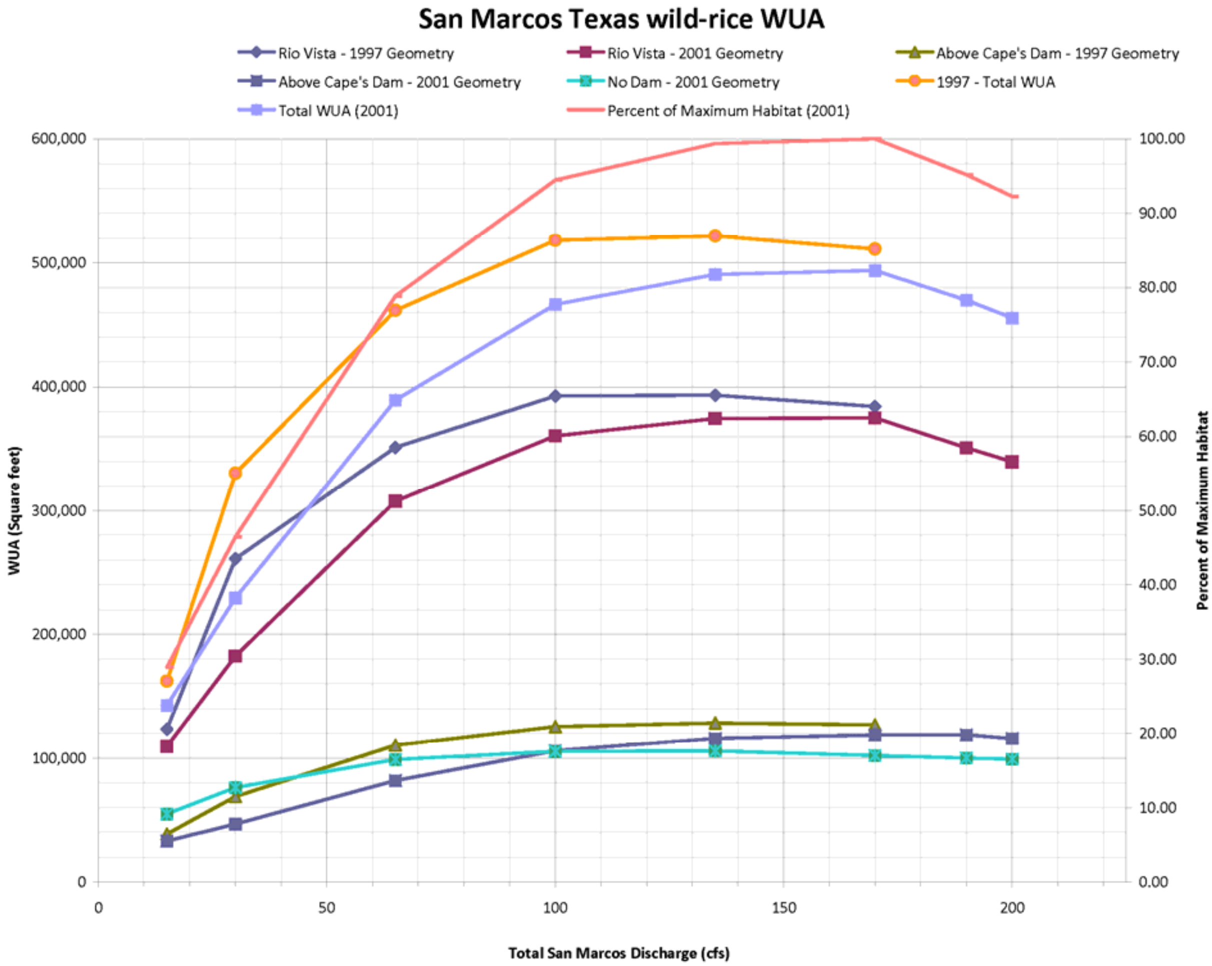


Figure 17: Simulated Texas wild-rice available habitat in sections of the San Marcos River (Hardy 2009) (cfs = cubic feet per second' WUA = weighted usable area).

As with all such models there is a difference between suitable cells (potential habitat) and the actual occupied cells. Also, the San Marcos River is fairly dynamic, with frequent changes in bathymetry related to flooding and sedimentation. Changes in bathymetry have occurred since the Saunders and others model was run. Bathymetry was redone in 2001 and used in the Hardy model (Hardy 2009). In order to compare potential or predicted vs. occupied habitat, the Texas wild-rice annual monitoring data from 2001 (Poole 2002) was overlaid on the Hardy model's computational grid. Flows in 2001 during the time of monitoring were similar to the 190 cubic feet per second flow that Hardy modeled. There was a 17 percent and 9 percent match between predicted habitat and occupied habitat in the Rio Vista and Above Capes sections, respectively. As a rooted plant, Texas wild-rice is not able to move quickly to areas of potential habitat as they become available. Thus, such models are of limited use in determining the decline of the population. The models are more useful in determining potential habitat for future reintroductions of Texas wild-rice.

As previously mentioned, an additional concern to this species is recreational use of the river, which is heavy (Bradsby 1994) and known to have measurable impacts on Texas wild-rice (Breslin 1997). Breslin (1997) details the relative impacts of various activities to Texas wild-rice, and Bradsby (1994) discusses the relative quantity of use of the river during different levels of flow, but there are no quantifiable impacts detailed at various discharge levels. Presumably, as discharge decreases, a greater percentage of the plants are exposed to tubers, canoeists, kayakers, and dogs, which increases potential negative consequences. As discussed for recreational impacts to the fountain darter, minimizing periods of low springflow provides a conservative approach to overcoming the problem of recreational impacts.

- San Marcos gambusia (*Gambusia georgei*)

The San Marcos gambusia has not been collected since 1982 (USFWS 1996) and is most likely extinct. As a precaution, the U.S. Fish and Wildlife Service (USFWS 1993) has issued take and jeopardy levels corresponding to those for the fountain darter in the San Marcos Springs System where the San Marcos gambusia was previously found. Major concerns for any existing San Marcos gambusia include elevated temperatures and the presence of quiet, shallow, open water with partial shading adjacent to fast-moving current. The exact cause for the decline of the species in the early 1980s is unknown, but hybridization with the western mosquitofish (*G. affinis*) is believed to have contributed. Although hybridization occurred in relatively small numbers historically, for unknown reasons collections in the early 1980s indicate hybrids had become many times more abundant than the pure strain of San Marcos gambusia. Another likely cause for the decline of this species is that suitable habitat is severely limited in the system; virtually all locations with the necessary conditions to support this species have been invaded by and overgrown with the exotic macrophyte, elephant ears (*Colocasia esculenta*). Because of the probability that this species is no longer found in the system, specific components of a flow regime aimed at its protection are not considered here. As indicated in the U.S. Fish and Wildlife Service Recovery Plan (USFWS 1996), the measures adopted to support the continued existence of the fountain darter are assumed to be sufficient to support any remaining San Marcos gambusia without incurring harm to the species.

- Texas blind salamander (*Eurycea rathbuni*)

Texas blind salamanders (*Eurycea rathbuni*) are found in the subterranean waters of the San Marcos area of the Edwards Aquifer. They live in water-filled cavernous areas, and are neotenic (reproduce in the larval form) and aquatic throughout their life. Primary concerns to the Texas blind salamander are depth of the water table and water temperature (Longley 1978, Berkhouse and Fries 1995). The latter is an assumption based on the constant temperatures of the water in which the species is found; more research is needed to address the affects of temperature changes to the species. Regardless, the temperature of the water stored in the aquifer is constant at approximately 69.8º F (21º C), which is unaffected by temperatures aboveground or fluctuations in discharge from spring openings. Depth of the water table fluctuates depending on recharge to the aquifer and withdrawals made from it. Despite concern for a decline in the water table, the springs feeding the San Marcos River (in Spring Lake) have not ceased flowing in recorded history. Concerns with water quality include human activities (that is, nonpoint source runoff, sewage leaks, and other chemical contamination) in the recharge zone and lowered aquifer levels preventing adequate dilution to these contaminants. There is also concern with encroachment of the "bad water" line into spring areas; however, evidence indicates that minimal salinity changes occur only in the transition zone, not at the springs under historical aquifer level changes. Springflow issuing from the major springs within Spring Lake might be sufficient for the protection of this species within the aquifer. However, with the unknowns surrounding the "bad water" line, the conservative approach would be to maintain springflow at no less than historically recorded values.

- San Marcos salamander (*Eurycea nana*)

San Marcos salamanders (*Eurycea nana*) are found throughout Spring Lake (at the headwaters of the San Marcos River) where rocks are associated with spring openings and in rocky areas up to 150 meters below Spring Lake Dam (Nelson 1993, BIO-WEST 2007c). The primary concerns facing the San Marcos salamander are water temperature, available physical habitat, and water quality.

Temperature requirements are known only from research conducted to determine critical thermal maximum for the species: 96.4º F (35.8º C) and 99.1º F (37.3º C) for juveniles and adults, respectively (Berkhouse and Fries 1995). Because of the constancy of the water temperature issuing from the springs (Groeger and others 1997), it is extremely unlikely that this temperature maximum will ever be reached. Temperatures at which sub-lethal effects, such as decreased fecundity and growth rates, begin to occur are unknown. A cautious approach is preferred in such instances, but the temperature of the water issuing from the springs fluctuates very little and the springs have not ceased to flow in known history. Downstream of Spring Lake Dam, there is a greater potential for water temperatures to increase; however, studies have shown that the temperature in this portion of the San Marcos salamander's range remains virtually unchanged from the temperature at the spring orifice (Groeger and others 1997, Saunders and others 2000, Hardy 2009). Thermal requirements of the San Marcos salamander should be met as long as water continues to flow from the spring openings in Spring Lake and over Spring Lake Dam.

One of the habitat requirements of the San Marcos salamander is silt free rocks around the spring openings within Spring Lake and downstream of the dam (Tupa and Davis 1976, Nelson 1993, BIO-WEST 2007c). Because the rocks utilized by the salamanders are located adjacent to spring openings, they are kept silt free as long as water is issuing from the springs. Rocks within the habitat downstream of the dam are more susceptible to being covered with detritus or silt that washes over the dam. No research is available to determine what discharge levels are necessary to prevent build up of silt and detritus in this reach. This area is close to the headwaters (Spring Lake); thus, little silt enters the system before it reaches this section. In addition, flow is generally rapid (sufficient to prevent siltation) in this reach as water travels over the dam and through this relatively shallow region just downstream.

In addition to using silt free rocks, the San Marcos salamanders are abundant in the filamentous algae found in the upper end or "hotel reach" section of Spring Lake (Tupa and Davis 1976, Nelson 1993, BIO-WEST 2007c). Investigators hypothesize that San Marcos salamanders find abundant food in the algae as well as increased protection from predators. Because of the stable water temperature, dissolved oxygen, and nutrients found in Spring Lake (McKinney and Sharp 1995), algae is abundant in this section of the lake. Within the period of record, changes in discharge from the springs have had very little affect on these water quality parameters.

Wetted perimeter is another concern for the San Marcos salamander, though the relative constancy of the water level in Spring Lake, even with changes in discharge, minimizes this concern. Unlike habitat in the lake itself, portions of the San Marcos salamander range found downstream of Spring Lake are subject to changes in wetted perimeter as discharge fluctuates. At a site immediately downstream of the San Marcos salamander's range (just upstream of University Drive Bridge), information gathered from Saunders and others (2000) reveals that a wetted width of 60.8 feet occurs when flows reach 172 cubic feet per second. At a discharge of 125 cubic feet per second, 56.8 feet (93 percent) of the wetted width remains, and at 81 cubic feet per second, 50.4 feet (83 percent) remains.

Recreation and water chemistry are other factors that can impact the San Marcos salamander population. Recreation is regulated and generally prohibited on Spring Lake, although archeological excavations and other scientific investigations may disturb sites where San Marcos salamanders are found. Downstream of the dam, the river is open to the public and portions are heavily used by recreationists, but impacts in the area immediately below the dam during higher flow conditions are limited because of the depth (west spillway) and underwater hazards (remains of old dam; east spillway). However, during lower flow conditions, the depth in the western spillway is reduced and the underwater hazards are exposed which causes the recreational use in this area to intensify.

There were no noted direct impacts from springflow to the San Marcos salamander population at the locations sampled for the Edwards Aquifer Authority variable flow study during the low-flow periods experienced in 2006 and 2009 (BIO-WEST 2007b, BIO-WEST 2010b). However, habitat conditions in the riverbed portion of Spring Lake in July 2009 were reduced due to extensive vegetation growth and corresponding siltation. This was not experienced during the reduced flow period in 2006. The shallower water depths below Spring Lake Dam as a result of the low discharge conditions in 2006 and 2009 did cause some indirect effects on San Marcos salamander habitat via increased recreational activity. Recreation in the immediate areas below the dam increased during these periods with many rocks being physically moved by people to create structures, dams, underwater rock art, and artificial channels (Figure 18). Although not captured in the snorkel surveys, the physical perturbation associated with this recreation as well as the habitat modification likely had some impacts on the resident salamander population below Spring Lake Dam.

Springflow issuing from the major springs within Spring Lake to the degree necessary to overflow Spring Lake dam and inundate the western spillway is anticipated to be sufficient for the protection of the San Marcos salamander. However, with the unknowns surrounding habitat conditions within Spring Lake under flows less than the historical record, the conservative approach would again be to maintain springflow at no less than historically recorded values.

Figure 18: Physical disturbance below Spring Lake Dam, September 2006.

- Comal Springs riffle beetle (*Heterelmis comalensis*)

Comal Springs riffle beetles (*Heterelmis comalensis*) have been found near spring orifices within Spring Lake (Gibson and others 2008). Unlike Comal Springs, there is no spring run habitat (for example, surface habitat) for modeling in Spring Lake, and only upwelling habitat areas are maintained. Similar to the salamanders, springflow issuing from the major springs within Spring Lake is anticipated to be sufficient for the protection of this species within upwelling areas and subsurface habitat. However, as mentioned for the salamanders, the conservative approach would be to not allow springflow to fall below historically observed flow conditions.

<u>Historical flows at San Marcos Springs</u>

Similar to the Comal Springs system, an evaluation of the historical hydrology was conducted to put the observed variable flow data from the past nine years, the Texas Parks and Wildlife Department Texas wild-rice annual monitoring data of more than 20 years, and predicted model results in perspective. The average discharge at San Marcos Springs during the period of record from 1940 to 2009 was approximately 164 cubic feet per second. The minimum recorded flow was 46 cubic feet per second on August 15 and 16, 1956. The minimum monthly average springflow of 53.5 cubic feet per second also occurred in August 1956. For an 18-month period (September 1955 through February 1957), monthly average springflow was 68.6 cubic feet per second and ranged from 76.8 cubic feet per second (September 1955) to 53.5 cubic feet per second (August 1956). This springflow condition, coupled with the duration of this event, resulted in an extreme low flow condition that no doubt had direct impacts on threatened and endangered species habitat and most likely directly on the species as well (especially Texas wild-rice). While all the listed San Marcos species (with the exception of the Comal Springs riffle beetle and the San Marcos gambusia) were known from the San Marcos ecosystem before and after the extreme low flow conditions of the 1950s, there is no evidence as to the size, distribution, or health of any of their populations immediately prior to or after that extended event. Additionally, conditions in the watershed of the San Marcos River have changed dramatically over the last 50 years, with increases in both urban and rural population, aquifer pumping, impervious cover and runoff, sedimentation, non-native invasive species, recreation, roads, bridges, and dam failures. The system is more stressed today than 50 years ago. Therefore, there is less confidence that the threatened and endangered species would necessarily persist if those extreme low flow conditions were repeated.

<u>San Marcos Springs flow regime recommendations</u>

Figure 19 provides an overview of the information used to develop the flow regime recommendations for the San Marcos Springs system. To develop an ecologically protective flow regime, a balancing of species specific requirements was conducted where results did not align identically. In instances where there were competing species specific requirements, the higher flow requirement was conservatively chosen in each case following an analysis and understanding that this recommendation would not negatively impact the other species or overall ecosystem integrity.

Based on the review of the best available science discussed throughout this report and summarized in Figure 19, we developed the San Marcos Springs Flow Regime as presented in Table 11.

With the assumptions noted, it is our determination that maintaining all components of the proposed flow regime would meet the goal of long term survival of the threatened and endangered species of the San Marcos Springs system in the wild.

The long-term average value flow of 140 cubic feet per second is supported by long-term monitoring data and modeling results. At these total discharge levels, populations of each of the threatened and endangered species are anticipated to maintain or increase their respective populations. The most important aspect of maintaining the long-term average component of the flow regime is that the system would not be able to have repeated 6-month or 1-month events also prescribed in the flow regime. As such, the lower flow criteria were developed with the understanding that if they should occur, they would rarely be experienced in the future.

Long-term average	Minimum 6-month average	Minimum 1-month average
Poole (2002, unpublished data) - 21 annual demographic monitoring surveys have been conducted since 1989, at discharges ranging from 78 cfs to 400 cfs. ***Edwards Aquifer Authority Variable Flow Study (BIO-WEST 2002b-2010b)*** - 22 comprehensive sampling events have been conducted since 2000 over a total discharge range of 105 cfs to 417 cfs. Total San Marcos Springs system discharge greater than 140 cfs has been shown to provide high quality habitat throughout the range for the species present in this system. ***Saunders and others (2000)*** - Diverse aquatic vegetation maintained at 140 cfs. - Maximum Texas wild-rice habitat predicted at 120 cfs in Segment 3 (Sewell Park reach) ***Bartsch and others (2000)*** - No discernable change in modeled fountain darter habitat from 135 to 100 cfs total discharge. - Temperature conditions are suitable for fountain darter reproduction within its entire range at 80 cfs. ***Hardy (2009)*** - Maximum predicted available habitat for fountain darter at 65 cfs. - Maximum predicted available habitat for Texas wild-rice at 170 cfs. - Approximately 95% of maximum predicted available habitat for Texas wild-rice at 100 cfs. ***Historical Hydrology*** - Average total discharge from 1956 – 2009 is 173 cfs. cfs = cubic feet per second	***Poole (2002, unpublished data)*** - 4 annual demographic monitoring surveys conducted during low flow (<110 cfs) periods. - Monitoring and transplanting Texas wild-rice during flows <100cfs in 2006 and 2009 as well as Cape's Dam breach in January 2000. ***Edwards Aquifer Authority Variable Flow Study (BIO-WEST 2002b, 2007b, 2010b)*** - 6 Critical period full monitoring events have been conducted since 2000 ranging in total discharge from 92 cfs to 108 cfs. - Aquatic vegetation reductions in highly recreated areas magnified below 100 cfs. - Slight siltation of San Marcos salamander habitat within riverbed area of Spring Lake below 100 cfs in 2009. - Nearly 20% reduction in Texas wild-rice coverage in 2009 following a 12-month duration of approximately 96 cfs. ***Saunders and others (2000)*** - Greater than 80% of maximum run, riffle, and pool habitat maintained at 60 cfs. - Greater than 60% of modeled aquatic vegetation maintained at 60 cfs throughout all segments. - Approximately 90% or greater and greater than 80% of maximum predicted available habitat for Texas wild-rice at 80 cfs and 60 cfs, respectively. ***Bartsch and others (2000)*** - Approximately 90% of maximum available fountain darter habitat predicted at 65 cfs. - Temperature conditions are suitable for fountain darter reproduction to Cape's Dam at 55 cfs. ***Hardy (2009)*** - Maximum available habitat for fountain darter predicted at 65 cfs. Approximately 85% and 75% of maximum predicted available habitat for Texas wild-rice at 80 cfs and 65 cfs, respectively. ***Historical Hydrology*** - Minimum 6-month average discharge was 61 cfs from May to November 1956.	***Edwards Aquifer Authority Variable Flow Study (BIO-WEST 2002d, McDonald and others 2007)*** - Comal Springs riffle beetle laboratory studies suggest that the beetle has a strong affinity for upwelling flow and will retreat into artificial substrate during periods of low discharge. - Laboratory study suggests trematode gill parasite did not have a significant impact on fountain darter reproduction. ***Saunders and others (2000)*** - Greater than 75% of maximum run, riffle, and pool habitat maintained at 50 cfs (lowest flow modeled). - Greater than 55% of modeled aquatic vegetation maintained at 50 cfs throughout all segments. - Approximately 96% (Segment 1), 79% (Segment 2), and 78 % (Segment 3) of maximum available habitat for Texas wild-rice predicted at 50 cfs. ***Bartsch and others (2000)*** - Approximately 90% and 55% of maximum available fountain darter habitat predicted at 65 cfs and 30 cfs, respectively. - Temperature conditions are suitable for fountain darter reproduction from Spring Lake to Rio Vista Dam at 30 cfs. ***Hardy (2009)*** - Approximately 75% of maximum available fountain darter habitat predicted at 30 cfs. - Approximately 75% and 55% of maximum available habitat for Texas wild-rice predicted at 65 cfs and 30 cfs, respectively. ***Historical Hydrology*** - Minimum 1- month average discharge was 53.5 cfs in August 1956. - Lowest flow recorded was 46 cfs in August 1956. - 18-month period (September 1955 through February 1957), monthly average springflow was 68.6 cfs.

Figure 19: Overview of results used to inform initial flow regime recommendation on the San Marcos Springs system.

Table 11: San Marcos Springs flow regime recommendation.

San Marcos Springs flow regime recommendation*		
Criteria	**Flow (cfs)**	**Notes**
Long-term average flow	140	
Minimum 6-month average	75	
Minimum 1-month average	60	No flow below 52 cfs

cfs = cubic feet per second

*Assumptions:

- Invasive species remain at current levels, both as to number of species and numbers of individuals/coverage.
- Gill parasite levels do not increase.
- Amount of sediment in the river does not increase.
- Recreation remains at current levels (that is, no new tube/canoe/kayak rental facilities, no new water parks)
- Current dam configuration remains unchanged.
- Flow recommendations do not reflect the U.S. Geological Survey discharge measurement accuracy range of up to plus or minus 10 percent based on physical and anthropogenic factors affecting stream velocity (that is, no buffers are added).
- Texas wild-rice survived the drought of record and recolonized the river without human assistance.
- No additional mitigation activities beyond those currently in practice.

The minimum 6-month average flow of 75 cubic feet per second is supported by a combination of observed data, model results, and aspects of historical hydrology woven together with professional judgment. Actual data collected and observed at flows slightly higher than this (about 80 to 90 cubic feet per second) show that effects to the fountain darter are minimal but decreases in Texas wild-rice areal coverage have been documented to be approximately 20 percent (BIO-WEST 2010b). The Expert Science Subcommittee is in agreement that dropping to 75 cubic feet per second would not greatly affect fountain darter habitat but would result in greater reductions in total areal coverage of Texas wild-rice, likely 25 to 30 percent or potentially greater.

Habitat model results (Saunders and others 2000 [Texas wild-rice], Hardy 2009 [fountain darter and Texas wild-rice]) show that greater than approximately 80 percent of available habitat is predicted at 75 cubic feet per second (note: 75 cubic feet per second was not actually modeled by either effort; thus, this approximation was made on the flow levels modeled above and below this value). At first glance, these percentages seemed high for this flow regime component, which is likely the case for the fountain darter. However, the interpretation of these results relative to Texas wild-rice is more complicated as it is a plant and cannot simply move to areas of predicted suitable habitat like the fountain darter. To check the predictive ability of these models, Texas wild-rice annual demographic data was used to compare occupied versus predicted habitat. A comparison was made using the Hardy 2001 bathymetry model (Hardy 2009) with the Texas Parks and Wildlife Department's 2001 Texas wild-rice GIS shapefiles (Poole 2002) at a flow of

190 cubic feet per second, as this was the average flow when the Texas Parks and Wildlife Department data was recorded. Using cells from the Hardy (2009) model with a greater than 0.45 suitability rating, 17 percent of the predicted suitable habitat from Spring Lake to Rio Vista was occupied and 9 percent of the predicted suitable habitat from Rio Vista to Cape's Dam was occupied. In addition to the low percentage of predicted habitat that was indeed occupied, it is important to point out that only depth, velocity, and substrate were considered as input parameters to the Texas wild-rice habitat model. As such, an area of river that met these three parameters was predicted to be suitable irrespective if the area was already occupied with another type of aquatic vegetation or shaded by bridges or riparian canopy. Based on these factors, the Expert Science Subcommittee determined that high (greater than 80 percent) percentages of modeled habitat were necessary to be protective of Texas wild-rice.

Finally, we reviewed the historical hydrology for the San Marcos River. The historic minimum 6-month average was approximately 61 cubic feet per second during the 1950s drought. Although the historical minimum 6-month average was less than the proposed 75 cubic feet per second, changing conditions in the San Marcos Springs system since the drought of record, especially increased sedimentation and recreation, coupled with the effects of the 1998 flood and the significant reduction in Texas wild-rice below Interstate 35, guided our determination that a shift upward from the historically observed average was warranted.

There was considerable discussion amongst subcommittee members over the interpretation and integration of the observed data, model results, historical hydrology, changing conditions in the river, and potential frequency of occurrence of this flow component within the context of implementing the flow regime. As with the Comal Springs recommendations, we used best professional judgment to interpret and integrate these components and determined that 75 cubic feet per second for a minimum 6-month average would be protective with the associated assumption that the flow regime is implemented as designed, which would mean that this 6-month average would be experienced very infrequently in the future.

The minimum 1-month average flow of 60 cubic feet per second with a minimum flow of 52 cubic feet per second is the threshold that we recommend the system not fall below with the current set of assumptions in place. The minimum 1-month average flow recommendation was based primarily on professional judgment and habitat modeling as this flow has not been observed by scientists on the biological workgroup or our subcommittee. Although data has not been collected at these flows, we used professional judgment to determine that if 25 to 30 percent reductions in Texas wild-rice are likely at 75 cubic feet per second, reductions at 60 cubic feet per second would be greater. How much more is unknown at this time but, with the refinement of existing habitat models (currently underway), more accurate estimates may be obtained in the near future.

Habitat model results (Saunders and others 2000 [Texas wild-rice], Hardy 2009 [fountain darter and Texas wild-rice]) show that greater than approximately 70 percent of available habitat is predicted at 60 cubic feet per second (note: 60 cubic feet per second was modeled by Saunders and others [2000] but not Hardy [2009]); thus, the interpretation of the latter was made on the flow levels modeled above and below 60 cubic feet per second). Although both models (with all their associated assumptions) still show relatively high percentages of available habitat at 60 cubic feet per second, Hardy (2009) does show a sharp decline below 65 cubic feet per second and Saunders and others (2000) only modeled down to 50 cubic feet per second. As 60 cubic feet per second is below the level of observed hydrology, modeling at this level represents an exercise in extrapolation that inherently creates greater uncertainty around model results. This, coupled with the additional analysis described above regarding occupied area of Texas wild-rice versus predicted area, led us to recommend that greater than 70 percent of modeled habitat was necessary to be protective of Texas wild-rice.

The historical hydrology (U.S. Geological Survey gage data) was again reviewed and revealed that the minimum 1-month average was approximately 54 cubic feet per second during the 1950s drought. Although the historical minimum was lower than the recommended 60 cubic feet per second, we determined that a shift upward from the historically observed monthly minimum was warranted based on the changing conditions in the San Marcos Springs system since the drought of record, especially increased sedimentation and recreation, coupled with the effects of the 1998 flood and the significant reduction in Texas wild-rice below Interstate 35. A component of the historical hydrology we examined closely was the relative gaps between historical events (during periods of drought and falling spring discharge) as represented by the proposed flow regime. For instance, the gap between the historical minimum 6-month average and the historical 1-day minimum was approximately 16 to 23 cubic feet per second. We used this analysis to help describe the 1-day minimum (75 cubic feet per second [6-month average] - 23 cubic feet per second = 52 cubic feet per second (proposed 1-day minimum). Additionally, the gap between the historical minimum 1-month average and historical 1-day minimum was approximately 8 to 15 cubic feet per second. We included an 8 cubic feet per second gap from the proposed minimum 1-month average (60 cubic feet per second) to the 1-day minimum (52 cubic feet per second).

As with the 6-month average recommendation for San Marcos, there was considerable discussion amongst subcommittee members over the interpretation and integration of the model results and embedded uncertainty, historical hydrology, changing conditions in the river, and potential frequency of occurrence of this flow component within the context of implementing the flow regime. We again used best professional judgment to interpret and integrate these components and determined that 60 cubic feet per second for a 1-month average with a minimum flow of 52 cubic feet per second would be protective with the associated assumption that the flow regime is implemented as designed resulting in a 1-month average that would be experienced very infrequently in the future.

We reiterate discussions throughout this report that emphasize that the flow regime recommendations for San Marcos Springs are based on the best available science and professional judgment at this time. We understand that the threatened and endangered species in the San Marcos Spring system can withstand short time periods of habitat loss and even some direct impact to the species themselves without resulting in long-term harm to the overall population. With that said, several questions remain: What frequency or duration of these events could be tolerated by these species without long-term consequences? How many individuals (or cover) can be lost before recovery is impeded or impossible? How long does recovery take, particularly in a population with diminished reproductive capacity? How much can the range be contracted before the probability of a stochastic event wiping out the species becomes significant? In the absence of those answers, we have chosen to exceed the historically observed flow statistics at San Marcos Springs because the condition of the threatened and endangered species populations following the 1950s drought is unknown.

Additional major factors discussed in the Comal Springs recommendations section but very much applicable in the San Marcos Springs recommendation as well are that (1) aquatic vegetation changes are not incorporated into the habitat modeling results, (2) U.S. Fish and Wildlife Service biologists have expressed concern that major die-offs and decomposition of aquatic vegetation during periods of low-flow may cause significant reductions in dissolved oxygen available for the fountain darter, and (3) reduction in aquatic vegetation could also cause crowding or clumping of darters in remaining suitable habitat which could possibly make them more vulnerable to predation or increased competition (native and non-native). These were factors addressed by our professional judgment during the review of model results.

Three additional factors standout in the San Marcos Springs system:

- Asian trematode (*Centrocestus formosanus*)

Should moderate flow exist for several years without any flash floods followed by low flows due to drought conditions, it is anticipated that cercarial abundance may increase to a more severe level (Tom Brandt, personal communication).

- Increased sedimentation

Over the past decade, the upper San Marcos River has filled in considerably from just below Spring Lake Dam (just downstream of the mouth of Sessom Creek) to the reconstructed Rio Vista Dam. If sedimentation is not controlled to some degree, it will likely continue to impact endangered species habitat or the species directly, as in the case of Texas wild-rice.

- Increased recreational pressure

Similar to the trends witnessed with sedimentation, qualitative observations of increasing recreational activity have been noted for the San Marcos Springs system. The main focus of the recreation on the San Marcos River starts immediately below Spring Lake Dam and extends to Cheatham Street Bridge below Rio Vista Dam. Recreational impacts are also increasing in the area below this. The upper stretch of the San Marcos River includes high quality habitat for the San Marcos salamander and fountain darter as well as supporting the highest areal coverages of Texas wild-rice. As with sedimentation, if not addressed, this will likely continue to impact San Marcos salamander and fountain darter habitat, and Texas wild-rice directly.

All the unknowns logically lead one to a conservative mindset in the setting of flow-related requirements. However, we made a conscious decision not to build in cushion to the proposed recommendations. It was our interpretation of the legislative charge to evaluate the best available science objectively, clearly state the assumptions associated with the recommendations, and acknowledge the need for further study where appropriate. For instance, if it is later revealed that significant impacts are not captured in the model results or efforts to control the parasite or its host, sedimentation, or recreation are not in place or successful in the future, then one needs to be cautious with strict implementation of the proposed flow recommendations. However, should information come forward that these species are able to tolerate short periods of lower flow conditions or more frequent occurrences without significant consequence, or mitigation activities are in place that could be effective in providing additional levels of protection, then the proposed flow regime recommendations for the San Marcos Springs System would also need to be revisited. One thing is clear, long-term monitoring is essential and further study and research specifically during critical low flow periods (or simulated critical low-flows) are needed to accurately determine the potential impacts to the species at San Marcos Springs.

Further studies

Several studies have already been funded by the Edwards Aquifer Recovery Implementation Program and are in progress, so only a summary of the studies with biological relevance will be provided in this section. One such study is the update of hydraulic and habitat models for both the Comal and San Marcos Springs systems. The update will include measuring current bathymetry of the systems where appropriate, updating aquatic vegetation maps for the entirety of each system, and an evaluation of canopy cover (shading) and its effect on Texas wild-rice habitat. This study is currently under contract with Dr. Thomas Hardy of the Texas State University, River Systems Institute. The Edwards Aquifer Recovery Implementation Program has also funded a feasibility study of potential Intensive Management Areas on the Comal Springs system. The two main components of this study are evaluating the potential for (1) in-situ refugia—the ability to maintain habitat and endangered species within the Comal Springs/River system itself under severely reduced discharge conditions—and (2) applied research—the ability to explore low and high flow responses of the endangered species and their habitats to better inform future (adaptive) management decisions. This study is currently under contract with BIO-WEST, Inc. The U.S. Fish and Wildlife Service's San Marcos National Fish Hatchery and Technology Center is also under contract with the Edwards Aquifer Recovery Implementation Program to conduct low-flow evaluations of habitat use and genetic diversity of fountain darters within the Comal and San Marcos springs systems.

We support ongoing monitoring efforts being conducted by Texas Parks and Wildlife Department and Edwards Aquifer Authority relative to the evaluation of flow rates on the threatened and endangered species in these systems. We recommend that the following studies be considered to address data gaps relative to flow responses of species requirements not currently being captured within either of those programs.

- Fountain darter
    - *Centrocestus formosanus* is an introduced gill parasite, in the Comal and San Marcos rivers that has the potential to affect resident populations of fountain darters. The research should see if correlations exist among springflow, *Melanoides tuberculatus* (snail host of *Centrocestus formosanus*) numbers, and parasite numbers within each system. Determination of correlations among flow, snail host, parasite, and fountain darter will permit the

development of a model to predict future effects of the parasite on fountain darter survival.

  - Research is needed to evaluate management alternatives for the control of *Centrocestus formosanus* and/or *Melanoides tuberculatus* within the Comal and San Marcos springs systems. Elimination of the parasite from the rivers is not likely. However, physical removal of the parasite's host snail, *Melanoides tuberculatus*, by dredging and using turbulence (dams, riffles, and air bubbles) to kill drifting parasites, needs to be evaluated as a possible method to manage the effects of the parasite on the fountain darter.
  - The effect of water temperature on fountain darter reproduction has been determined. The effects of temperatures between 81° F (27.2° C) and 95° F (35° C) have on fountain darter growth and survival has not been determined. This information is needed to model the stress placed on the population as water temperatures rise within the systems.
- Texas wild-rice
  - Determine the minimum buffer size, both horizontally and vertically within the water column, needed to protect Texas wild-rice from recreational damage.
  - Determine why Texas wild-rice has not re-established well in the San Marcos River below Interstate 35. Specifically investigate CO_2 levels as well as water clarity.
  - Determine the rate at which Texas wild-rice may recolonize following dry periods or floods. This would be an essential component of determining the frequency and duration of low flow events that result in population decline.
- Comal Springs riffle beetle
  - Study the use of subsurface habitat during normal and low-flow conditions to evaluate the size and importance of this habitat type during periods of low flow.
  - Evaluate the potential for maintaining successful reproduction of this species in captivity.
- Comal Springs dryopid beetle and Peck's Cave amphipod
  - Conduct laboratory studies on the life history requirements of these species.
  - Evaluate the potential for maintaining successful reproduction of this species in captivity.
- Invasive species monitoring
  - Monitoring of the Comal and San Marcos rivers to identify newly introduced species. Twice yearly surveys of the plants, invertebrates, and fishes should be done to identify newly introduced species and to determine if significant changes in native species have occurred. Introduced species need to be

removed immediately. Causes of significant changes in native species numbers or distributions need to be determined and addressed.

  - We also recommend that special studies targeted at potential management plans be conducted to protect the listed species directly or through the protection of water quality and/or physical habitat within the San Marcos and Comal rivers.

- Recreation
  - Conduct a study to quantify recreational use and economic benefit on the Comal and San Marcos rivers.
  - Conduct an evaluation to quantify impacts that recreational activity has on threatened and endangered species habitat or directly on the species in both the Comal and San Marcos ecosystems.
  - Develop a recreational management plan for both systems.
- Sedimentation
  - Conduct a study to quantify sediment transport within the San Marcos River.
  - Conduct an evaluation to quantify impacts of sedimentation on fountain darter, San Marcos salamander, and Texas wild-rice within the San Marcos River.
  - Develop a sedimentation management plan for the San Marcos River.

We support the San Marcos River and Comal River restoration committees. Both entities have conducted several meetings and have prepared restoration plans for their respective systems. Within these proposed restoration plans, it is our understanding that each committee will be making recommendations for further studies and/or potential management activities to explore. Finally, we also support interaction and coordination with the Edwards Aquifer Recovery Implementation Program during the preparation of the Habitat Conservation Plan and the Southern Edwards Aquifer Recovery Team during their process of developing a recovery plan for the listed species independent of the Edwards Aquifer Recovery Implementation Program. It is anticipated that the Habitat Conservation Plan and Recovery Plan development will involve several consistent objectives for which we might be able to provide valuable input.

Task 2: Analyze withdrawal reductions and stages for critical period management

Results: The following withdrawal reductions and stages for critical period management resulted from the species requirements in relation to spring discharge rates:

San Antonio Pool

Comal (cfs)	San Marcos (cfs)	J-17 (feet)	Stage -	Reduction (%)
<225	<96	<665	I	85

Uvalde Pool

J-27 (feet)	Stage -	Reduction (%)
< 865	I	85

where cfs is cubic feet per second.

Our interpretation of the task

This task is focused on developing withdrawal reductions and stages for critical period management based on the flow requirements from Task 1. Specifically, statute required us to:

> "*Based on*…[the results of Task 1]…*and the elements required to be considered by the authority under Section 1.14 of this article, the expert science subcommittee shall, through a collaborative process designed to achieve consensus, develop recommendations for withdrawal reduction levels and stages for critical period management including, if appropriate, establishing separate and possibly different withdrawal reduction levels and stages for critical period management for different pools of the aquifer needed to maintain target spring discharge and aquifer levels.*"
> (see Appendix B for the full text).

Among other items, Section 1.14 of the Edwards Aquifer Authority Act (Appendix B) states that the Edwards Aquifer Authority shall (1) protect the water quality of the aquifer, (2) protect the water quality of the surface streams to which the aquifer provides springflow, (3) achieve water conservation, (4) maximize the beneficial use of water available for withdrawal from the aquifer, (5) recognize the extent of the hydrogeologic connection and interaction between surface water and groundwater, (6) protect aquatic and wildlife habitat, (7) protect species that are designated as threatened or endangered under applicable federal or state law, and (8) provide for instream uses, bays, and estuaries.

Based on the wording of the act, we assumed that our task was limited to adjusting withdrawal (pumping) reduction levels and stages for critical period management. We did not suggest changes to the overall permitting cap or how the act or the authority implements withdrawal reductions or permitting (although we did request model runs at different levels of constant pumping to better understand how the aquifer responds to different levels of pumping). Therefore, we restricted ourselves to considering adjustments of (1) the current number of stages; (2) the current trigger levels for J-17, J-27, Comal Springs, and San Marcos Springs; and (3) reductions in pumping at each of the stages.

Based on our interpretation of the task, we developed withdrawal reductions and stages for critical period management that met or exceeded the flow requirements for the endangered species from Task 1—we did not consider minimum pumping (or additional water supply infrastructure) needed to maintain health and human safety or any management actions that could be taken to lower springflow requirements. Our understanding is that these policy issues will be considered by the Steering Committee during the development of a habitat conservation plan.

With respect to the charge, we did not extensively address all elements under Section 1.14 of the Edwards Aquifer Authority Act. Although we considered the need to protect the water quality of the aquifer and that of the aquatic and wildlife habitats in and near the springs with respect to movement of the bad water line and potential contamination, water quality in general was not explicitly considered. We did not consider the protection of aquatic and wildlife habitat in the downstream reaches of the river and its the associated bay and estuary. We did not explicitly consider provisions for instream uses (Senate Bill 3 created a separate process—the environmental flows process—to evaluate the flow requirements for bays and estuaries, a process that is just starting for the Guadalupe-San Antonio River Basin and the Guadalupe Estuary).

Approach

We used an existing numerical groundwater flow model of the Edwards Aquifer to develop withdrawal reductions and stages for critical period management. We used the model to consider different "scenarios", where a scenario included adjustments to critical period management, maximum pumping, or a model parameter such as an initial condition. After deciding on a scenario we wanted to investigate or consider, we filed a request with staff at the Edwards Aquifer Authority to run the model to simulate the scenario, what we refer to as a "model run request". Edwards Aquifer Authority staff used the model developed by Lindgren and others (2004) using MODFLOW-NR (Southwest Research Institute 2007). We used this model because it is (1) the best available tool at this time to evaluate the effects of pumping and recharge on water levels at J-17 and J-27 and springflows at Comal and San Marcos springs, (2) it is used by the Edwards Aquifer Authority for managing the aquifer, and (3) it is recognized by the Texas Water Development Board as a groundwater availability model for the San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer. Where appropriate, the Edwards Aquifer Authority's management module was used to evaluate scenarios. The management module applies withdrawal reductions based on the triggers placed into the module. Edwards Aquifer Authority staff wrote a report of the results and, after internal review at the Edwards Aquifer Authority, delivered the report and output files to the chair of the subcommittee. This report includes our run requests, model run reports from the

Edwards Aquifer Authority, and the model run output files (appendices F, G, and H, respectively).

Based on the results of Task 1, we used the model to look at meeting or exceeding three flow criteria for each of the two springs: a 1-month minimum, a 6-month minimum, and a long-term average for Comal Springs and a 1-month minimum, a 6-month minimum, and a long-term average for San Marcos Springs. Our requested model runs (simulations) fell into three broad categories: (1) runs at constant pumping, (2) runs to investigate the sensitivity of the model to various parameters and scenarios, and (3) runs to attempt to meet springflow requirements while maintaining the permitted pumping cap recognized in Senate Bill 3. We also requested a simulation to serve as a baseline application of current critical period management.

We requested various model runs at constant pumping (that is, no critical period management) to gain an understanding of springflow at different levels of pumping (that is, no critical period management reductions; runs 002, 003, 004, 005, 006, 007, 008, 014, 015, 030, and 032) to help estimate pumping reductions to meet springflow requirements. Although one could come to policy conclusions based on these runs, our intent was not to suggest a modification to the permitting cap or the removal of critical period management.

We requested various model runs to investigate the sensitivity of different parameters and scenarios (runs 009, 010, 016, 017, 018, 019, 020, 021, 022, 023, 024, 028, 029, and 031) to gain an understanding of how springflows might respond to changes in these parameters. Although one could come to policy conclusions based on these runs, our intent was not to suggest modifications to the management of the aquifer based on the runs. For example, Run 031 specified no pumping in Comal and Hays counties. We requested this run to assess the sensitivity of pumping near the springs on springflow and not to suggest that pumping should not be allowed in these counties.

A number of the sensitivity runs examine the effects of limiting the non-critical period pumping at 437,000 acre-feet per year. This number represents what we believe to be the actual recent past maximum amount of permitted pumping given current management policies and current critical period management. Because our model runs generally assume that the maximum permitted volume that can be pumped will be pumped, we wanted to assess how springflow might respond to current levels of maximum pumping. Note that when we refer to pumping amounts (for example, 572,000 acre-feet per year), we are referring to the maximum permitted volumes pumped by permitted users. These numbers do not include exempt uses, which are estimated to be about 20,000 acre-feet per year (Hamilton and others 2009) but are included in the model (although at a level of 13,000 acre-feet per year) and, therefore, all of the model runs discussed in this report.

Based on draft springflow requirements and what we learned from the constant pumping and sensitivity runs, we requested runs intended to meet or exceed the minimum springflow requirements for the endangered species of concern (runs 011, 012, 013, 030, and 034). These runs are in two groups, the first was in response to the initial draft springflow requirements presented on July 8, 2009, (runs 011, 012, and 013), and the second was in response to the revised draft numbers presented on September 21, 2009, (runs 030, 031, 032, 033, 034, 035a, 036a, and 037a). Runs 025, 026, and 027 were withdrawn once the biologists on the subcommittee revised springflow requirements. Consensus on the springflow requirements was not reached until early December 2009.

Below is a brief description of each run:

Run 001: Current critical period management (maximum 40 percent reduction in pumping for the San Antonio Pool and maximum 35 percent reduction in pumping for the Uvalde Pool)

Run 002: No pumping

Run 003: Constant pumping at 100,000 acre-feet per year

Run 004: Constant pumping at 200,000 acre-feet per year

Run 005: Constant pumping at 300,000 acre-feet per year

Run 006: Constant pumping at 400,000 acre-feet per year

Run 007: Constant pumping at 500,000 acre-feet per year

Run 008: Constant pumping at 572,000 acre-feet per year

Run 009: Pumping at Stage IV not lower than 320,000 acre-feet per year with pumping not allowed to exceed 437,000 acre-feet per year

Run 010: Pumping at Stage IV not lower than 340,000 acre-feet per year with pumping not allowed to exceed 437,000 acre-feet per year

Run 011: Adjustments in pumping reductions for stages III and IV (maximum 50 percent reduction in pumping for the San Antonio Pool and maximum 50 percent reduction in pumping for the Uvalde Pool)

Run 012: Adjustments in pumping reductions for stages III and IV (maximum 60 percent reduction in pumping for the San Antonio Pool and maximum 60 percent reduction in pumping for the Uvalde Pool)

Run 013: Adjustments in pumping reductions for stages III and IV (maximum 70 percent reduction in pumping for the San Antonio Pool and maximum 70 percent reduction in pumping for the Uvalde Pool)

Run 014: Constant pumping at 250,000 acre-feet per year

Run 015: Constant pumping at 350,000 acre-feet per year

Run 016: Current critical period management (Run 001) but starting the simulation with no initial pumping

Run 017: Current critical period management (Run 001) but starting the simulation with twice the initial pumping

Run 018: Adjustments in pumping reductions for stages III and IV (Run 011) but with pumping not allowed to exceed 437,000 acre-feet per year

Run 019: Adjustments in pumping reductions for stages III and IV (Run 012) but with pumping not allowed to exceed 437,000 acre-feet per year

Run 020: Adjustments in pumping reductions for stages III and IV (Run 013) but with pumping not allowed to exceed 437,000 acre-feet per year

Run 021: Adjustments in pumping reductions for stages III and IV; in J-17 triggers for stages I, II, III, and IV; and in J-27 triggers for stages II, III, and IV (maximum 70 percent reduction in pumping for the San Antonio Pool and maximum 70 percent reduction in pumping for the Uvalde Pool)

Run 022: Adjustments in pumping reductions for stages III and IV and in Comal triggers for stages I, II, III, and IV (maximum 70 percent reduction in pumping for the San Antonio Pool and maximum 70 percent reduction in pumping for the Uvalde Pool)

Run 023: Adjustments in pumping reductions for stages III and IV and in J-27 triggers for stages I, II, III, and IV (maximum 70 percent reduction in pumping for the San Antonio Pool and maximum 70 percent reduction in pumping for the Uvalde Pool)

Run 024: Adjustments in pumping reductions for stages I, II, III, and IV for the San Antonio Pool and for stages II and III for the Uvalde Pool (maximum 70 percent reduction in pumping for the San Antonio Pool and maximum 70 percent reduction in pumping for the Uvalde Pool)

Run 025: Withdrawn

Run 026: Withdrawn

Run 027: Withdrawn

Run 028: Adjustments in pumping reductions for stages I, II, III, and IV for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stages I, II, III, and IV (maximum 60 percent reduction in pumping for the San Antonio Pool and maximum 70 percent reduction in pumping for the Uvalde Pool)

Run 029: Adjustments in pumping reductions for stages I, II, III, and IV for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stages I, II, III, and IV (maximum 70 percent reduction in pumping for the San Antonio Pool and maximum 70 percent reduction in pumping for the Uvalde Pool)

Run 030: Adjustments in pumping reductions for stages I, II, III, and IV for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stages I, II, III, and IV (maximum 90 percent reduction in pumping for the San Antonio Pool and maximum 90 percent reduction in pumping for the Uvalde Pool)

Run 031: Adjustments in pumping reductions for stages I, II, III, and IV for the San Antonio and Uvalde pools; adjustments in J-17 and J-27 triggers for stages I, II, III, and IV (maximum 90 percent reduction in pumping for the San Antonio Pool and maximum 90 percent reduction in pumping for the Uvalde Pool); and no pumping in Hays and Comal counties.

Run 032: Constant pumping at 40,000, 55,000, 65,000, and 75,000 acre-feet per year

Run 033: Adjustments in pumping reductions for stages I, II, III, and IV for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stages I, II, III, and IV (maximum 80 percent reduction in pumping for the San Antonio Pool and maximum 80 percent reduction in pumping for the Uvalde Pool)

Run 034a: Adjustments in pumping reductions for stages I, II, III, and IV for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stages I, II, III, and IV

Run 034b: Adjustments in pumping reductions for stages I, II, III, and IV for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stages I, II, III, and IV (Run 034a) but with pumping not allowed to exceed 437,000 acre-feet per year (maximum 100 percent reduction in pumping for the San Antonio Pool and maximum 100 percent reduction in pumping for the Uvalde Pool)

Run 035a: Removal of stage IV and adjustments in pumping reductions for stages I, II, and III for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stages I, II, and III (maximum 100 percent reduction in pumping for the San Antonio Pool and maximum 100 percent reduction in pumping for the Uvalde Pool)

Run 036a: Removal of stages III and IV and adjustments in pumping reductions for stages I and II for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stages I and II (maximum 100 percent reduction in pumping for the San Antonio Pool and maximum 100 percent reduction in pumping for the Uvalde Pool)

Run 037a: Removal of stages II, III, and IV and adjustments in pumping reductions for stage I for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stage I (maximum 100 percent reduction in pumping for the San Antonio Pool and maximum 100 percent reduction in pumping for the Uvalde Pool)

Run 038: Removal of stages II, III, and IV and adjustments in pumping reductions for stage I for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stage I

Assumptions

As with any scientific study, we made a number of assumptions that may affect our results, which are ultimately related to predicting springflow. While some assumptions probably overestimate springflow, other assumptions probably underestimate springflow. With this task, we assumed that:

- all reductions and increases in pumping due to critical period management were instantaneous,

- the maximum amount of groundwater that could be pumped under any given scenario would be pumped,
- climate and drought in the future would look like climate and drought in the past (specifically from 1947 through 2000),
- there was no movement in the location of pumping,
- the model accurately simulates springflows at Comal and San Marcos springs and water levels at J-17 and J-27, and
- the subcommittee did not consider either the minimum amount of pumping needed to maintain human health and safety requirements or potential strategies to meet those requirements.

The management module for the model does not allow for the non-instantaneous implementation of the critical period management plan. The assumption on instantaneous pumping reductions probably leads to underestimated impacts to springflow. In practice, entering or exiting any given critical period management stage is dictated by a 10-day average of springflow or water-level elevation. While we believe municipal and industrial pumping reductions are nearly instantaneous (for example, San Antonio quickly reduced its use over the past summer), agricultural reductions may be delayed depending on the timing of the drought and when critical period management triggers are crossed. There may, in fact, be as much as a one-year delay to reductions in agricultural pumping. We assumed instantaneous reductions and increases in pumping because the management module for the groundwater model operates under this assumption. In other words, the model assumes instantaneous pumping reductions and increases when going into and out of critical period management.

The assumption that the maximum amount of groundwater that could be pumped under any given scenario would be pumped probably leads to overestimated impacts to springflow. For example, the most that has been annually pumped from the aquifer was 542,500 acre-feet in 1989 and, in the last 10 years, 454,500 acre-feet per year (compare that to the permitted amount of 572,000 acre-feet; both estimates are from Hamilton and others 2009, and include estimated exempt and unreported use). However, the maximum amount pumped will likely increase over time as agricultural use converts to municipal use, municipal use increases, and municipal users conjunctively manage water from the Edwards Aquifer. We do not have a projection of how much of the permitted use might be realized in the future. Although pumping is likely to increase, it is not likely to reach the maximum permitted amount.

The assumption that climate and drought in the future will statistically resemble climate and drought in the past probably leads to overestimated springflow. Global climate models used by the International Panel on Climate Change suggest that Texas will be warmer and most suggest that Texas will be drier (Kundzewicz and others 2007). Warmer temperatures increase evapotranspiration which decreases runoff (all other factors remaining the same), an important factor for recharge to the Edwards Aquifer. A recent study commissioned by the Lower Colorado River Authority and the San Antonio Water System showed that even with increased rainfall, runoff was expected to decrease in the contributing basins to the Highland Lakes (CH2M Hill 2008).

The assumption that there is no movement in the location of pumping may underestimate or overestimate springflow. Pumping that moves closer to the springs will tend to have a greater effect on springflow (LBG-Guyton Associates 2008) while pumping that moves away from springs will tend to have a lesser effect on springflow. Note that about 66,000 acre-feet per year of pumping rights have been transferred since completion of the base pumping distribution files in 2005 for the Edwards Aquifer model used in the preparation of this report (EAA 2009). In addition, leases of withdrawal rights have increased from about 98,000 acre-feet per year to about 138,000 acre-feet per year (EAA 2009). To the extent that additional pumping would be expected to occur closer to Comal and San Marcos springs as a result of such transfers, model results presented herein would tend to overestimate springflow during drought periods. Also note that the distribution of pumping in the model reflects the location of permits as of 2005. In December 2009, the Edwards Aquifer Authority approved rules to limit the transfer of Edwards Aquifer withdrawal rights east of Cibolo Creek.

The assumption that the model accurately simulates springflows at Comal and San Marcos springs and water levels at J-17 and J-27 probably leads to underestimates and overestimates in springflows. According to calibration statistics in Lindgren and others (2004), flows at Comal and San Marcos springs have a small bias toward overestimating flows, mostly due to simulating higher flows between 1958 and 1961 and the late 1980s. Although it appears that flows at San Marcos Springs are generally overestimated by the model for the calibration period, the model does a good job of matching flows during the drought of record (1947 through 1956). For J-17, the model generally does a good job of matching observed values although it underestimates levels during the deepest part of the drought of record and a few other extreme droughts and slightly overestimates some high levels. For J-27, the model consistently underestimates water levels until about 1970 when it mostly overestimates levels.

The assumption that the subcommittee could not consider the minimum amount of pumping needed to maintain human health and safety requirements or strategies to meet those requirements comes from an interpretation of the language in Senate Bill 3.

Analysis and results

A comparison of the springflow requirements from Task 1 to historical flows at San Marcos and Comal springs (figures 20 and 21, respectively) shows that, at least with historical levels of pumping, the springflow requirements are met except at the end of the drought of the 1950s in the summer of 1956. However, it is important to note that during the drought of the 1950s pumping increased from about 167,000 acre-feet per year in 1947 to about 321,000 acre-feet per year in 1956 (Hamilton and others 2009). At present time, we would expect the opposite: that pumping would decrease in response to drought and critical period management.

The Edwards Aquifer Authority manages water levels and spring flows in the aquifer with two basic approaches: (1) a cap on total permitted pumping of 572,000 acre-feet per year and (2) protecting springflows during drought periods with critical period management rules. These rules require different classes of users to reduce pumping by a

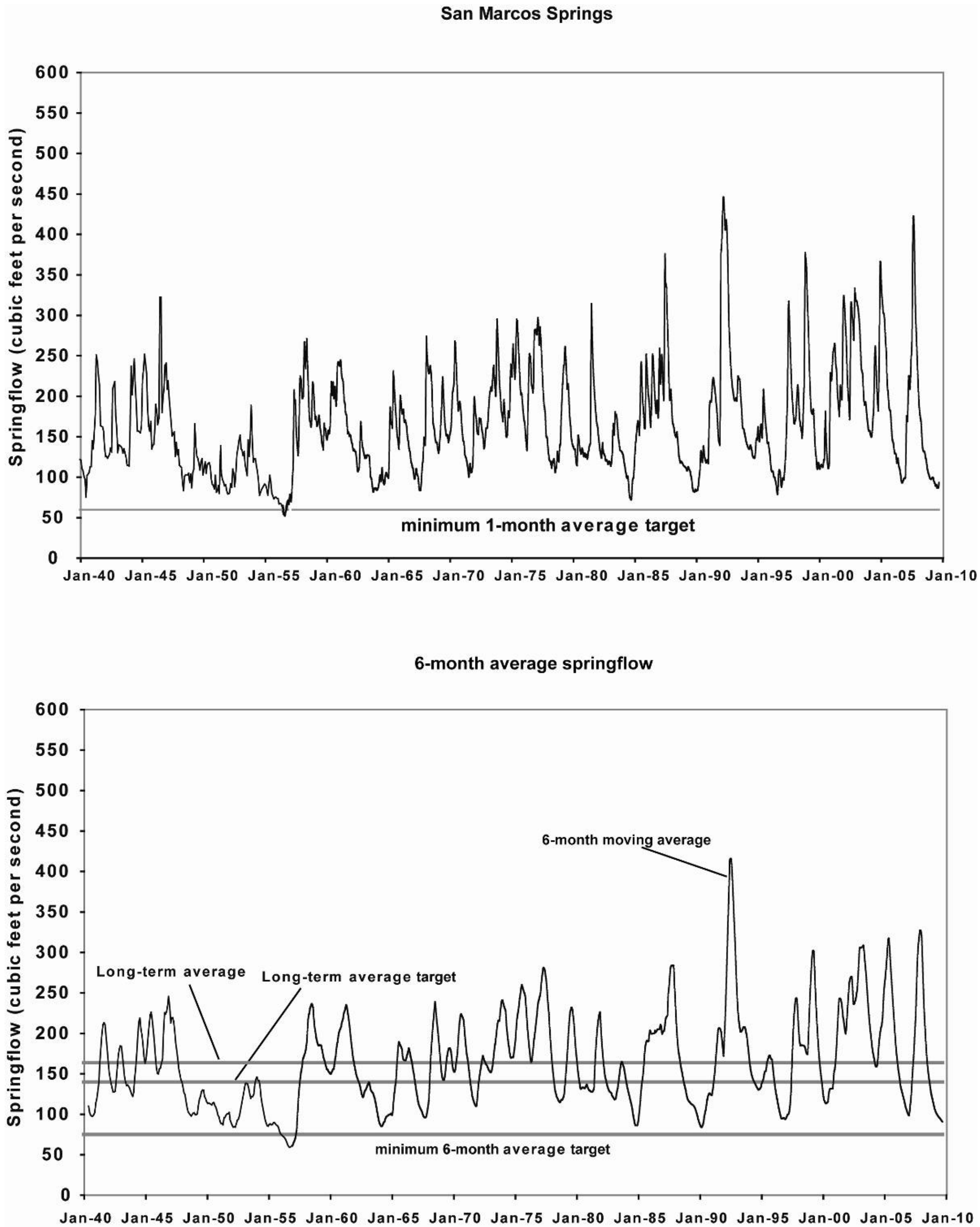


Figure 20: Record of historical discharge from San Marcos Springs compared to the biological flow regime requirements (data before 1956 from GBRA 1988, data for 1956 and later from USGS 2009).

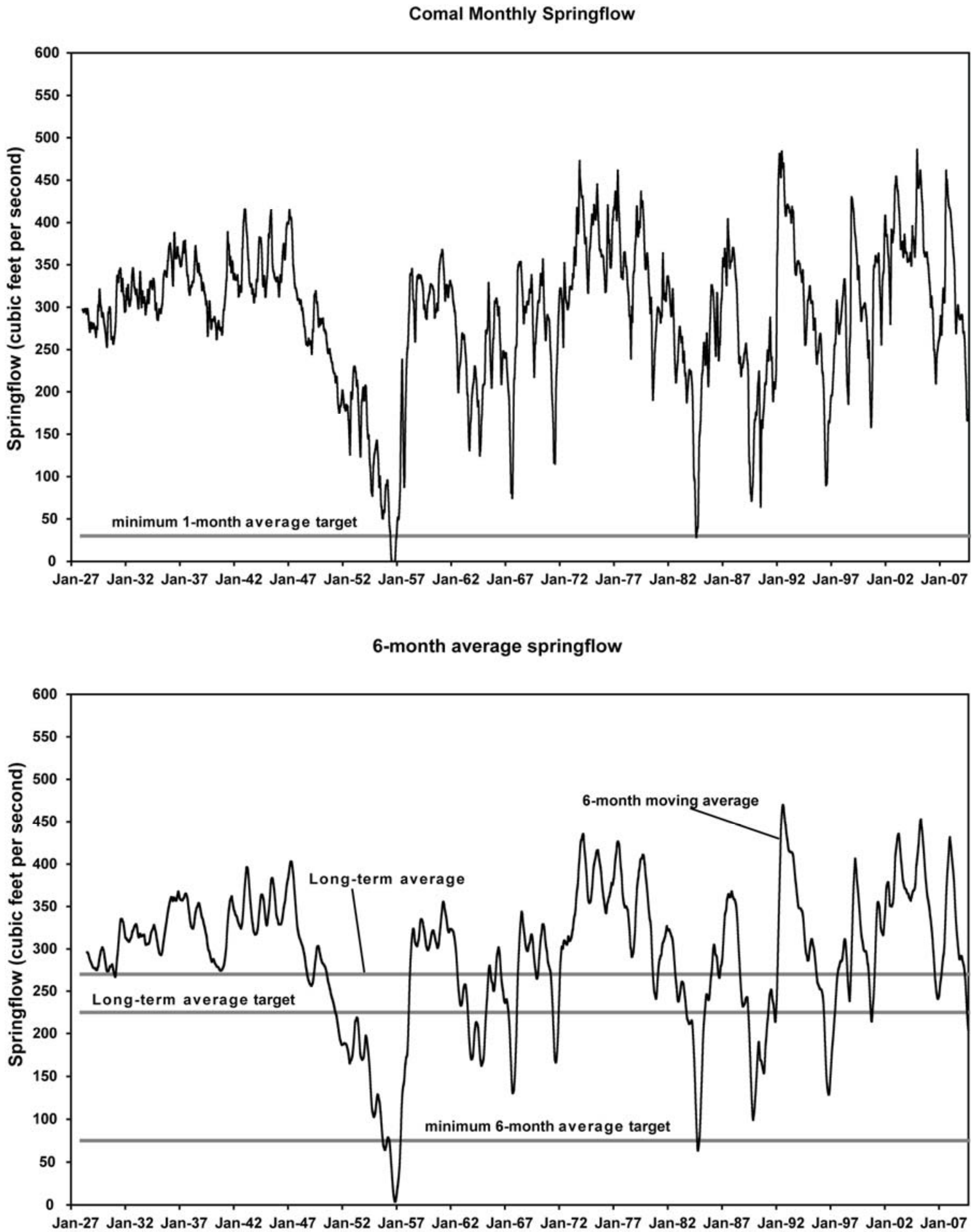


Figure 21: Record of historical discharge from Comal Springs compared to the biological flow regime requirements (data from Miller, 2009).

percentage of their total water right as springflows decline below an established springflow or water levels in index wells decline below an established level. Declining springflows (or water levels) may pass through different trigger levels as a drought worsens. The current critical period management rules define four triggers or stages. Upon reaching each trigger, the percent cut back increases. In the San Antonio Pool, for example, Stage I requires a 20 percent reduction; Stage II requires a 30 percent reduction; Stage III requires a 35 percent reduction, and Stage IV requires a 40 percent reduction (Table 12). The purpose of these cutbacks is to preserve springflow (and therefore the endangered species). We evaluated the potential effectiveness of this critical period management approach by using the Edwards MODFLOW model with critical period management module to simulate several different management scenarios to determine which trigger approach gets us through the "drought of record".

The current critical period management plan in the Edwards Aquifer Authority Act (Table 12) does not achieve the springflow requirements in Task 1 (Table 13; figures 22 and 23). In fact, the groundwater model (Run 001) suggests that Comal Springs would stop flowing for 13 consecutive months and 29 months total. Under this scenario, pumping decreases from the maximum permitted amount (572,000 acre-feet per year) to about 362,000 acre-feet per year (EAA 2009).

Model runs assuming different levels of constant pumping (that is, no critical period management) suggest that the minimum 6-month flow average for San Marcos Springs would be the primary driver in achieving the springflow requirements and would require pumping reductions in the neighborhood of 85 percent (Figure 24).

Given that there are six different springflow criteria, it is not surprising that one would be the controlling criterion depending on the value of that criterion and the predicted effects of pumping on springflows. For example, based on constant levels of pumping (no critical period management), the 1-month minimum flow criterion for San Marcos Springs would allow for about 200,000 acre-feet per year of pumping; however, the 6-month minimum flow criteria would only allow for about 90,000 acre-feet of pumping (Table 13 and Figure 24).

In evaluating the sensitivity of simulated springflow to various adjustments and assumptions, we learned that:

- restricting the maximum amount of pumping to 437,000 acre-feet per year instead of 572,000 acre-feet per year generally, but not always, increased 1-month, 6-month, and long-term average springflows (from comparing runs 009 and 010 to Run 001, Run 018 to Run 011, Run 019 to Run 012, and Run 020 to Run 013; Table 13);
- raising or lowering the amount of pumping that defines the initial condition of the transient simulations lowers or raises the springflows, respectively (from comparing Run 017 to Run 001 and Run 016 to Run 001, respectively);
- raising the triggers for J-17 and J-27 by five feet increased 1-month, 6-month, and long-term average springflows from 0 to 2 cubic feet per second (from comparing Run 021 to Run 013; Table 13);

Table 12: The current critical period management plan in the Edwards Aquifer Authority Act.

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<660	I	20
<200	<80	<650	II	30
<150	N/A	<640	III	35
<100	N/A	<630	IV	40

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
-	I	0
<850	II	5
<845	III	20
<842	IV	35

- raising the triggers for Comal Springs by 15 cubic feet per second increased some springflow statistics, decreased some springflow statistics, and did not affect other springflow statistics (from comparing Run 022 to Run 013; Table 13);
- having larger pumping reductions in stages I and II raises long-term average springflow and allows smaller pumping reductions in stages III and IV (from comparing Run 024 to Run 013 and Run 033 to Run 030; Table 13); and
- decreasing pumping in the areas near the springs increases springflow, especially for San Marcos Springs (from comparing Run 031 to Run 030; Table 13).

Run 34 represented the start of a series of model runs to obtain a critical period management plan that met all the draft biological flow requirements from Task 1. Runs 34 through 37a include 100 percent reductions in pumping during progressively fewer critical period management triggers. We did this as a screening exercise to determine how few triggers we would need to meet the draft springflow requirements. In other words, if a model run showed that we could not achieve or surpass all of the springflow targets with a 100 percent reduction in pumping, we knew we could not achieve or surpass the draft targets with a smaller reduction.

Consensus on the final springflow requirements, which differed from previous numbers under consideration, was not reached until early December 2009. Out of the existing model runs, we had 11 that met or exceeded all of the springflow requirements (Table 13). One of the 11 had no pumping (Run 2), 4 had fixed pumping equal to or less than 75,000 acre-feet per year (runs 32-40, 32-55, 32-65, and 32-75), 1 had two critical period management stages (Run 36a), and 5 had one critical period management stage with varying pumping reductions (runs 37a-100, 37a-98, 37a-97, 37a-96, and 37a-94).

Table 13: Springflow statistics resulting from the model runs.

Run	Maximum pumping (AFY)	Description	Comal springflow (cubic feet per second) Min. 1-month avg.	Min. 6-month avg.	Long-term avg.	San Marcos springflow (cubic feet per second) Min. 1-month avg.	Min. 6-month avg.	Long-term avg.
Historical	NA	1947-2000	***0***	***4***	270	***54***	***61***	158
Criteria	**NA**	**Task 1**	**30**	**75**	**225**	**60**	**75**	**140**
1	572,000	SB3	***0***	***0***	***184***	***10***	***20***	153
2	**0**	**fixed Q**	**288**	**290**	**526**	**89**	**92**	**203**
3	100,000	fixed Q	183	190	436	72	***74***	187
4	200,000	fixed Q	75	87	367	60	***63***	177
5	300,000	fixed Q	***0***	***1***	294	***36***	***45***	167
6	400,000	fixed Q	***0***	***0***	***212***	***0***	***0***	155
7	500,000	fixed Q	***0***	***0***	***129***	***0***	***0***	***137***
8	572,000	fixed Q	***0***	***0***	***72***	***0***	***0***	***116***
9	437,000	sensitivity	***0***	***0***	229	***26***	***35***	158
10	437,000	sensitivity	***0***	***0***	***222***	***15***	***25***	157
11	572,000	CPM adjust.	***0***	***3***	***195***	***40***	***48***	154
12	572,000	CPM adjust.	***22***	***38***	***200***	***54***	***57***	155
13	572,000	CPM adjust.	57	***73***	***202***	***59***	***62***	155
14	250,000	fixed Q	***19***	***35***	331	***54***	***57***	172
15	350,000	fixed Q	***0***	***0***	254	***10***	***20***	162
16	572,000	sensitivity	***0***	***0***	***189***	***16***	***25***	153
17	572,000	sensitivity	***0***	***0***	***176***	***0***	***6***	151
18	437,000	sensitivity	***0***	***3***	***217***	***41***	***48***	157
19	437,000	sensitivity	***23***	***39***	***222***	***55***	***57***	157
20	437,000	sensitivity	38	***60***	***224***	***57***	***59***	157
21	572,000	sensitivity	59	***74***	***207***	***59***	***61***	155
22	572,000	sensitivity	55	78	***208***	60	***61***	155
23	572,000	sensitivity	*29*	***64***	***199***	***59***	***61***	155
24	572,000	sensitivity	58	***74***	***207***	***59***	***61***	155
28	572,000	sensitivity	41	***70***	***224***	***59***	***61***	157
29	572,000	sensitivity	47	75	***213***	***59***	***61***	156
30	572,000	sensitivity	33	83	***216***	***53***	***61***	156
31	572,000	sensitivity	38	87	***223***	70	***73***	178
32-40	**40,000**	**fixed Q**	**244**	**246**	**475**	**78**	**80**	**193**
32-55	**55,000**	**fixed Q**	**230**	**233**	**466**	**77**	**79**	**192**
32-65	**65,000**	**fixed Q**	**220**	**224**	**459**	**76**	**78**	**191**
32-75	**75,000**	**fixed Q**	**210**	**214**	**452**	**75**	**77**	**190**
33	572,000	CPM adjust	42	84	225	***54***	***62***	157
34a	572,000	CPM adjust	41	98	227	***55***	***62***	157
35a	572,000	CPM adjust	57	118	238	***55***	***64***	158
36a	**572,000**	**CPM adjust**	**84**	**161**	**259**	**67**	**76**	**161**
37a-100	**572,000**	**CPM adjust**	**87**	**203**	**284**	**70**	**82**	**165**
37a-98	**572,000**	**CPM adjust**	**63**	**200**	**282**	**67**	**80**	**164**
37a-97	**572,000**	**CPM adjust**	**73**	**199**	**282**	**73**	**80.1**	**164**
37a-96	**572,000**	**CPM adjust**	**83**	**201**	**283**	**73**	**79.9**	**164**
37a-94	**572,000**	**CPM adjust**	**80**	**205**	**282**	**73**	**79**	**164**
38	**572,000**	**CPM adjust**	**109**	**196**	**278**	**72**	**75**	**164**

Runs 25, 26, and 27 were withdrawn. Runs in **bold red** and shaded meet all of the springflow criteria shown in **bold blue**. Springflows in ***bold italics*** do not meet the springflow criteria. adjust. = adjustment; AFY = acre-feet per year; avg. = average; CPM = critical period management; Min. = minimum; NA = not applicable; Q = pumping; SB3 = Senate Bill 3. See p. 72–74 and Appendix F for more complete descriptions of each run.

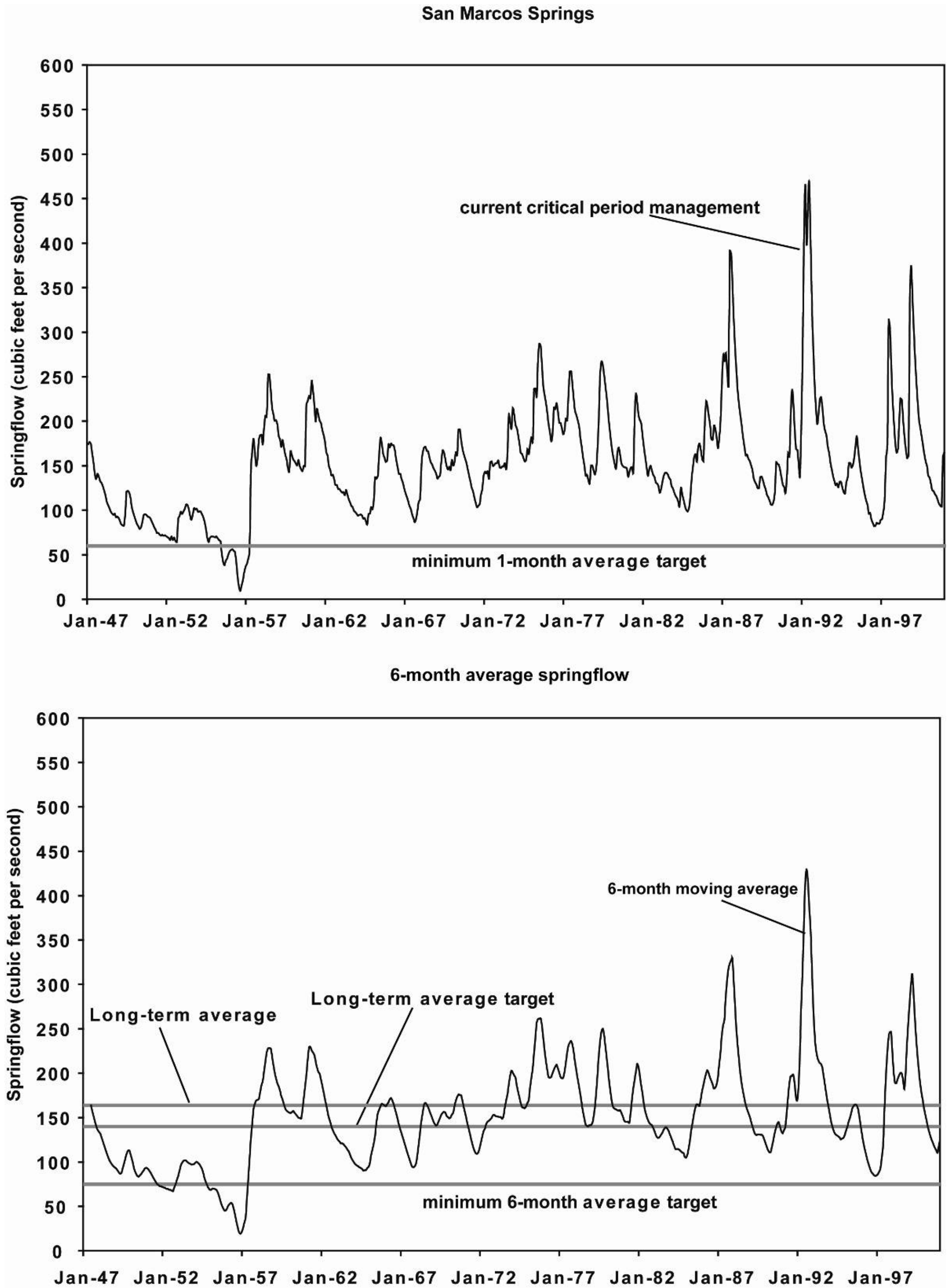


Figure 22: Predicted discharge statistics for San Marcos Springs under the current critical period management plan compared to the biological flow regime requirements (Run 1).

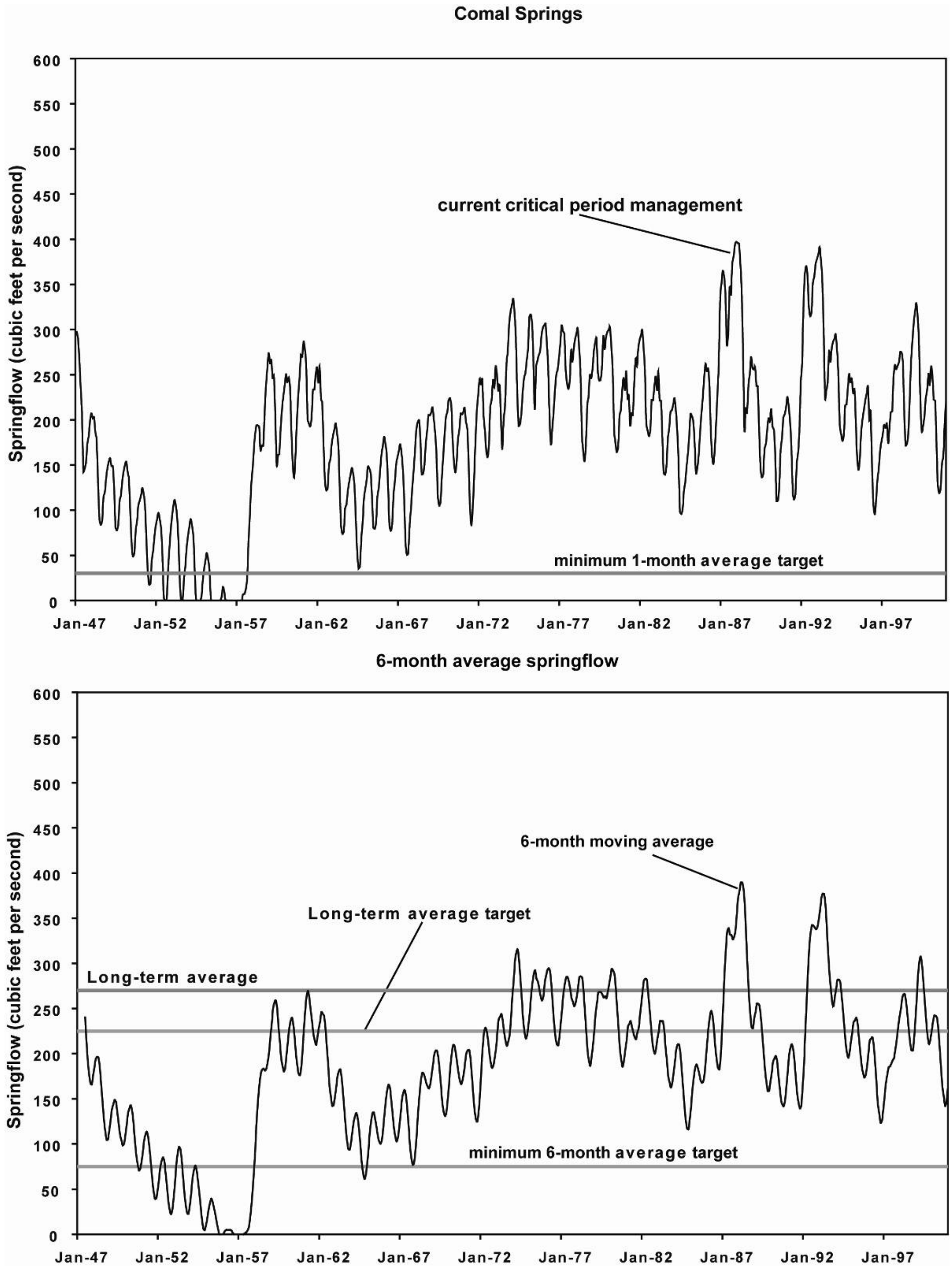


Figure 23: Predicted discharge statistics for Comal Springs under the current critical period management plan compared to the biological flow regime requirements (Run 1).

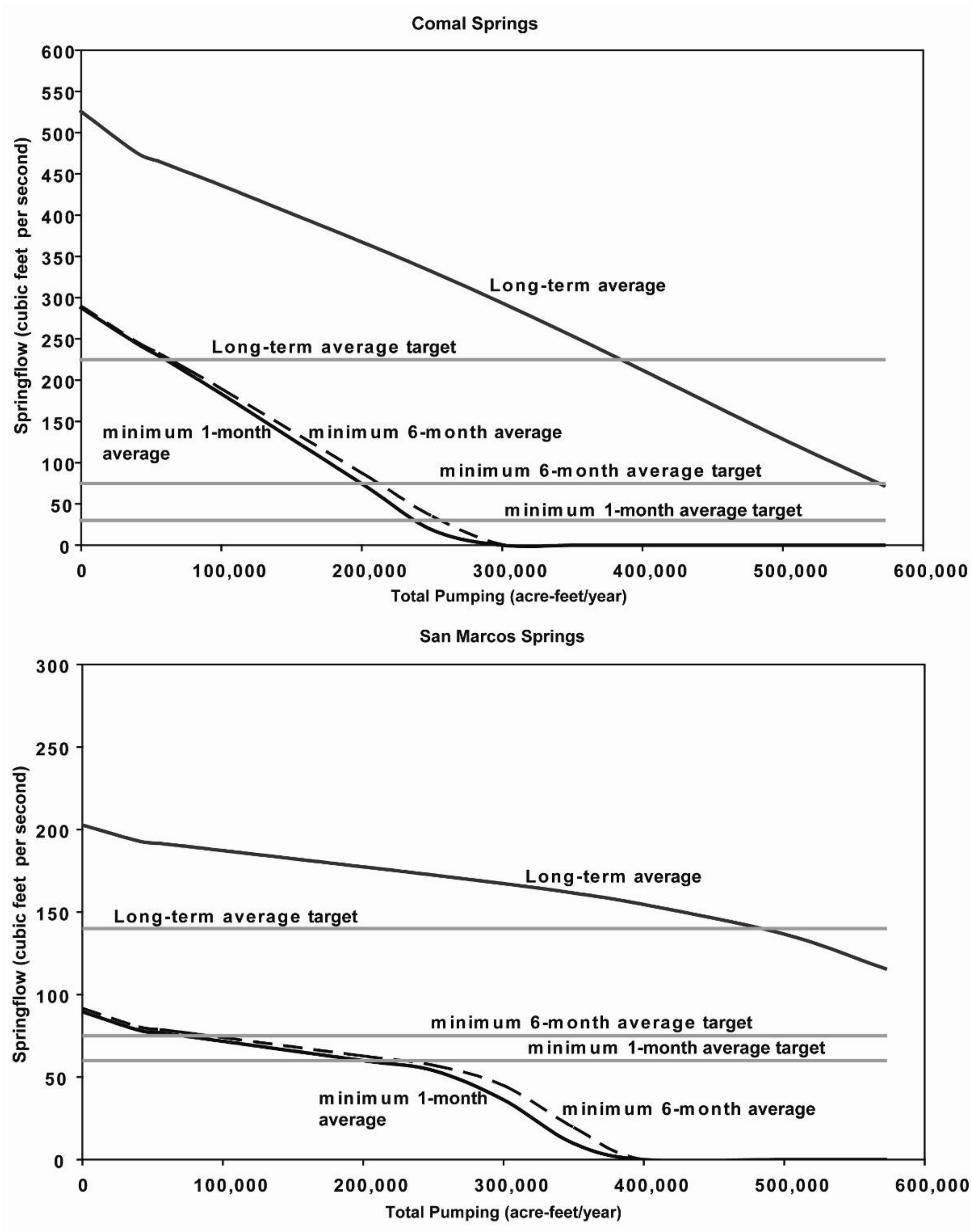


Figure 24: Predicted discharge statistics for Comal and San Marcos springs with different levels of constant pumping compared to the biological flow regime requirements. These plots are based on the results of model runs 2, 3, 4, 5, 6, 7, 8, 14, 15, and 32.

Run 36a actually came the closest to meeting the 6-month minimum flow requirement for San Marcos Springs at 76 cubic feet per second; however, this was achieved with a 30 percent reduction of pumping in Stage I and a 100 percent reduction of pumping in Stage II.

Because we did not want to suggest a 100 percent reduction in pumping, we requested an additional run (Run 38) with a single stage critical period management and a pumping reduction to achieve the minimum 6-month average flow at San Marcos Springs (with the assumption, supported by Run 37, that the other springflow criteria would be met if this criterion was met). The results of this run—Run 38—showed that pumping needed to be reduced 85 percent to meet the minimum 6-month average flow at San Marcos Springs (Table 13; figures 25 and 26; Run 38). Therefore, the final critical period management scenario that meets or exceeds the final springflow recommendations is

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<**665**	I	**85**

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
< **865**	I	**85**

where cfs is cubic feet per second. The cumulative distribution function of simulated flow at Comal and San Marcos springs for Run 038 (Figure 27) shows that simulated springflow achieves the minimum 6-month-average flow target at San Marcos Springs only one time for the simulation period and that the other flow targets are never achieved.

We recognize that this final run that reduces permitted pumping by 85 percent at Stage I does not take advantage of the Edwards Aquifer Authority's current critical period management approach in which higher percentage withdrawal reductions are phased in as springflows and water levels decline and drought becomes more severe. While a multi-stage critical period management approach is possible, the magnitude of withdrawal reductions necessary to meet springflow criteria would require very rapid passage through the initial stages and/or complete cessation of permitted pumping beyond the initial stages.

Given the legislatively mandated deadline for the report, we did not have time to investigate multi-stage critical period management with the final springflow requirements. For example, Run 36a had two stages, the first with a 30 percent reduction in pumping and the second with a 100 percent reduction. An increase in the Stage I pumping reduction should allow a decrease in the Stage II pumping reduction. Additional stages might also be possible. Also, note that Run 31—a run with four stages ending with a 90 percent reduction in pumping—nearly met all of the springflow requirements; however, this run had no pumping in the Edwards Aquifer in Comal and Hays counties.

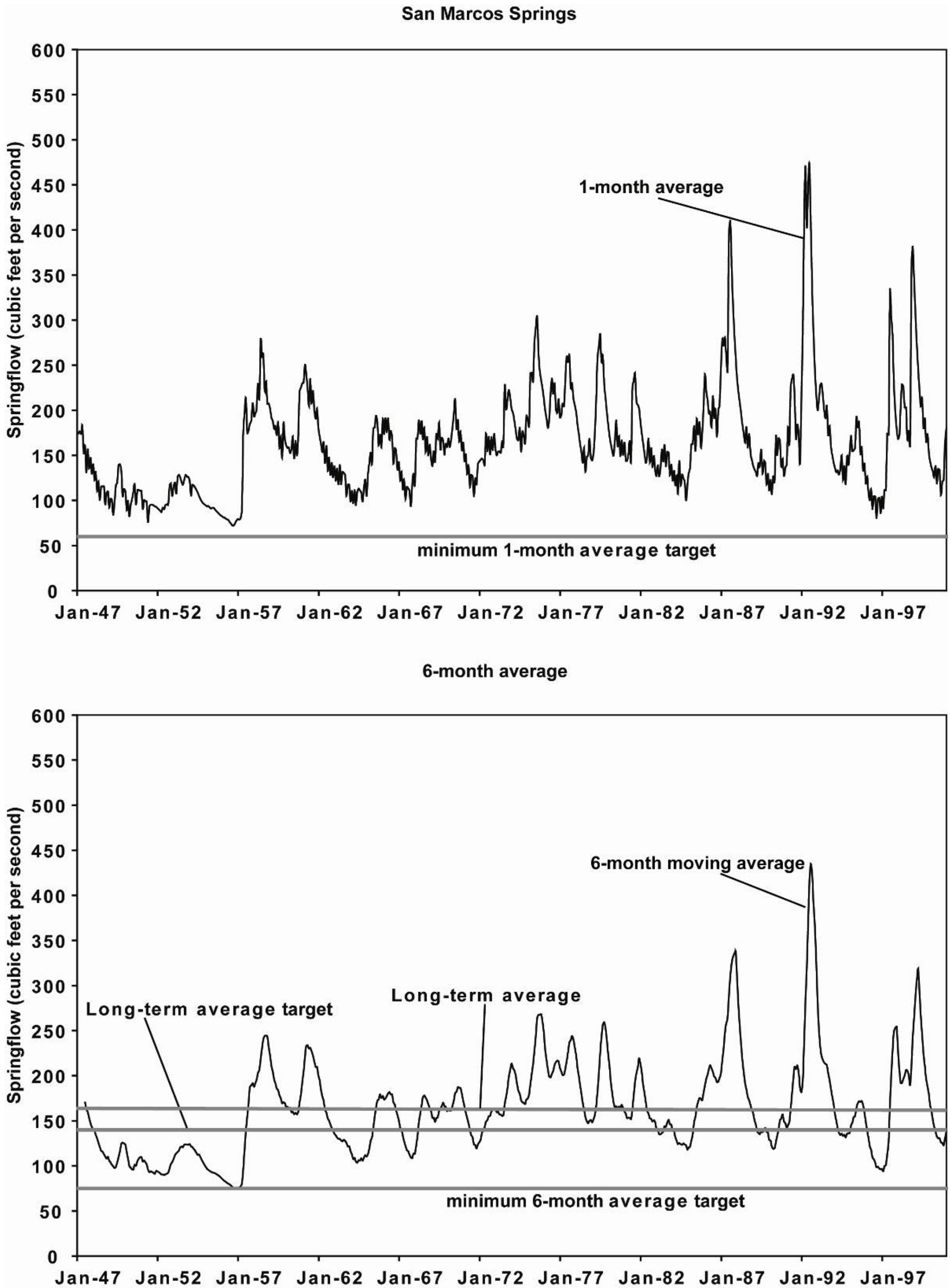


Figure 25: Predicted discharge statistics for San Marcos Springs with one critical period management stage with an 85 percent reduction in pumping (Run 38).

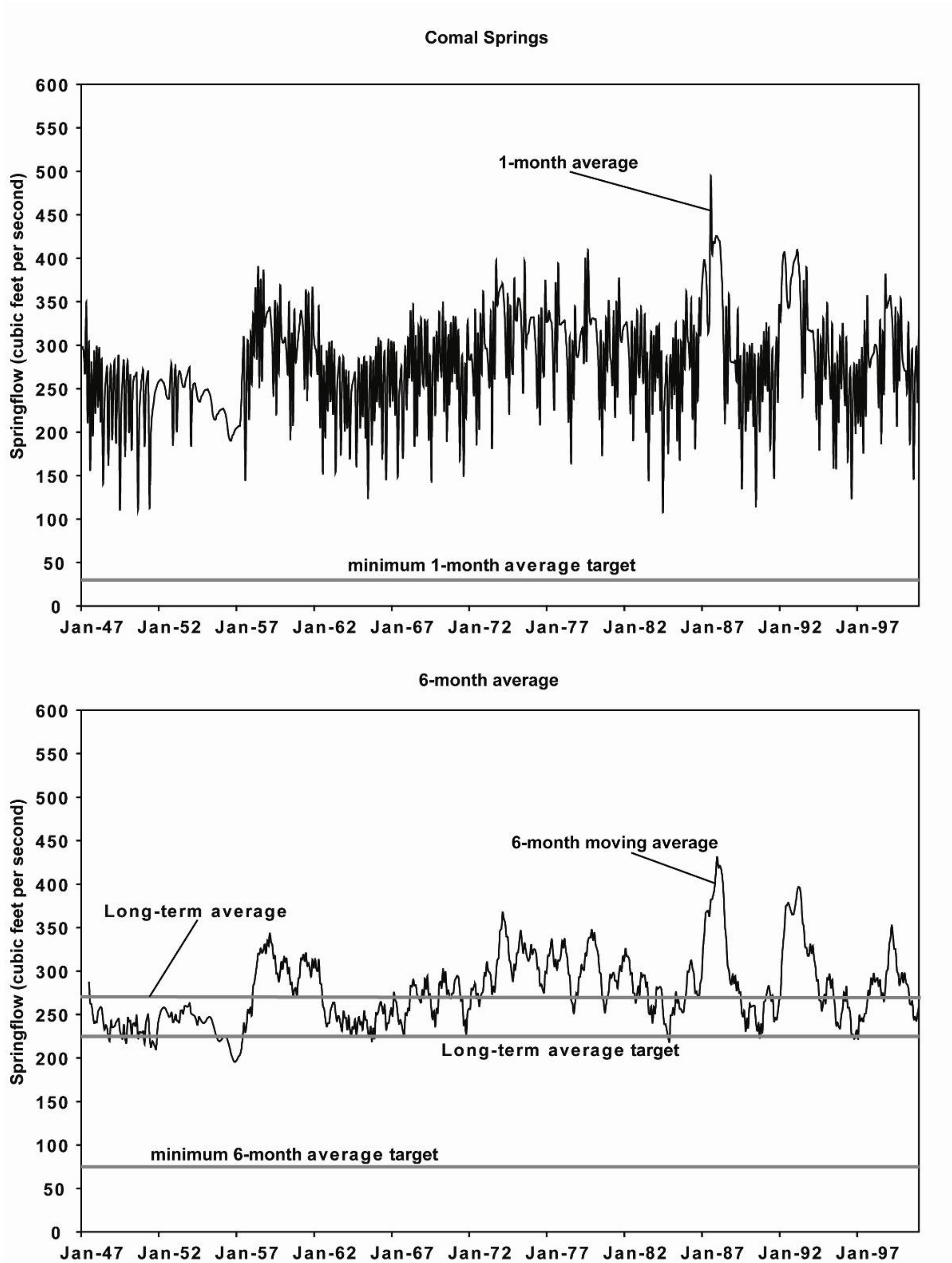


Figure 26: Predicted discharge statistics for Comal Springs with one critical period management stage with an 85 percent reduction in pumping (Run 38).

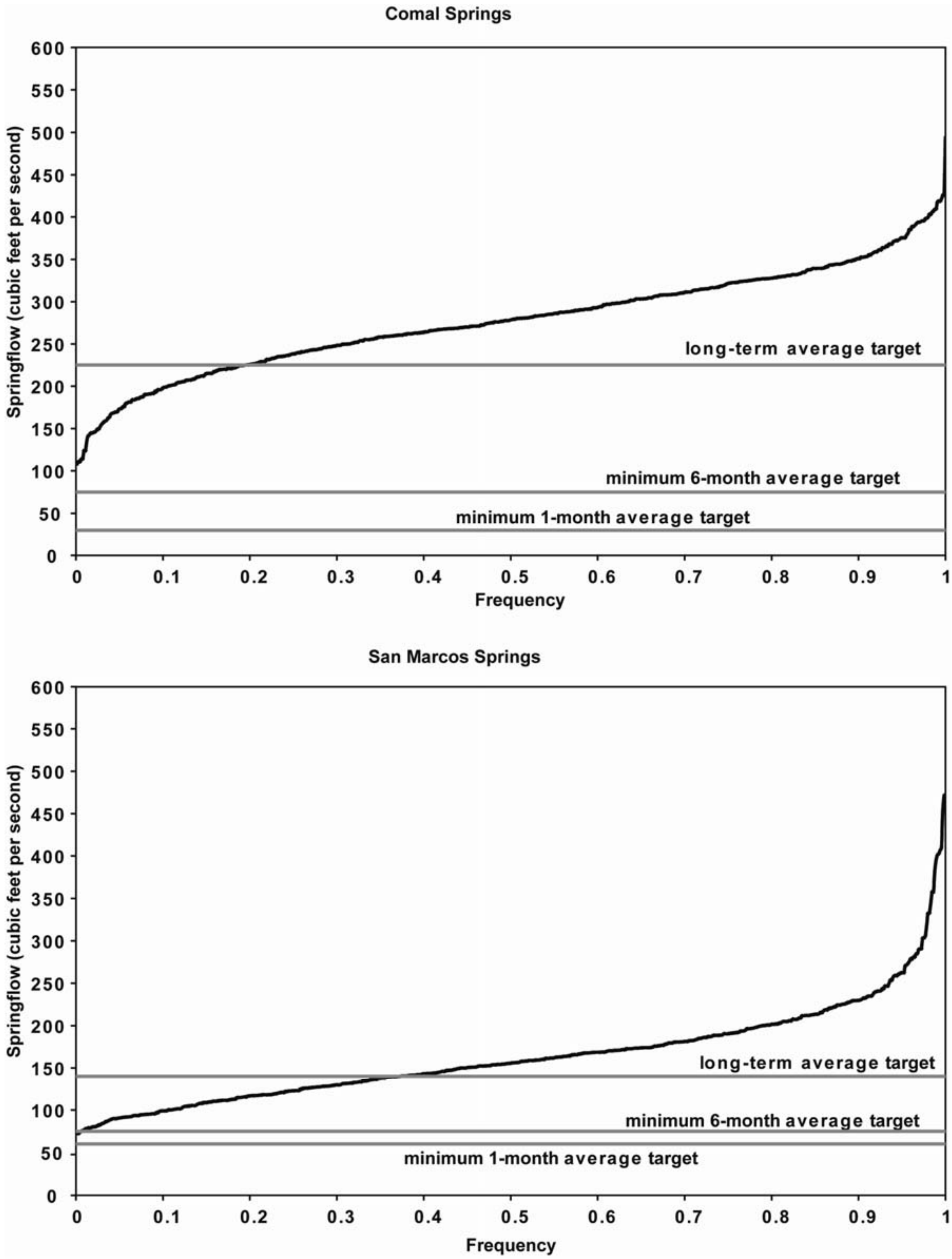


Figure 27: Cumulative distribution function of simulated flow at Comal and San Marcos springs for Run 38. This plot shows the frequency at which any given springflow is exceeded.

Springflow at San Marcos Springs appears less sensitive to San Antonio Pool pumping and the Senate Bill 3 critical period management pumping reductions when compared to similar times and similar simulations for Comal Springs. Much of the pumping reductions for the San Antonio Pool result in greater increases in springflow at Comal Springs than at San Marcos Springs. In other words, Comal Springs responds with much greater springflow changes than does San Marcos Springs. Because of this relative lack of sensitivity of San Marcos Springs to western regional pumping reductions, greater pumping reductions are needed from the general aquifer to cause any significant increase in flow at San Marcos Springs. Run 34a (Appendix G) for Comal Springs shows a wide range of springflows as the aquifer goes in and out of high percent pumping reductions. A similar plot for San Marcos Springs (Appendix G) does not show these wide oscillations. This indicates that the pumping changes west of Comal Springs are significantly dampened by the time they reach San Marcos Springs as springflow. In addition, deleting the pumping in Comal and Hays counties in the model significantly raises the minimum 1-month average, the minimum 6-month average, and the long-term average for San Marcos Springs by 17, 12, and 22 cubic feet per second, respectively (Table 12). When pumping is removed from Comal and Hays counties, an additional 14 to 20 cubic feet per second of springflow is added at San Marcos Springs during the 1950s and 20 to 25 cubic feet per second of springflow is added from 1960 to 2000. These two observations indicate that much larger pumping cuts have to be made in Bexar, Medina, and Uvalde counties than in Comal and Hays counties to have similar increases in springflow at San Marcos.

A single critical period management stage and the size of the reduction during this stage results in some large and abrupt fluctuations in water levels and springflows in response to the aquifer entering and exiting critical period management (see Figure 26 as well as various figures in Appendix G). Outside of critical period management, 572,000 acre-feet per year are being pumped from the aquifer. As declining water levels or springflows cause the simulated aquifer to go into critical period management, the pumping is abruptly reduced to about 86,000 acre-feet per year. This reduction can cause a quick rebound in water levels and springflows thus bringing the aquifer out of critical period management and suddenly increasing pumping to 572,000 acre-feet per year, which then lowers water levels and springflows.

Managing the aquifer in this fluctuating manner may not be good for the species (rapid swings in springflows) or for associated infrastructure (turning wells on and off). Furthermore, these pumping reductions result in long-term flow averages much higher than historical values which may also be detrimental to the species. It is also probably not realistic to bring permit holders in and out of critical period management on a monthly basis. Although less of a cutback at a relatively continuous rate might stabilize springflows, it is not possible to simulate such a scenario with the current management module.

Although the critical period management that results from the flow recommendations may not appear realistic, our study shows that pumping reductions will need to exceed 80 percent to achieve springflow goals during a repeat of the drought of record. Any decisions on a final critical period management plan that includes large reductions in pumping will need to include an assessment of how fluctuations in springflows and much higher long-term average springflows may affect the species.

Further studies

We believe further study is needed to (1) improve springflow measurement, (2) conduct sensitivity analyses, (3) run optimization models, (4) estimate the probability of recurrence of the 1950s drought, (5) evaluate the potential effects of climate variability on recharge, (6) conduct additional runs to refine withdrawal reductions, (7) update the model, (8) refine the calibration of the model, (9) enhance the management module, and (10) refine model calibration between San Marcos and Barton springs.

Improve springflow measurement

Additional field studies could be done to improve the accuracy of current springflow measurements and evaluate alternative instrumentation. These studies include:

- Measuring flows to test the accuracy of the stage-discharge relationships whenever springflows approach drought triggers. The accuracy of measurements could also be increased by additional measurements in the upper portions of the rating curves. Periodic discharge measurements could be made at a cross section located about 150 feet downstream of the Comal Springs control structure and compared to the discharge measured at the upstream cross section to assess the accuracy of the measurements.

- Coordinating with the U.S. Fish and Wildlife Service and other resource agencies to select an appropriate location for a low-flow control section in the San Marcos River that minimizes the disturbance of endangered species and maximizes accuracy of continuous measurements.

- Continuing studies to evaluate various types of instruments to directly measure spring orifice discharge and stream velocities to determine whether more accurate instrumentation and methodologies might improve the overall accuracy and timeliness of springflow measurements.

- Establishing a water-level monitoring network in the San Marcos Springs area and conducting field studies to correlate groundwater levels to flow at San Marcos Springs.

Conduct sensitivity analyses

We made several assumptions to complete our analysis, including those affecting the timing of reductions in irrigation pumping and the effects of increasing and shifting demands for groundwater over time. As the effects of these assumptions on model results are not fully understood, it is impossible to know the extent to which assumptions of a different type or direction may have altered model results and, ultimately, our results.

Therefore, to obtain a better understanding of how the Edwards Aquifer might respond to these and other assumptions, we recommend that a systematic sensitivity analysis be conducted to determine the specific effects on our various model assumptions.

Run optimization models

Since the early 1960s, hydrologists and water managers have increasingly depended upon the results of numerical simulations to evaluate groundwater flow systems and preferred strategies of groundwater development. For some time, groundwater models have been used to test the merits of different water-management scenarios using trial-and-error approaches to isolate the seemingly most-plausible plan from sets of alternative strategies. Typically, management decisions are made in consideration of the alternatives that simulated results indicate as best satisfying specific water-management goals and hydrologic constraints. However, due to the complex nature of groundwater systems and the variety of competing interests often stemming from different political, legal, and economic factors, the process of selecting the "best" operating procedure or policy can be extremely difficult or impossible. To address this dilemma, groundwater simulation models can be coupled with optimization techniques (Ahlfeld and Mulligan 2000) to determine optimal management strategies from competing alternatives.

Because hydrologic optimization models are designed to account for the combined effects of the most relevant water-management objectives and hydrogeologic constraints, such an approach can greatly increase the efficiency and effectiveness of groundwater studies as well as the legitimacy of their overall conclusions. Using a simulation-optimization approach, the modeler specifies the desired end products of specific water-management needs and (or) hydrologic conditions (such as minimum required springflows or maximum allowable groundwater declines). The model then provides the solution—from a set of potential management scenarios—for a management strategy that is numerically determined to most-effectively satisfy the specified desired conditions.

Since 1985, several computer codes have been developed to facilitate the application of groundwater simulation-optimization modeling (Lefkoff and Gorelick 1987, Greenwald 1998, Zheng and Wang 2002, Ahlfeld and Riefler 2003, and Peralta 2004). These codes differ, for the most part, in terms of what numerical model is believed most appropriate for representing the particular aquifer and solving the management problems of interest.

Given the proven utility and cost-effectiveness of simulation-optimization models used in studies of aquifers with hydrogeologic characteristics and problems similar to those of the Edwards Aquifer, it is recommended that efforts be undertaken to develop an optimization model of the Edwards Aquifer and apply it toward obtaining a better understanding of (and more-effective management strategies for) the Edwards Aquifer. For example, rather than relying on the laborious, drawn-out process (using minimum springflow constraints) to evaluate the effects of different critical-period trigger levels and percent pumping reductions, a properly designed and calibrated optimization model might have saved the subcommittee significant time and effort toward arriving at the optimum balance among the choices for triggers and cutbacks while maximizing pumping.

Estimate the probability of recurrence of the 1950s drought

The hydrologic modeling analyses done in support of these results for critical period management are based on the climate history from 1947 to 2000. This period of time includes the drought of the 1950s. It would be valuable to know the chance that any one year will experience rainfall deficits at least as severe as the worst part of the 1950s drought. Reconstructed climate history based on tree-ring data (Cleaveland 2006) might be used to estimate the frequency of annual rainfall deficits as severe as or worse than those that occurred during the worst part of the drought of the 1950s.

Evaluate the potential effects of climate variability on recharge

Global climate models used by the International Panel on Climate Change suggest that Texas will be warmer and most suggest that Texas will be drier (Kundzewicz and others 2007). Warmer temperatures increase evapotranspiration which decreases runoff (all other factors remaining the same), an important factor for recharge to the Edwards Aquifer. A recent study commissioned by the Lower Colorado River Authority and the San Antonio Water System showed that even with increased rainfall, runoff was expected to decrease in the contributing basins to the Highland Lakes (CH2M Hill 2008).

Several authors have investigated climate change and the Edwards Aquifer (Loáiciga and others 1996, Loáiciga and others 2000, Chen and others 2001, Mace and Wade 2008), but a regional study that includes an assessment of runoff in the Hill Country with the updated climate models is needed. The assumption that climate and drought in the future will look like climate and drought in the past needs to be examined. The study should evaluate the currently available literature and studies that have been produced related to the predicted effects of climate change and global warming, to aid in forming recommendations related to withdrawal reduction levels and states for critical period management. The study should analyze the range of potential effects on the Edwards Aquifer and the spring ecosystems due to climate change, including the effects of warmer temperatures and increased evapotranspiration with resulting decreases runoff (all other factors remaining the same), an important factor for recharge to the Edwards Aquifer. Additional climatic modeling, analysis of risk factors of climate change, and predictive atmospheric modeling of precipitation and temperature patterns in the Edwards region will assist in the planning efforts to deal with the uncertainties of future climatic conditions.

Conduct additional runs to refine withdrawal reductions

Although we are delivering withdrawal reductions in this report that meet the flow requirements, we did not have time to request and consider model runs to potentially refine those reductions. For example, given additional time, we would have requested model runs to investigate different trigger levels and withdrawal reductions.

Refine the calibration of the model

The current version of the model was released in 2004; however, no aquifer characterization data after 2002 was incorporated into the model, and most data and information used in the model assembly are from much earlier times. In terms of calibration, the transient calibration period for the Edwards Aquifer model was 1947 through 1990. Transient simulation included a model testing period of 1991 through 2000 to establish greater confidence in the ability of the model to reproduce measured hydraulic heads and springflows.

The period of 2001 through 2009 has exhibited several extreme hydrologic events including periods of excessive precipitation and recharge interspersed with at least one period of severe drought (2007 through 2009). Hydrologic data collection during this time has been significantly more extensive and comprehensive compared with prior time periods. Near historic groundwater highs in the Edwards Aquifer in 2002 and 2007 were followed by different periods of reduced precipitation. High resolution precipitation data for the periods following the 2002 and 2007 periods of groundwater high levels can be correlated with groundwater highs and spring discharges to gain insight on ability of the aquifer to store water. Performing this analysis will help ascertain the ability of the model to predict aquifer response to periods of prolonged drought. We recommend that a post-audit be performed on the model for 2001 through 2009 and, if appropriate, adjustments be made to the calibration. We also recommend that more robust calibration technologies, such as PEST or Bayesian inversion, be employed to provide the best possible outcome.

Study the response of the aquifer during the drought of 2007 through 2009

From September 2007 through January 2009, San Antonio experienced the driest 17-month period since 1885, according to records kept by the National Weather Service (2009). Because of abundant rainfall in the first eight months of 2007, aquifer levels and springflows did not reach critically low levels during 2008. J-17 began 2008 at 689 feet above mean sea level and was below 660 feet for two weeks in late June 2008, reaching a low of 657 feet. On January 1, 2009, J-17's water level was approximately at 670 feet. On April 24, 2009, when J-17 reached the Stage I trigger level of 660 feet, pumping in the San Antonio Pool east of Uvalde County was reduced by 20 percent, in accordance with the critical period management plan in Senate Bill 3. The Edwards Aquifer Authority Act exempts agricultural pumping from mandatory reduction if crops have been planted prior to the triggers being met. Thus, agricultural irrigators pumped until approximately July 1, 2009, when they traditionally begin to harvest their corn crop. As a result of agricultural pumping and increased summer pumping in the municipal sector, J-17 levels as well as springflow levels continued to drop through the first six months of 2009. J-17 water levels reached the Stage II trigger level (650 feet) on June 14, 2009, resulting in a 30 percent reduction in municipal and industrial pumping in the area east of Uvalde County.

On approximately July 1, 2009, as irrigation pumping ended, water levels in J-17, as well as flow at Comal Springs, appeared to stabilize. J-17 water levels varied from 640 to 645 feet for the period from July 1 until mid-September, when the region began to receive rain events. This came at the end of the hottest year-to-date on record for the San Antonio area, where the National Weather Service recorded 67 days of temperatures reaching or exceeding 100 degrees. Cumulative rainfall for 2009 in Bexar County prior to September 1 was officially 8.43 inches, approximately 44 percent of normal rainfall to that date.

Historical data for J-17 and Comal and San Marcos springs have traditionally shown a rapid decline from March through July with a continuing but less rapid decline from July through October. The aquifer's behavior during the summer and early fall of 2009 has therefore raised questions as to what caused the observed response. J-17 water levels, as well as springflow measured at Comal Springs, when analyzed on a daily basis, appear to have reacted to watering restrictions imposed by the San Antonio Water System, the Bexar Metropolitan Water District, and other surrounding municipalities. Levels dropped from Monday through Thursday each week, leveled off on Friday, and rose on Saturday and Sunday. This occurred even though the area received no rainfall and dealt with extended periods of temperatures exceeding 100 degrees.

This response during the summer and early fall of 2009—the leveling of water levels in J-17 and springflows—needs to be further analyzed to determine what factors caused it to occur and what the implications are for maintaining aquifer and springflow levels in the future. One proposed method of analysis would be to look at the aquifer response with the model after it has been recalibrated with additional data collected through 2009. An analysis of pumping levels and pumping distribution on a monthly basis, compared with aquifer response, may also provide useful information.

Update the model

The model should be updated to incorporate (1) additional aquifer characterization data and information collected since the development of the model and (2) new modeling software, such as MODFLOW-2005 (CFP) and MODFLOW-DCM, that accommodate both diffuse and conduit flow.

Considerable new data and interpretations of groundwater flow in the Edwards Aquifer have come forth since the development of the current model. These data and interpretations provide reconceptualizations of boundary conditions, geologic structure, hydraulic architecture, recharge, and water budget. Although not all aspects of characterizing the Edwards Aquifer are known, there has been sufficient advance in the characterization of the aquifer to justify consideration of updating the current model at this time.

Enhance the management module

The critical period management module does not accurately model the Edwards Aquifer Authority's rules for reduction of pumping by water rights holders. There are two issues.

- The model for the Edwards Aquifer with the Critical Period Management Module instantaneously reduces pumping by all pumpers when triggers are reached for springflow or water levels in the monitoring wells. The Authority's regulations, however, do not require that these reductions in pumping be made "instantaneously". Instead, a water right holder cannot exceed his reduced permitted water right by the end of the year. The water right holder does not have to start reducing when the trigger level is hit. The reduced permitted amount is calculated at the end of the year and based on a percentage for the number of days that the aquifer is in a declared critical management stage. Additionally, an irrigator is not required to reduce his pumping by any amount once the crop is in the ground. The Critical Period Management Module needs to be revised to account for how pumping reductions are actually implemented. Alternatively, the Edwards Aquifer Authority might consider modification of its rules to provide for more immediate responses to critical period management triggers.

- Hydrogeologically, the Uvalde Pool is considered to be west of the Knippa Gap. Administratively, the Uvalde Pool is considered to be west of the Medina-Uvalde county line. This means that many pumpers in eastern Uvalde County are in the San Antonio Pool from a hydrogeologic perspective, but in the Uvalde Pool from an administrative basis. These eastern Uvalde County wells, however, are subject to the critical period management cutbacks of the Uvalde Pool and not the San Antonio Pool. It is important that the model and the administration of the critical period management rules are in synch.

Evaluate the hydraulic relationship between the Trinity and Edwards aquifers

The connection between the Edwards Aquifer and the Trinity Aquifer should be refined, especially with respect to cross-formational flow from the Trinity Aquifer to the Edwards Aquifer in the San Marcos Springs area. As reflected in the model, there are two primary sources of flow from the Trinity Aquifer to the Edwards Aquifer: (1) that sourced from recharge to the Trinity Aquifer from Cibolo Creek and (2) that sourced from elsewhere in the Trinity Aquifer. Flow into the Edwards Aquifer sourced from Cibolo Creek is allowed to vary over time in the model whereas flow sourced from the rest of the Trinity Aquifer remains the same over time. Along the northern boundary in the steady-state model of the Edwards Aquifer, the general-head boundary package of MODFLOW was used to simulate a head-dependant flux boundary condition in order to estimate the equilibrium inflow from the Trinity Aquifer to the Edwards Aquifer. The boundary heads for the simulation were based on published historical water levels for the Edwards-Trinity Aquifer system. For the transient simulation, the MODFLOW well package was used to simulate a constant flux, equal to the model-calculated head-dependant flux from the steady-state simulation (Lindgren and others, 2004). In reality, this flow probably varies over time. Given the probable importance of this flow to maintaining springflows in San Marcos Springs, additional study is warranted to better understand—and better model—this flow.

Refine model calibration between San Marcos and Barton springs

The model of the Edwards Aquifer presently includes the portion of the aquifer located between San Marcos and the Colorado River (Barton Springs) as one continuous system and provides estimates of Barton Springs discharge and leakage to the Colorado River. It is understood and demonstrated by model results that calibration of the model within this segment of the aquifer was perceived to be less critical than for other segments, in part because of the historical recognition of a transient groundwater divide generally coincident with Onion Creek, north of the Blanco River watershed boundary. A number of studies have referenced the occurrence of this groundwater divide or mounding during wet and average periods; however, recent studies and field measurements during 2009 have demonstrated that this mounding dissipates or disappears during drought. Hence, a groundwater level gradient from San Marcos Springs to Barton Springs has been shown to exist during drought, indicating that recharge in the San Antonio Segment of the aquifer is migrating to the Barton Springs Segment and that pumping in the San Antonio Segment affects discharge from Barton Springs. Recalibration and refinement of the model would facilitate more accurate simulation of flows between the San Antonio and Barton Springs segments of the Edwards Aquifer, thereby allowing more rigorous consideration of withdrawal reduction levels and stages for critical period management.

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Appendix A: The formation and operation of the Edwards Aquifer Area Expert Science Subcommittee

The Texas Legislature required the Steering Committee for the Edwards Aquifer Recovery Implementation Program to establish an Edwards Aquifer Area Expert Science Subcommittee of individuals “with technical expertise regarding the Edwards Aquifer system, the threatened and endangered species that inhabit that system, springflows, or the development of withdrawal limitations.” The legislature required the subcommittee to prepare “initial recommendations by December 31, 2008”, regarding:

- The option of designating a separate San Marcos pool, how such a designation would affect existing pools, and the need for an additional well to measure the San Marcos pool if designated;
- The necessity to maintain minimum springflows, including a specific review of the necessity to maintain a flow to protect federally threatened and endangered species; and
- Whether adjustments in the trigger levels for the San Marcos Springs flow for the San Antonio pool should be made.

The Steering Committee refers to these recommendations as the “k” charges. In making their recommendations, the Science Subcommittee was tasked to “consider all reasonably available science” and “base its recommendations solely on the best science available.” In addition, the legislature tasked the subcommittee to “operate on a consensus basis to the maximum extent possible.”

The Steering Committee appointed 15 scientists to serve on the Expert Science Subcommittee and one non-voting member. A list of the members and their affiliations is included at the beginning of this report (page iii).

Members were seated using a formal nomination and selection process:

- The Steering Committee established an Expert Science Subcommittee nominations workgroup to handle the application process.
- The workgroup accepted nominations from members of the Edwards Aquifer Recovery Implementation Program (an individual could also nominate themselves).
- Nominated individuals were asked to complete and submit an application summarizing their applicable areas of expertise and any possible conflicts of interest.
- The workgroup reviewed and compiled all applications by area of expertise.
- The compiled applications information was made available to all members of the Edwards Aquifer Recovery Implementation Program.
- Members of the Edwards Aquifer Recovery Implementation Program were invited to endorse nominees without limitation on the number of endorsements.
- The workgroup presented the endorsement results to the Steering Committee.
- At the January 2008 general Edwards Aquifer Recovery Implementation Program meeting, the Steering Committee held open discussions regarding the selection of

the Expert Science Subcommittee members. Consensus was reached to seat seven members, and these seven members were tasked to make recommendations to the Steering Committee regarding filling the remaining eight vacancies from the original pool of nominees/applicants.

- The newly-formed Expert Science Subcommittee met in late January 2008 and reached consensus regarding recommendations to fill the remaining eight vacancies.
- At the February 2008 general Edwards Aquifer Recovery Implementation Program meeting, the Steering Committee reached consensus on the eight nominees recommended by the Expert Science Subcommittee. At this same meeting, the Steering Committee reached consensus on the addition of one non-voting member to the subcommittee.
- Subsequent filling of available Expert Science Subcommittee slots (due to resignations) was accomplished by the Expert Science Subcommittee reaching consensus on a nominee/applicant from the original pool and making a recommendation to the Steering Committee. In each case, the subcommittee's recommendation was accepted by the Steering Committee.

Additional information about the establishment and the work of the Expert Science Subcommittee can be found at http://earip.tamu.edu/SciComm.cfm.

Appendix B: Excerpts from the Edwards Aquifer Authority Act, as amended by Senate Bill 3, Regular Session, 80th Legislature, that concern the Edwards Aquifer Area Expert Science Subcommittee

Section 1.14 WITHDRAWALS

(a) Authorizations to withdraw water from the aquifer and all authorizations and rights to make a withdrawal under this Act shall be limited in accordance with this section to:

  (1) protect the water quality of the aquifer;
  (2) protect the water quality of the surface streams to which the aquifer provides springflow;
  (3) achieve water conservation;
  (4) maximize the beneficial use of water available for withdrawal from the aquifer;
  (5) recognize the extent of the hydro-geologic connection and interaction between surface water and groundwater;
  (6) protect aquatic and wildlife habitat;
  (7) protect species that are designated as threatened or endangered under applicable federal or state law; and
  (8) provide for instream uses, bays, and estuaries.

(b) *Repealed by Act of May 28, 2007, 80th Leg., R.S., ch. 1351, § 2.09, 2007 Tex. Gen. Laws 4612, 4634; Act of May 28, 2007, 80th Leg., R.S., ch. 1430, § 12.09, 2007 Tex. Gen. Laws 5848, 5908.*

(c) Except as provided by Subsections (f) and (h) of this section and Section 1.26 of this article, for the period beginning January 1, 2008, the amount of permitted withdrawals from the aquifer may not exceed or be less than 572,000 acre-feet of water for each calendar year, which is the sum of all regular permits issued or for which an application was filed and issuance was pending action by the authority as of January 1, 2005.

(d) *Repealed by Act of May 28, 2007, 80th Leg., R.S., ch. 1351, § 2.09, 2007 Tex. Gen. Laws 4612, 4634; Act of May 28, 2007, 80th Leg., R.S., ch. 1430, § 12.09, 2007 Tex. Gen. Laws 5848, 5908.*

(e) The authority may not allow withdrawals from the aquifer through wells drilled after June 1, 1993, except for replacement, test, or exempt wells or to the extent that the authority approves an amendment to an initial regular permit to authorize a change in the point of withdrawal under that permit.

(f) If the level of the aquifer is equal to or greater than 660 feet above mean sea level as measured at Well J-17, the authority may authorize withdrawal from the San Antonio pool, on an uninterruptible basis, of permitted amounts. If the level of the aquifer is equal to or greater than 845 feet at Well J-27, the authority may authorize withdrawal from the Uvalde pool, on an uninterruptible basis, of permitted amounts.

(h) To accomplish the purposes of this article, the authority, through a program, shall implement and enforce water management practices, procedures, and methods to ensure that, not later than December 31, 2012, the continuous minimum springflows of the Comal Springs and the San Marcos Springs are maintained to protect endangered and threatened species to the extent required by federal law and to achieve other purposes provided by Subsection (a) of this section and Section 1.26 of this article. The authority from time to time as appropriate may revise the practices, procedures, and methods. To meet this requirement, the authority shall require:

   (1) phased adjustments to the amount of water that may be used or withdrawn by existing users or categories of other users, including adjustments in accordance with the authority's critical period management plan established under Section 1.26 of this article; or

   (2) implementation of alternative management practices, procedures, and methods.

Act of May 30, 1993, 73rd Leg., R.S., ch. 626, § 1.14, 1993 Tex. Gen. Laws 2350, 2360; as amended by Act of May 28, 2007, 80th Leg., R.S., ch. 1351, § 2.02, 2007 Tex. Gen. Laws 4612, 4627; Act of May 28, 2007, 80th Leg., R.S., ch. 1430, § 12.02, 2007 Tex. Gen. Laws 5848, 5901.

Section 1.26A DEVELOPMENT OF WITHDRAWAL REDUCTION LEVELS AND STAGES FOR CRITICAL PERIOD MANAGEMENT THROUGH RECOVERY IMPLEMENTATION PROGRAM.

(h) Where reasonably practicable or as required by law, any meeting of the steering committee, the Edwards Aquifer area expert science subcommittee, or another subcommittee established by the steering committee must be open to the public.

(i) The steering committee appointed under this section shall appoint an Edwards Aquifer area expert science subcommittee not later than December 31, 2007. The expert science subcommittee must be composed of an odd number of not fewer than seven or more than 15 members who have technical expertise regarding the Edwards Aquifer system, the threatened and endangered species that inhabit that system, springflows, or the development of withdrawal limitations. The Bureau of Economic Geology of The University of Texas at Austin and the River Systems Institute at Texas State University shall assist the expert science subcommittee. Chapter 2110, Government Code, does not apply to the size, composition, or duration of the expert science subcommittee.

(j) The Edwards Aquifer area expert science subcommittee shall, among other things, analyze species requirements in relation to spring discharge rates and aquifer levels as a function of recharge and withdrawal levels. Based on that analysis and the elements required to be considered by the authority under Section 1.14 of this article, the expert science subcommittee shall, through a collaborative process designed to achieve consensus, develop recommendations for withdrawal reduction levels and stages for critical period management including, if appropriate, establishing separate and possibly different withdrawal reduction levels and stages for critical period management for different pools of the aquifer needed to maintain target spring discharge and aquifer levels. The expert science subcommittee shall submit its recommendations to the steering committee and all other stakeholders involved in the recovery implementation program under this section.

(k) The initial recommendations of the Edwards Aquifer area expert science subcommittee must be completed and submitted to the steering committee and other stakeholders not later than December 31, 2008, and should include an evaluation:

(1) of the option of designating a separate San Marcos pool, of how such a designation would affect existing pools, and of the need for an additional well to measure the San Marcos pool, if designated;

(2) of the necessity to maintain minimum springflows, including a specific review of the necessity to maintain a flow to protect the federally threatened and endangered species; and

(3) as to whether adjustments in the trigger levels for the San Marcos Springs flow for the San Antonio pool should be made.

(l) In developing its recommendations, the Edwards Aquifer area expert science subcommittee shall:

(1) consider all reasonably available science, including any Edwards Aquifer-specific studies, and base its recommendations solely on the best science available; and

(2) operate on a consensus basis to the maximum extent possible.

(m) After development of the cooperative agreement, the steering committee, with the assistance of the Edwards Aquifer area expert science subcommittee and with input from the other recovery implementation program stakeholders, shall prepare and submit recommendations to the authority. The recommendations must:

(1) include a review of the critical period management plan, to occur at least once every five years;

(2) include specific monitoring, studies, and activities that take into account changed conditions and information that more accurately reflects the importance of critical period management; and

(3) establish a schedule for continuing the validation or refinement of the critical period management plan adopted by the authority and the strategies to achieve the program and cooperative agreement described by this section.

Act of May 28, 2007, 80th Leg., R.S., ch. 1351, § 2.06, 2007 Tex. Gen. Laws 4612, 4630; Act of May 28, 2007, 80th Leg., R.S., ch. 1430, § 12.06, 2007 Tex. Gen. Laws 5848, 5904.

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Appendix C: Memorandum of Agreement for the Edwards Aquifer Recovery Implementation Program

MEMORANDUM OF AGREEMENT FOR EDWARDS AQUIFER RECOVERY IMPLEMENTATION PROGRAM

This Memorandum of Agreement ("MOA") is intended to serve as the Memorandum of Agreement for the Edwards Aquifer Recovery Implementation Program (the "Program") under the Endangered Species Act and as the Memorandum of Agreement required by Senate Bill 3. It is made and agreed to by the Parties signing below and is effective on the Effective Date. The Parties will work together in good faith and cooperation to achieve the purposes and goals provided in the following provisions of this MOA.

Article 1. Purposes

Section 1.1. The purpose of this MOA is to formally initiate the development and implementation of the Edwards Aquifer Recovery Implementation Program. The Program is a collaborative initiative among stakeholders to participate in efforts to contribute to the recovery of the Edwards Species, develop aquifer management measures, and develop conservation measures for the Edwards Aquifer.

Section 1.2. During the 80^{th} Regular Session, the Texas Legislature enacted Senate Bill 3, establishing, among other things, minimum requirements applicable to the Program. It is the intent of the Parties to comply with those minimum requirements and to build upon them to ensure that the Program is as effective and as inclusive as is reasonably possible, while also maintaining compliance with applicable provisions of the Endangered Species Act.

Section 1.3. The Parties acknowledge that Program efforts will be mindful of minimizing impacts on other protected species when advancing Program initiatives. The Parties also acknowledge the necessity of finding ways to balance the Program's contribution to recovery of Edwards Species with human water needs, while maintaining compliance with applicable provisions of the Endangered Species Act.

Article 2. Goals

Section 2.1. The goals of the Program, which are intended to be broadly interpreted, include, but are not limited to, the following:

(a) review, develop, and implement sound scientific research, analysis and other measures which contribute to understanding and meeting the needs of the Edwards Species;
(b) review, develop, and implement strategies which balance the needs of the Edwards Species with overall water use and supply in the Edwards Aquifer region;
(c) develop and complete an implementing agreement by December 31, 2009;
(d) develop and complete a program document by September 1, 2012, that shall take effect December 31, 2012, and may be in the form of a habitat conservation plan for the Edwards Species;
(e) implement the program document; and

(f) secure federal, state, and other available funding to assist with the development and implementation of the Program.

Section 2.2. The Parties to this MOA will participate in good faith in a cooperative, consensus-based process consistent with the purposes of the Program, and the requirements and deadlines imposed by Senate Bill 3. The Parties acknowledge that reasonable flexibility to adapt Program activities, particularly in response to new information and changed circumstances, is necessary to effectively meet the purposes of the Program.

Article 3. Definitions and Construction.

Section 3.1. Definitions. In this MOA, the following terms shall have the meanings assigned in this section unless the context clearly specifies a different meaning:

"Edwards Aquifer" means the same as the definition for "Aquifer" used in The Edwards Aquifer Authority Act.

"Edwards Species" means aquatic species that (1) are listed as threatened or endangered pursuant to the Endangered Species Act, and (2) are found in the Edwards Aquifer or found in or around the springs associated with the Edwards Aquifer. The Edwards Species, as of the Effective Date, are as follows: fountain darter, San Marcos gambusia, San Marcos salamander, Texas blind salamander, Comal Springs riffle beetle, Comal Springs dryopid beetle, Peck's cave amphipod, and Texas wild rice. This definition may be expanded by decision of the Steering Committee, without amending the MOA, to include additional species that are proposed for listing as threatened or endangered and that otherwise meet the definition of Edwards Species.

"Effective Date" means the date this MOA is effective, which shall be that date on which the MOA has been executed by duly authorized representatives of (1) the Edwards Aquifer Authority, United States Fish and Wildlife Service, Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, Texas Department of Agriculture, Texas Water Development Board and (2) of other interests designated in Senate Bill 3 as initial members of the Steering Committee such that, collectively, at least 75% of the initial members of the Steering Committee have signed the document.

"Endangered Species Act" means the federal Endangered Species Act of 1973, as amended, 16 U.S.C. §§ 1531, et seq.

"Habitat Conservation Plan" means a conservation plan as referred to in Section 10 (a)(2), 16 U.S.C. § 1539 (a)(2), of the Endangered Species Act.

"Recovery" means the process by which the decline of an endangered or threatened species is arrested or reversed, and threats removed or reduced so that the species' long term survival in the wild can be ensured.

"Senate Bill 3" means Article 12 of Senate Bill 3, 80^{th} Regular Session, 2007, of the Texas Legislature and Article 2 of House Bill 3, 80^{th} Regular Session, 2007, of the Texas Legislature.

The Articles amend the Edwards Aquifer Authority Act ("Act"), Chapter 626, Acts of the 73rd Legislature, Regular Session, 1993, Section 1.26(A) of the Act provides for the development of a recovery implementation program. Identical provisions are included in Article 2 of House Bill 3, 80th Regular Session of the Texas Legislature.

Section 3.2. Construction. The Parties intend this MOA to be construed to comply with Senate Bill 3 establishing, among other things, minimum requirements applicable to the Program and with applicable requirements of the Endangered Species Act.

Article 4. Participation

Section 4.1. The Parties pledge to participate in good faith in an open, voluntary, and cooperative process that will strive to reach consensus on issues that further the purposes and goals of the Program. To achieve these purposes and goals, the Program will be overseen by a Steering Committee designed to ensure opportunities for participation and adequate representation of stakeholders. The Steering Committee will adopt procedures consistent with the MOA to ensure the Program includes, but is not limited to, the following procedural elements: an open process, advance public notice of meetings and proposed actions, opportunity for stakeholder participation, open communication, and consensus-based decision-making.

Section 4.2. Senate Bill 3 established the composition of an initial Steering Committee. Senate Bill 3 also allows, upon execution of this MOA, the initial Steering Committee to vote to add Members and to change the composition of the Steering Committee. In order to ensure adequate stakeholder representation on the Steering Committee, the signatories of this MOA recommend that the Steering Committee, at its earliest opportunity, add to the Steering Committee five other persons in the following categories:

(a) A representative of a holder of an Edwards Aquifer Authority initial regular permit issued to a small municipality (population under 50,000) located east of San Antonio,
(b) A representative of Edwards Aquifer region municipal ratepayers/general public,
(c) A representative of Guadalupe River Basin municipal ratepayers/general public,
(d) A representative of a conservation organization, and
(e) A representative of the Nueces River Authority.

Section 4.3. The Steering Committee will adopt procedures for the designation of primary, alternate, and replacement members of the Steering Committee. When changing or adding members, including members in addition to those listed in Section 4.2, the Steering Committee shall seek to maintain the balance of interests represented in the initial Steering Committee as set out in Senate Bill 3.

Section 4.4. In accordance with Senate Bill 3, the Steering Committee shall appoint an Edwards Aquifer area expert science subcommittee no later than December 31, 2007. As soon as reasonably possible, the Steering Committee shall establish a recharge facility feasibility subcommittee; other subcommittees shall be established as the Steering Committee determines appropriate. The Steering Committee shall ensure procedural elements are adopted to ensure an open process, advance public notice of meetings and proposed actions, opportunity for stakeholder participation, open communication, and consensus-based decision-making are followed in subcommittees.

Article 5. Governance

Section 5.1. In addition to the responsibilities expressed in Senate Bill 3, the Steering Committee will adopt procedures to: address employment of a Program Manager and determine the Program Manager's role in the Program; establish appropriate Program subcommittee processes, to include membership, responsibilities, and decision-making recommendations; obtain funding for the Program ; adopt or amend Program Operational Rules; and other matters for which the Steering Committee determines procedures are necessary.

Section 5.2. The goal of the Steering Committee is to achieve consensus-based decision-making. Consensus is reached when no Member of the Steering Committee is opposed to a proposal. It is understood and accepted that in order to achieve a consensus on the Steering Committee, each Member will be open to pursuing "win-win" alternatives and to considering variations on the proposal that he or she might initially prefer. In its deliberations, the Steering Committee shall seek to exhaust every reasonable and practicable effort to reach consensus.

Section 5.3. In furtherance of consensus-based decision-making, when a proposal to the Steering Committee involving a Tier 1 decision (as set out in Section 5.5) does not achieve consensus, the Steering Committee will adopt a process which requires further deliberation and development of the proposal by an Issue Team. The Issue Team will be a smaller team of stakeholders as appointed by the Steering Committee and will include, to the extent practicable, participants representing all different viewpoints on the proposal, which may include participants who are not members of the Steering Committee. The Issue Team process will provide an opportunity for input from other stakeholders. The goal of the Issue Team is to achieve consensus on the proposal, or to develop a restatement of the proposal that may better achieve consensus of the Steering Committee. If after resubmission to the Steering Committee, or restatement of the proposal and resubmission to the Steering Committee, consensus has not been achieved, the Steering Committee will then vote on the proposal. A resubmitted or restated proposal will be deemed to have been approved by the Steering Committee when at least 75 percent of the entire Steering Committee has voted in favor of the proposal in accordance with voting procedures to be adopted by the Steering Committee.

Section 5.4. The Steering Committee will adopt procedures for appointment of Issue Teams, time requirements for resubmission and restatement of proposals, flexibility to continue to pursue consensus, an allowance for a minority report to be included with Tier 1 decisions, and voting procedures. These procedures to be adopted by the Steering Committee will apply to all Tier 1 decisions.

Section 5.5. The following types of decisions are considered to be Tier 1 decisions:

(a) Hiring or terminating of Program Manager;
(b) Approval of annual budget;
(c) Formal Recommendations to the EAA;

(d) Recommendations or Reports to the Legislature;
(e) Membership, responsibilities, and procedures of subcommittees;
(f) Changes to the membership of the Steering Committee beyond initial changes set out in Section 4.2 above;
(g) Adoption and amendment of the decision process of the Steering Committee;
(h) Decisions related to adoption or amendment of any Program agreements including, but not limited to the Memorandum of Agreement, the Implementing Agreement, the Cooperative Agreement, and the Program Document;
(i) Adoption or amendment of Program Operational Rules; and
(j) Any significant action determined by the Steering Committee to require Tier 1 decision-making in accordance with procedures to be developed.

Section 5.6. The Steering Committee will adopt simplified procedures for all other decisions of the Steering Committee. For those decisions other than Tier 1 decisions, a decision will be deemed to have been approved by the Steering Committee when a majority of the entire Steering Committee has voted in favor of the proposal in accordance with voting procedures adopted by the Steering Committee. Non-Tier 1 decisions are not subject to the Issue Team process described in Section 5.3.

Article 6. General Provisions

Section 6.1. This MOA shall remain in effect until the earlier of September 1, 2012 or the execution of a program document in compliance with the requirements of Senate Bill 3 and the Endangered Species Act. However, any signatory retains the ability to withdraw from the Program at any time by providing written notice of withdrawal to the Steering Committee. This MOA, including the term of the MOA, may be amended by action of the Parties in accordance with Senate Bill 3 and the decision processes established by the Steering Committee.

Section 6.2. Nothing herein shall constitute, nor be deemed to constitute, an obligation of future appropriations by the signatories to this MOA where creating such an obligation would be inconsistent with applicable federal, state, or local laws. Funding commitments made under this MOA by the signatories are understood to be contingent on obtaining approval and appropriations by the applicable local, state, or federal regulatory or legislative bodies. This MOA does not create an exclusive arrangement between the United States Fish and Wildlife Service (Service) or the Department of the Interior and the Parties to this agreement or commit the Service or the Department of the Interior to enter into any contract or other binding obligation. By entering into this MOA, no Party is obligated to enter into any contract or other binding obligation. This MOA is subject to and is intended to be consistent with all applicable federal, state, and local laws.

Section 6.3. All signatories to this MOA recognize that various parties have statutory responsibilities that cannot be delegated. Nothing in this MOA shall be construed to abrogate any of the statutory responsibilities of any signatory of the MOA**,** including:

(1) responsibilities that relate to implementing specific strategies included in the Program Document;

(2) authority to decide whether to approve any document, or amendment thereto, specifically required to be entered into by the parties under Senate Bill 3; or

(3) the Service's statutory authority under the Endangered Species Act.

Section 6.4. This MOA is effective on the date fully signed as described in the Definition of Effective Date. The MOA may be signed by additional stakeholders, including other appropriate federal agencies, following the Effective Date of the MOA.

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Appendix D. Presentations made to the Edwards Aquifer Area Expert Science Subcommittee

Steve Clouse (Chief Operating Officer, San Antonio Water Supply) and Pablo Martinez (Planner III, San Antonio Water Supply)
TOPIC: Recycled water

Phillip Cook, P.E. (Director of Production, San Antonio Water Supply) and Jeff Haby, P.E. (Manager of Production, San Antonio Water Supply)
TOPIC: Aquifer storage and recovery/conservation efforts and successes

Brock Curry (Assistant General Manager–Administration and Operation, Edwards Aquifer Authority)
TOPIC: Critical period—Evolution of drought management (1989–Present)

John Hoyt, P.G., (Assistant General Manager–Aquifer Management, Edwards Aquifer Authority)
TOPIC: Edwards Aquifer Authority water quantity management

Karen Guz (Director of Conservation, San Antonio Water Supply)
TOPIC: Conservation efforts and successes

Rick Illgner (Governmental Affairs Officer, Edwards Aquifer Authority)
TOPIC: Critical period management: Quarterly versus annual allocations

Charles Jackson, Ph.D. (Institute for Geophysics, University of Texas at Austin)
TOPIC: Climate changes in Texas

Barbara Mahler (U.S. Geological Survey)
TOPIC: Work on Barton Springs Segment of the Edwards Aquifer

Darwin Ockerman (U.S. Geological Survey)
TOPIC: Streamflow gains and losses in the Guadalupe relative to the major springs

George Ozuna (U.S. Geological Survey)
TOPIC: Basic Hydrology and San Marcos Springs

Geary Schindel, P.G. (Chief Technical Officer, Edwards Aquifer Authority)
TOPIC: Edwards Aquifer MODFLOW model—Development, benefits, limitations, current and future applications

Geary Schindel, P.G. (Chief Technical Officer, Edwards Aquifer Authority)
TOPIC: EAA San Marcos report (Evaluation of the option to designate a separate San Marcos pool for critical period management)

Sam Vaugh, P.E. (Vice President, HDR Engineering, Inc.)
TOPIC: Environmental flows in the Guadalupe River Basin

Adam Zerrenner (U.S. Fish and Wildlife Service)
TOPIC: Reviewing influence diagrams and how they can provide flexibility

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Appendix E. Position papers submitted by the stakeholders of the Edwards Aquifer Recovery Implementation Program

The Edwards Aquifer Area Expert Science Subcommittee solicited position papers from any interested stakeholder involved with the Edwards Aquifer Recovery Implementation Program. Instructions were to identify, per task/charge, three references that the stakeholder felt the subcommittee needed to consider and a position paper limited to one page. The positions are given according to Senate Bill 3's charges to the subcommittee (see Appendix B). We have not edited these submissions. This appendix includes these submissions, listed in alphabetical (citation style) order.

J Charge Position

Submitted by Guadalupe Basin Coalition:
Contact: **Tom Taggart**
Date: **August 12, 2009**
Email Address: **ttaggart@sanmarcostx.gov**
Contact Phone Number: **512-393-8004**

Top Three Position Supporting References:

(1) Johnson, S.B., and Schindel, G.M., 2008, Evaluation of the Option to Designate a Separate San Marcos Pool for Critical Period Management, 151 p.
(2) Most Current versions of ModFlow andGWSIM models as appropriate
(3) HDR Technical Memo Re: Hydrologic Connection of the Edwards Aquifer between San Marcos Springs and Barton Springs, October 18, 2008
(4) HDR Technical Memo Re: Impact of Pumping LCRA Well on Flow from Comal and San Marcos Springs during 1950s Drought, July 2, 2008

Your Position (limited to two pages):

1. Science Subcommittee recommendations on the items listed in the J charge, including any proposed withdrawal reduction stages and critical period management reduction amounts, should be based solely on the best available science.

2. A separate pool for San Marcos Springs or Hays County should not be designated.

3. While the impacts to springflow from additional recharge merit further study, additional recharge should not be an assumption built into the Science Subcommittee's recommendations at this time.

4. Refugia should not be considered an acceptable adaptive management strategy for maintenance of the endangered and threatened species in lieu of adequate springflow.

5. Recirculation initiatives have not included scientific studies to demonstrate that the quality of aquifer water will be protected (**EAA Act, Section 1.14(a)(2)**) and that adequate flows for instream uses, bays and estuaries will be ensured (**EAA Act, Section 1.14(a)(8))**. In fact, water quality effects have been largely ignored in the multiple studies to date. These initiatives should not be advanced related to the J charges.

6. Supposition of effects or impacts related to springflows based on anecdotal, incomplete data, and speculative studies (e.g. LCRA well influence suppositions) should be avoided in completing this task.

J Charge Position

Submitted By: **Guadalupe Blanco River Authority**
Contact: **Todd Votteler**
Date: **August 12, 2009**
Email Address: **tvotteler@gbra.org**
Contact Phone Number: **830-379-5822**

Top Three Position Supporting References:

(1) Land, Larry, and Paula Jo Lemonds, HDR Technical Memo Re: Hydrologic Connection of the Edwards Aquifer between San Marcos Springs and Barton Springs, October 18, 2008

(2) Land, Larry, HDR Technical Memo Re: Impact of Pumping LCRA Well on Flow from Comal and San Marcos Springs during 1950s Drought, July 2, 2008

(3) Votteler, Todd H., *1996 Emergency Withdrawal Reduction Plan for the Edwards Aquifer*. Prepared for the U.S. District Court, Western District of Texas, The Honorable Lucius Bunton, Presiding, August 23, 1996, pp. 37.

Your Position (limited to two pages):

1. Science Subcommittee recommendations on the items listed in the J charge, including any proposed withdrawal reduction stages and critical period management reduction amounts, should be based solely on the best available science.

2. Any management plan for groundwater withdrawals should include a requirement for weekly pumping reporting by permit holders during critical periods.

3. Any proposed withdrawal reduction stages and critical period management reduction amounts should consider reductions to base usage, and below if required. Base usage is indexed to the monthly winter usage, i.e., average of the three lowest months of November, December, January, and February.

4. Supposition of effects or impacts related to springflows based on anecdotal, incomplete data, and speculative studies (e.g. LCRA well influence suppositions) should be avoided in completing this task.

5. The potential impacts of Edwards Aquifer groundwater withdrawals upon discharge rates at Barton Springs should be considered in any proposed withdrawal reduction stages and critical period management reduction amounts by the Science Subcommittee once data from the current U.S. Geological Survey-Barton Springs Edwards Aquifer Conservation District-HDR-Guadalupe Blanco River Authority monitoring program is available in September.

6. A separate pool for San Marcos Springs or Hays County should not be designated.

7. While the impacts to springflow from additional recharge merit further study, additional recharge should not be an assumption built into the Science Subcommittee's recommendations at this time.

8. Refugia should not be considered an acceptable adaptive management strategy for maintenance of the endangered and threatened species in lieu of adequate springflow.

9. Recirculation initiatives have not included scientific studies to demonstrate that the quality of aquifer water will be protected (**EAA Act, Section 1.14(a)(2)**) and that adequate flows for instream uses, bays and estuaries will be ensured (**EAA Act, Section 1.14(a)(8))**. In fact, water quality effects have been largely ignored in the multiple studies to date. These initiatives should not be advanced related to the J charges.

J Charge Position

Submitted By: Regional Clean Air & Water Association
Date: August 12, 2009
Email Address: cgpatterson@grandecom.net
Contact Phone Number: 210 824-3407

Top Three Position Supporting References:

(1) "Recharge and Recirculation Edwards Aquifer Optimization Program," prepared by Todd Engineers for the EAA in Phase I, II, III and IV Reports

(2) Evaluation of Augmentation Methodologies in Support of In Situ Refugia at Comal and San Marcos Springs," prepared by LBG-Guyton Associates for the EAA in 2004.

(3) Edwards Aquifer Authority Enabling Act, Sec. 1.14

Your Position (limited to four pages):

The "RCAWA Position Statement" on the 'j' Charge" was passed unanimously at the July 28th 2009 meeting of Regional Clean Air and Water Association.

Regional Clean Air and Water Association believes that the information described in the RCAWA Position Statement that follows (which includes the options of Recharge and Recirculation and Augmentation/In Situ) should be described and developed by some part of the EARIP process (not necessarily the Science Subcommittee) before a final recommendation can be made as to reductions in the pumping cap or floor or critical period reductions.

While we recognize that it is appropriate to provide "baseline" computer simulations, we do not think believe that the "j" charge will be complete without full consideration of the items referred to in Sec. 1.14 of the EAA Act, which includes "alternative management practices, procedures and methods" as described in Sec. 1.14 (h). We also believe that in the "j" charge, the analysis of species requirements in relation to spring discharge is made a "function of recharge and withdrawal levels."

For those reasons and for the reason that we need to be inclusive of options that have been proposed, we believe that before a final recommendation can be made by the EARIP processes with regard to withdrawal reduction levels or critical period stages, an analysis that includes these alternative management practices, procedures and methods should be provided.

/s/ Carol Patterson, President, Regional Clean Air & Water Association

<u>RCAWA POSITION STATEMENT ON THE "j" CHARGE:</u>

In reference to the "j" charge to the EARIP Science Subcommittee found in the EAA Act as amended by S.B. 3, Sec. 1.26A, subsection (j), Regional Clean Air and Water Association (RCAWA) respectfully requests that model runs and other information be provided on the options of (1) enhanced recharge & recirculation, and (2) in situ refugia / augmentation, in coordination with present pumping limits and critical period reductions found in S.B. 3.

These model runs and information would relate to:

(1) The beneficial effect that enhanced recharge and recirculation might have on providing a minimum springflow regime at Comal Springs and San Marcos Springs in a repeat of the drought of record, with the present pumping limits and critical period rules of S.B. 3 in place, including providing enhanced recharge from the sources identified in the Recharge & Recirculation Study and other studies of recharge enhancement possible for the Edwards Aquifer, to meet the goal of providing a minimum springflow regime in an efficient manner;

(2) The beneficial effect that in situ refugia / augmentation of springflows might have on providing waters for maintaining the habitat of the endangered species in the Comal River and the San Marcos River in a repeat of the drought of record, with the present pumping limits and critical period rules of S.B. 3 in place, including providing waters for maintaining the habitat by such means as were identified in the study entitled "Evaluation of Augmentation Methodologies in Support of In Situ Refugia at Comal and San Marcos Springs" done by LBG-Guyton Associates for the EAA in 2004.

It is the position of RCAWA that the "j" charge asks the Science Subcommittee to consider meeting species water requirements as a function of both "recharge" and "withdrawals", *and that the Science Subcommittee should base its recommendations on that analysis as well as "the elements required to be considered by the authority under Section 1.14 of this article"* which include the implementation of "alternative management practices, procedures and methods" referred to in Sec. 1.14(h) of the EAA Act.

RCAWA therefore asks that that the Science Subcommittee provide modeling and other information describing and evaluating these "alternative management practices, procedures and methods" as alternatives to further pumping reductions or to increased critical period reductions from those presently found in S.B. 3, and do this as a part of its work in providing recommendations and useful information to the Steering Committee.

Position Statement was adopted by RCAWA on July 28, 2009.
/s/ Carol Patterson, President of Regional Clean Air & Water Association

San Antonio Water System

San Antonio Water System
J-Charges Position Paper
Submitted by: Calvin Finch, SAWS
Date: July 31, 2009

The San Antonio Water System (SAWS) appreciates the opportunity to provide written comment on Senate Bill 3 "J" charges as requested by the Area Expert Science Subcommittee. SAWS commends the volunteers for taking on this important and difficult task.

In General:

- Decline in critical habitat is influenced by a variety of factors. Pumping is currently the most defined and tightly controlled variable. However, climate, impacts from recreational activities, floods, storm water runoff, and non-native species are some of the equally important variables that are inadequately quantified and defined. Other important factors include unregulated water withdrawals from the Edwards aquifer (domestic wells and unregistered wells) and other more localized contributing sources, such as the Trinity aquifer. SAWS urges that the task of the Science Subcommittee will be incomplete until these other factors are rigorously incorporated into the analysis.

- The spatial distribution of pumping can be just as detrimental to springflow as the amount or timing of the withdrawals. Anecdotal evidence increasingly suggests that pumping in close proximity to the springs has a disproportionately negative impact to the springflow versus pumping elsewhere in the Edwards region. For the first time ever, San Marcos Springs first triggered regional Critical Period cutbacks in spring 2009. In 2006, San Marcos Springs held the region in the Critical Period for several months after J-17 and Comal Springs recovered. We hope that the Science Subcommittee will, as part of developing the J-charge, consider the impact of local, as well as regional, pumping on the springs, and consider variations of critical period management which address appropriate local pumping curtailment. (LBG-Guyton & Associates 2004, LBG-Guyton & Associates 2008)

What are the species requirements?:

- We believe it is undisputed that most of the species of concern have survived past droughts, including the Drought of Record. This fact is supported by observation and acknowledged by the United States Fish & Wildlife Service (USFWS, 2007). The one exception to this observation is the Comal fountain darter, and even the darter might have survived the adverse situation at Comal if not for local activities impacting that ecosystem. Such local activities are known to have included pumping from the power plant well (LBG-Guyton & Associates, 2004), localized flood events, and may also have included rotenone poisoning (BIO-WEST 2003, Linam etal., 1993, Schenck etal., 1976, USFWS, 1996). Observations such as these are *key components* to the scientific process. SAWS has concerns that these valid observations being offered to the Area Expert Science Subcommittee and EARIP are being portrayed as mere "outlier" positions, rather than certain and irrefutable factual observations. We urge that these observations be given substantive recognition and attention by the Subcommittee.

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- What scientific work, judgment or observations linking a given discharge of springflow during a specified duration lead the Subcommittee to conclude the situation is adequate for recovery? We urge the Subcommittee to carefully document the scientific basis for their reasoning.

- Dr. Thom Hardy and his Team have drafted influence diagrams outlining factors that have an impact on the "sentinel" endangered species. Stakeholders were given the opportunity to comment on those influence diagrams. The Science Subcommittee should draw upon the SAWS comments to assist it in addressing the observations above (local activities impacting the ecosystem).

- Accurate measurement of springflow is a key concern for regional water users, and equally important for biological monitoring activities and endangered species relocation and mitigation. The San Marcos springflow volume measurement methodology does not inspire confidence and is currently regarded as less than reliable. This reliability issue results in situations that are problematic for water supply management and for the species. Recalibration of San Marcos spring discharge in early July 2009 resulted in "higher" springflows than initially reported. As a result, critical period biological monitoring was initiated, and Texas Wild-rice was re-planted as called for in the low-flow monitoring and salvaging plan, despite the lack of a "need" to do so after recalibration. As an additional example, imprecise springflow measurements in 2006 were a contributing factor to the decision by SAWS to recover thousands of acre-feet of stored groundwater from the Aquifer Storage and Recovery (ASR) storage facility. This resulted in an unwarranted additional financial cost to the ratepayers of San Antonio above normal operating costs, amounting to millions of dollars.

- The Science Subcommittee should recognize that the Edwards Aquifer receives natural recharge varying between approximately 50,000 acre-feet to more than 2,000,000 acre-feet per year (Edwards Aquifer Authority, 2008). This presents opportunities for optimization and management that can both meet the species requirements and human water supply. To the extent Section 1.14(a) is considered in the formulation of the J-charge recommendation, this optimization component should be considered along with others in Section 1.14(a) (Senate Bill 3, 2007).

- A robust refugium program that pays close attention to genetic integrity of species has been implemented in a number of recovery programs and remains a prudent tool and planning response to protracted drought or other disasters, whether natural or unnatural. The cost to permit-holders to drastically cutback any further is much higher than the cost of a state-of-the-art refugium. Droughts of varying intensity and duration have occurred in the past. While work has been done to evaluate drought during deep historical periods, the Science Subcommittee members should remain focused on the "Drought of Record." A refugium could play a vital role in a reoccurrence of a drought with greater intensity or duration.

- The risk to the endangered species of extinction from springflow cessation is currently low as analyzed in a report by BIO-WEST in 2003. This report included an impact and risk analysis approach to springflow cessation at a variety of pumping levels. This analysis indicated the risk of 0 cfs at Comal was low (0 – 6.2%) with a regional pumping floor of 340,000 acre-feet, and that San Marcos Springs would continue to flow (BIO-WEST, 2003). Garnering any additional "certainty" for springflow utilizing modeling and measurement tools with well-known and acknowledged shortcomings is scientifically unsound.

- The concept of a flow regime for maintenance of endangered species populations has been a topic of discussion among the members of the Science Subcommittee and the 2008 report (Edwards Aquifer Recovery Implementation Program, 2008). The Science Subcommittee seems to be trying to apply the "regime" concept to the lowest biologically-acceptable flow level. From a species perspective, flow regime determinations should focus on the context of the lower end of the scale of flow volumes for endangered species survival. Some of the peer reviewers of the "K-charge" report indicated that a regime approach to species that are adapted for habitat conditions of relative constancy, such as in temperature or water clarity, was unproven (Sustainable Ecosystems Institute, 2009).

- The correlation between the San Antonio segment of the Edwards Aquifer and the San Marcos Springs is deficient with an r^2=0.51 (T. Votteler, presentation to Science Subcommittee April 21, 2008). Water quality data (Johnson and Schindel, 2008; LBG-Guyton & Associates, 2004) has implicated numerous sources for the springs – local unconfined Edwards, regional artesian/confined Edwards, the Blanco River, and the Trinity aquifer all contribute to springflows upon with the species depend. The EAA report (LBG-Guyton & Associates, 2004) states that artesian/confined Edwards accounts for approximately 50 cfs at San Marcos springs during drought periods. If species are dependant on flows greater than this amount, local sources contributing to springflow should be included in the critical period plan.

Development of a Critical Period Management Regimen:

- Before considering alterations to the current critical period management plan, the Science Subcommittee should consider whether or not the current plan is adequate and clearly describe why or why not. One major shortfall in the current policies is they apply disproportionately to different users of the aquifer. SAWS suggests that adjustments should only be recommended if they are to focus on the disproportionate standards applied to various regional water users, who should all contribute to the conservation and recovery of the endangered species.

- Municipal and Industrial permit holders bear the full brunt of early drought cutbacks while controlling less than half of the permitted water uses. Pumping cutbacks on municipal and industrial permit-holders alone will not accomplish springflow protection and do not represent a balanced solution to the regional water challenge.

- In light of the limitations of the tools we have available, a monitoring plan implementing defined elements in an adaptive management framework would be the most prudent approach when considering withdrawal levels. Drought cutback regimes should also be consistently applied and monitored for a minimum of a decade. This would allow for the gathering of data concerning species and ecosystem responses and region-wide water user behavior through various weather patterns. If a robust refugium program is implemented, risks during the adaptive management implementation could be mitigated.

- Recent decisions by the Edwards Aquifer Authority indicate common ground between the EAA Board and SAWS regarding an understanding of the effects of pumping near the springs. Additional or special management considerations for areas near the springs have already been implicitly acknowledged (LBG-Guyton & Associates, 2008). This substantiates our repeated observations that areas east of the Cibolo Creek and down-gradient of Comal Springs deserve special management considerations, especially as the Expert Science Subcommittee develops management recommendations regarding critical period cutbacks.

- EAA provided an extensive report describing how regional flows are important below 100 cfs at San Marcos Springs (Johnson and Schindel, 2008). SAWS believes that flow level is actually below 50 cfs based on work by the USGS (Lindgren etal., 2004 pg. 40 - citing Puente (1976)), Edwards Aquifer Authority (LBG-Guyton & Associates, 2004 pg B-45), and observations from the drought of record, when San Marcos Springs declined to 46 cfs. We urge the Subcommittee to consider in their deliberations special management considerations for Edwards aquifer water use near the springs and that local pumping and locally-sourced springflow be managed before declining to these regional flows.

- The data resource challenges facing the Science Subcommittee in particular, and the EARIP stakeholders more broadly, are significant. Acknowledgement of the limitations of the tools used in developing recommendations, and of the information needed to further refine those recommendations, will assist the EARIP as it develops an Adaptive Management plan.

Thank you for soliciting stakeholder input and for providing your expertise in the formulation of recommendations to assist the EARIP Steering Committee. We hope these comments will contribute to your work.

Sincerely,

Calvin Finch

Calvin Finch
San Antonio Water System

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Linam, G.W., K.B. Mayes, and K.S. Saunders, 1993. *Habitat utilization and population size estimate of fountain darters,* Etheostoma fonticola, *in the Comal River, Texas.* Texas Journal of Science 45(4):341-348.

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Votteler, T.H., 2008. *Presentation of analysis of J-17 predicting springflow* based on work in "*Water from a stone: The limits of the sustainable development of the Texas Edwards Aquifer*" (January 1, 2000).

Appendix F. Requests for Edwards Aquifer model runs

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Run Request 1

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Run 001: Baseline (current permitted amount+exempt, current distribution of pumping, current critical period management)

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<660	I	20
<200	<80	<650	II	30
<150	N/A	<640	III	35
<100	N/A	<630	IV	40

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
-	I	0
<850	II	**5**
<845	III	20
<842	IV	35

Run 002: No pumpage.

Run 003: 100,000 acre-feet per year of pumpage (+exempt, current distribution, no critical period management)

Run 004: 200,000 acre-feet per year of pumpage (+exempt, current distribution, no critical period management)

Run 005: 300,000 acre-feet per year of pumpage (+exempt, current distribution, no critical period management)

Run 006: 400,000 acre-feet per year of pumpage (+exempt, current distribution, no critical period management)

Run 007: 500,000 acre-feet per year of pumpage (+exempt, current distribution, no critical period management)

Run 008: 572,000 acre-feet per year of pumpage (+exempt, current distribution, no critical period management)

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Run Request 2

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The next two runs relate to using the Senate Bill 3 critical period management scheme with a pumping ceiling based on what would have been pumped in 2008 (a dry year) with no critical period reductions. Actual pumping in 2008 is estimated at 430,000 acre-feet. Pumping in 2008 with no critical period reductions would probably have been 437,000 acre-feet. Run 009 ends with pumping at a rate of 320,000 acre-feet per year in Stage IV, while Run 010 ends with pumping at a rate of 340,000 acre-feet per year in Stage IV. Changes from Senate Bill 3 are indicated in bolded red text.

Stage	**SB 3**	**Run 009**	**Run 010**
-	**(AFY)**	**(AFY)**	**(AFY)**
0	572,000	437,000	437,000
I	486,000	401,000	391,000
II	436,000	378,000	365,000
III	393,000	359,000	343,000
IV	350,000	320,000	340,000

Run 009

Pumping is capped at a rate of 437,000 acre-feet per year with reductions in pumping that end with a rate of 320,000 acre-feet per year.

San Antonio Pool

Comal	**San Marcos**	**J-17**	**Stage**	**Reduction**
(cfs)	**(cfs)**	**(feet)**	**-**	**(%)**
<225	<96	<660	I	**14**
<200	<80	<650	II	**21**
<150	N/A	<640	III	**24**
<100	N/A	<630	IV	**28**

Uvalde Pool

J-27	**Stage**	**Reduction**
(feet)	**-**	**(%)**
-	I	0
<850	II	**3**
<845	III	**14**
<842	IV	**24**

Run 010

Pumping is capped at a rate of 437,000 acre-feet per year with reductions in pumping that end with a rate of 340,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	San Marcos (cfs)	J-17 (feet)	Stage -	Reduction (%)
<225	<96	<660	I	**11**
<200	<80	<650	II	**17**
<150	N/A	<640	III	**20**
<100	N/A	<630	IV	**23**

Uvalde Pool

J-27 (feet)	Stage -	Reduction (%)
-	I	0
<850	II	**3**
<845	III	**11**
<842	IV	**20**

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The next three runs relate to adjustments to the current critical period management scheme. The trigger levels will remain the same in these runs, but the percent reductions are adjusted. Changes from Senate Bill 3 are indicated in bolded red text. The purpose of these runs is to understand what reductions may be required to maintain springflow.

Stage -	Run 011 (AFY)	Run 012 (AFY)	Run 013 (AFY)
0	572,000	572,000	572,000
I	486,000	486,000	486,000
II	436,000	436,000	436,000
III	350,000	350,000	350,000
IV	286,000	229,000	172,000

Run 011

Pumping is capped at a rate of 572,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<660	I	20
<200	<80	<650	II	30
<150	N/A	<640	III	**40**
<100	N/A	<630	IV	**50**

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
-	I	0
<850	II	5
<845	III	**35**
<842	IV	**50**

Run 012

Pumping is capped at a rate of 572,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<660	I	20
<200	<80	<650	II	30
<150	N/A	<640	III	**40**
<100	N/A	<630	IV	**60**

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
-	I	0
<850	II	5
<845	III	**35**
<842	IV	**60**

Run 013

Pumping is capped at a rate of 572,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<660	I	20
<200	<80	<650	II	30
<150	N/A	<640	III	**40**
<100	N/A	<630	IV	**70**

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
-	I	0
<850	II	5
<845	III	**35**
<842	IV	**70**

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Run Request 3

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The following two runs are "fill-in" runs similar to the constant pumping runs 002 through 008.

Run 014: 250,000 acre-feet per year of pumpage (+exempt, current distribution, no critical period management)

Run 015: 350,000 acre-feet per year of pumpage (+exempt, current distribution, no critical period management)

It is our understanding that the model runs start with a steady-state initial condition with pumping at about 170,000 acre-feet per year. The following two runs are intended to assess the sensitivity of model results (specifically Run 001) to this "lead in" pumping.

Run 016: Run 001 but with pumping for the steady-state initial condition set at 0.

Run 017: Run 001 but with pumping for the steady-state initial condition set at twice whatever the initial condition pumping is.

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Run Request 4

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The following three runs are a variation of runs 11, 12, and 13 but with permitted pumping not allowed to be greater than a rate of 437,000 acre-feet per year. Changes from Senate Bill 3 are indicated in bolded red text.

Stage -	**Run 018 (AFY)**	**Run 019 (AFY)**	**Run 020 (AFY)**
0	437,000	437,000	437,000
I	437,000	437,000	437,000
II	437,000	437,000	437,000
III	350,000	350,000	350,000
IV	284,000	227,000	175,000

Run 018

Permitted pumping is not allowed to be greater than a rate of 437,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<660	I	**0**
<200	<80	<650	II	**0**
<150	N/A	<640	III	**20**
<100	N/A	<630	IV	**35**

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
-	I	0
<850	II	**0**
<845	III	**20**
<842	IV	**35**

Run 019

Permitted pumping is not allowed to be greater than a rate of 437,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	San Marcos (cfs)	J-17 (feet)	Stage -	Reduction (%)
<225	<96	<660	I	**0**
<200	<80	<650	II	**0**
<150	N/A	<640	III	**20**
<100	N/A	<630	IV	**48**

Uvalde Pool

J-27 (feet)	Stage -	Reduction (%)
-	I	**0**
<850	II	**0**
<845	III	**20**
<842	IV	**48**

Run 020

Permitted pumping is not allowed to be greater than a rate of 437,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	San Marcos (cfs)	J-17 (feet)	Stage -	Reduction (%)
<225	<96	<660	I	**0**
<200	<80	<650	II	**0**
<150	N/A	<640	III	**20**
<100	N/A	<630	IV	**60**

Uvalde Pool

J-27 (feet)	Stage -	Reduction (%)
-	I	**0**
<850	II	**0**
<845	III	**20**
<842	IV	**60**

==

Run Request 5

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Run 021

The purpose of this run is to test the sensitivity of the aquifer to adjustments in the water-level triggers. This is Run 013 but with the J-17 and J-27 triggers raised by five feet.

		San Antonio Pool		
Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<**665**	I	20
<200	<80	<**655**	II	30
<150	N/A	<**645**	III	**40**
<100	N/A	<**635**	IV	**70**

	Uvalde Pool	
J-27 (feet)	**Stage -**	**Reduction (%)**
-	I	0
<**855**	II	5
<**850**	III	**35**
<**847**	IV	**70**

Run 022

The purpose of this run is to test the sensitivity of the aquifer to adjustments in the trigger for Comal Springs. This is Run 013 but with the Comal Springs triggers raised by 15 cubic feet per second.

		San Antonio Pool		
Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<**240**	<96	<660	I	20
<**215**	<80	<650	II	30
<**165**	N/A	<640	III	**40**
<**115**	N/A	<630	IV	**70**

	Uvalde Pool	
J-27 (feet)	**Stage -**	**Reduction (%)**
-	I	0
<850	II	5
<845	III	**35**
<842	IV	**70**

Run 023

The purpose of this run is to test the sensitivity of the aquifer to adjustments in the triggers for the Uvalde Pool. The adjustments to the Uvalde Pool triggers were based on an analysis of how often the San Antonio Pool was in stage I, II, III, and IV for Run 013. We then chose J-27 triggers, again based on Run 013, to achieve similar frequency for the Uvalde Pool.

	J-17 trigger (feet)	**%**	**J-27 "new" (feet)**	**J-27 "SB3" (feet)**
Stage I	660	74.4	870	N/A
Stage II	650	46.0	853.5	850
Stage III	640	18.1	839.4	845
Stage IV	630	0.5	807.6	842

Therefore, this run is Run 013 but with adjustments to the J-27 triggers.

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<660	I	20
<200	<80	<650	II	30
<150	N/A	<640	III	**40**
<100	N/A	<630	IV	**70**

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
<**870**	I	0
<**854**	II	5
<**839**	III	**35**
<**808**	IV	**70**

Run 024

The purpose of this run is to test the sensitivity of the aquifer to adjustments to reductions in the first two stages. This is Run 013 with adjustments to stages I and II.

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<660	I	**25**
<200	<80	<650	II	**35**
<150	N/A	<640	III	**40**
<100	N/A	<630	IV	**70**

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
-	I	0
<850	II	5
<845	III	**35**
<842	IV	**70**

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Run Request 6

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Run 025 (Withdrawn)

The purpose of this run is to test the sensitivity of the aquifer to adjustments in the water-level triggers and reductions in the Uvalde Pool. The San Antonio Pool triggers and reductions are the same as for Run 013.

Pumping is capped at a rate of 572,000 acre-feet per year.

San Antonio Pool				
Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<660	I	20
<200	<80	<650	II	30
<150	N/A	<640	III	**40**
<100	N/A	<630	IV	**70**

Uvalde Pool		
J-27 (feet)	**Stage -**	**Reduction (%)**
< **865**	I	**10**
<**860**	II	**20**
<**855**	III	**35**
<**852**	IV	**70**

Run 026 (Withdrawn)

The purpose of this run is to test the sensitivity of the aquifer to increased reductions at early stages and less reduction at Stage IV for the San Antonio Pool. This is Run 013 with adjustments to reductions for the San Antonio Pool.

Pumping is capped at a rate of 572,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	San Marcos (cfs)	J-17 (feet)	Stage -	Reduction (%)
<225	<96	<660	I	**30**
<200	<80	<650	II	**35**
<150	N/A	<640	III	**45**
<100	N/A	<630	IV	**60**

Uvalde Pool

J-27 (feet)	Stage -	Reduction (%)
-	I	0
<850	II	5
<845	III	**35**
<842	IV	**70**

Run 027 (Withdrawn)

The purpose of this run is to test the sensitivity of the aquifer to increased triggers and increased reductions at early stages and less reduction at Stage IV for the San Antonio Pool. This is Run 013 with adjustments to reductions for the San Antonio Pool.

Pumping is capped at a rate of 572,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	San Marcos (cfs)	J-17 (feet)	Stage -	Reduction (%)
<225	<96	<**665**	I	**30**
<200	<80	<**655**	II	**35**
<150	N/A	<**645**	III	**45**
<100	N/A	<**635**	IV	**60**

Uvalde Pool

J-27 (feet)	Stage -	Reduction (%)
-	I	0
<850	II	5
<845	III	**35**
<842	IV	**70**

Run 028

The purpose of this run is to test the sensitivity of the aquifer to combining increased triggers and increased reductions at early stages for the San Antonio Pool with increases in the water-level triggers and reductions in the Uvalde Pool. This is Run 025 for J-27 and Run 027 for J-17.

Pumping is capped at a rate of 572,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	San Marcos (cfs)	J-17 (feet)	Stage -	Reduction (%)
<225	<96	<**665**	I	**30**
<200	<80	<**655**	II	**35**
<150	N/A	<**645**	III	**45**
<100	N/A	<**635**	IV	**60**

Uvalde Pool

J-27 (feet)	Stage -	Reduction (%)
< **865**	I	**10**
<**860**	II	**20**
<**855**	III	**35**
<**852**	IV	**70**

Run 029

The purpose of this run is to test the sensitivity of the aquifer to increased triggers and reductions for both the San Antonio Pool and the Uvalde Pool.

Pumping is capped at a rate of 572,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	San Marcos (cfs)	J-17 (feet)	Stage -	Reduction (%)
<225	<96	<**665**	I	**20**
<200	<80	<**655**	II	**30**
<150	N/A	<**645**	III	**40**
<100	N/A	<**635**	IV	**70**

Uvalde Pool

J-27 (feet)	Stage -	Reduction (%)
< **865**	I	**20**
<**860**	II	**30**
<**855**	III	**40**
<**852**	IV	**70**

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Run Request 7

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Run 030

This run is the same as Run 029 except with 90 percent reductions at Stage IV.

Pumping is capped at a rate of 572,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<**665**	I	**20**
<200	<80	<**655**	II	**30**
<150	N/A	<**645**	III	**40**
<100	N/A	<**635**	IV	**90**

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
< **865**	I	**20**
<**860**	II	**30**
<**855**	III	**40**
<**852**	IV	**90**

Run 031

This run is the same as Run 030 except with all pumping eliminated in Comal and Hays counties at all stages to test the model's sensitivity to pumping in those counties. Pumping is capped at a rate of 572,000 acre-feet per year (minus Comal and Hays pumping).

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<**665**	I	**20**
<200	<80	<**655**	II	**30**
<150	N/A	<**645**	III	**40**
<100	N/A	<**635**	IV	**90**

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
< **865**	I	**20**
<**860**	II	**30**
<**855**	III	**40**
<**852**	IV	**90**

Run 032

The purpose of this run is to determine, through trial and error, the maximum amount of annual permitted pumping that will allow the following criteria to be met:

Comal Springs minimum 1-month discharge = 30 cubic feet per second
Comal Springs minimum 6-month average discharge = 75 cubic feet per second
Comal Springs long-term average discharge = 225 cubic feet per second

San Marcos Springs minimum 1-month discharge = 65 cubic feet per second
San Marcos Springs minimum 6-month average discharge = 80 cubic feet per second
San Marcos Springs long-term average discharge = 140 cubic feet per second

The run should not include any critical period management, just fixed annual pumping.

Run 033

The purpose of this run is to combine runs 028 (for J-17) and 029 (for J-27) with increased reductions at Stage IV.

Pumping is capped at a rate of 572,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	San Marcos (cfs)	J-17 (feet)	Stage -	Reduction (%)
<225	<96	<**665**	I	**30**
<200	<80	<**655**	II	**35**
<150	N/A	<**645**	III	**45**
<100	N/A	<**635**	IV	**80**

Uvalde Pool

J-27 (feet)	Stage -	Reduction (%)
< **865**	I	**20**
<**860**	II	**30**
<**855**	III	**40**
<**852**	IV	**80**

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Run Request 8

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Run 034

The purpose of this run is to (a) find a critical period management scenario that meets the springflow requirements and (b) use that critical period management scenario with pumping "capped" at 437,000 acre-feet per year (to reflect the maximum pumping experienced in recent history).

For part (a):

Pumping is capped at a rate of 572,000 acre-feet per year.

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<**665**	I	**30**
<200	<80	<**655**	II	**35**
<150	N/A	<**645**	III	**45**
<100	N/A	<**635**	IV	***TBD***

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
< **865**	I	**30**
<**860**	II	**35**
<**855**	III	**45**
<**852**	IV	***TBD***

TBD means "to be determined" by the modeler through trial and error such that the minimum 6-month average for San Marcos Springs (80 cubic feet per minute) can be met.

Because we are not convinced that the minimum 6-month average for San Marcos Springs can be met with this run, please first run Stage IV with a 100 percent reduction. If the minimum 6-month average for San Marcos Springs is not met with this reduction (in other words, the minimum 6-month average is less than 80 cubic feet per second), then please contact the expert science subcommittee as soon as possible and await further instructions.

If the minimum 6-month average for San Marcos is greater than the springflow requirement (in other words, greater than 80 cubic feet per second), then please refine, through trial and error, the minimum percent reduction (rounded to the whole percentage point) required to meet the minimum 6-month average for San Marcos. If, once you have this reduction number, any of the other flow criteria are not met, then please notify the expert science subcommittee and await further instruction. Once completed, please write the report and submit it for review to your management as soon as possible. Once you submit the report to your management, you are ready to immediately work on part (b).

To address part (b), we need to "cap" pumping at 437,000 acre-feet per year and calculate reductions for each stage that is equivalent to the amount of pumping allowed in part (a):

Stage	Part (a) Reduction	Part (a) Pumping	Equivalent Part (b) Reduction
-	(%)	(AFY)	(%)
I	**30**	**400,400**	**8.38**
II	**35**	**371,800**	**14.92**
III	**45**	**314,600**	**28**
IV	***TBD***	***X***	***Y***

where

$$X = 572{,}000\left(\frac{100 - TBD}{100}\right)$$

and

$$Y = 100\left(\frac{437{,}000 - X}{437{,}000}\right)$$

Therefore, the run for part (b) is:

Pumping is capped at a rate of 437,000 acre-feet per year.

San Antonio Pool

Comal	San Marcos	J-17	Stage	Reduction
(cfs)	(cfs)	(feet)	-	(%)
<225	<96	<**665**	I	**8.38**
<200	<80	<**655**	II	**14.92**
<150	N/A	<**645**	III	**28**
<100	N/A	<**635**	IV	***Y***

Uvalde Pool

J-27	Stage	Reduction
(feet)	-	(%)
< **865**	I	**8.38**
<**860**	II	**14.92**
<**855**	III	**28**
<**852**	IV	***Y***

Once completed, please write the report and submit it for review to your management as soon as possible.

Run 035

Removal of Stage IV and adjustments in pumping reductions for stages I, II, and III for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stages I, II, and III (maximum 100 percent reduction in pumping for the San Antonio Pool and maximum 100 percent reduction in pumping for the Uvalde Pool).

Run 036

Removal of stages III and IV and adjustments in pumping reductions for stages I and II for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for stages I and II (maximum 100 percent reduction in pumping for the San Antonio Pool and maximum 100 percent reduction in pumping for the Uvalde Pool).

Run 037

Removal of stages II, III, and IV and adjustments in pumping reductions for Stage I for the San Antonio and Uvalde pools and adjustments in J-17 and J-27 triggers for Stage I (maximum 100 percent reduction in pumping for the San Antonio Pool and maximum 100 percent reduction in pumping for the Uvalde Pool).

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Run Request 9

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Run 035

The purpose of this run is to identify the pumping reduction required to meet a minimum average 6-month springflow requirement for San Marcos Springs of 75 cubic feet per second.

Pumping is capped at a rate of 572,000 acre-feet per year. There is only one stage:

San Antonio Pool

Comal (cfs)	**San Marcos (cfs)**	**J-17 (feet)**	**Stage -**	**Reduction (%)**
<225	<96	<**665**	I	**X**

Uvalde Pool

J-27 (feet)	**Stage -**	**Reduction (%)**
< **865**	I	**X**

where **X** is the pumping reduction required to meet a minimum average six-month springflow requirement for San Marcos Springs of 75 cubic feet per second. Based on previous runs, we believe **X** is in the vicinity of 86 percent.

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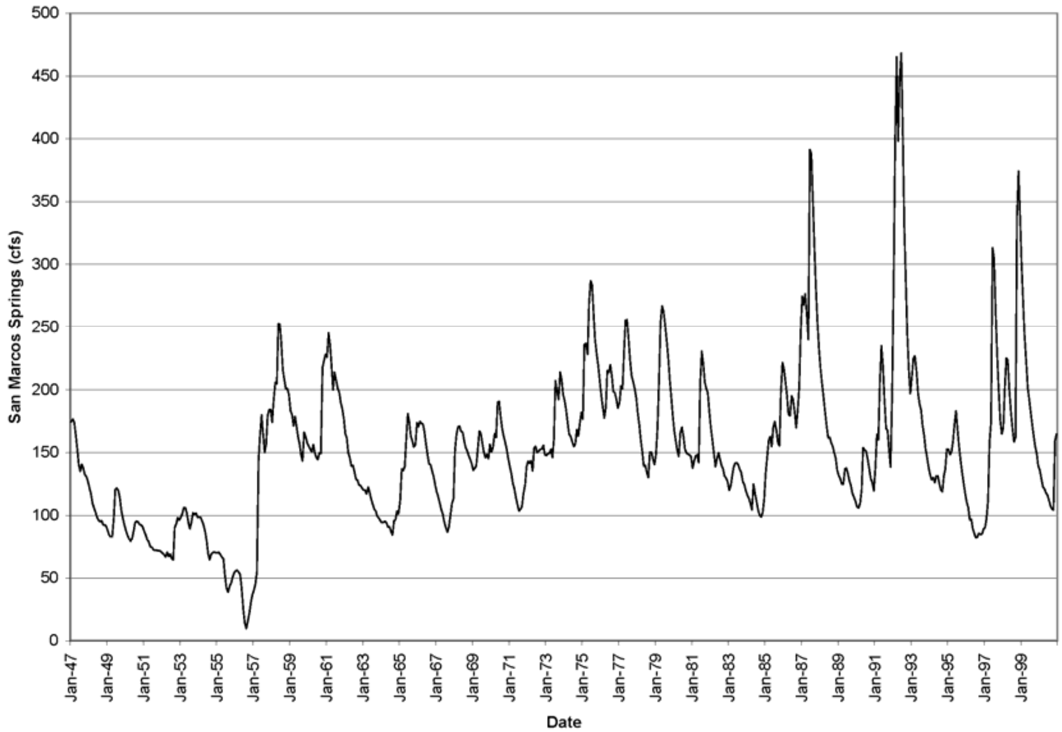
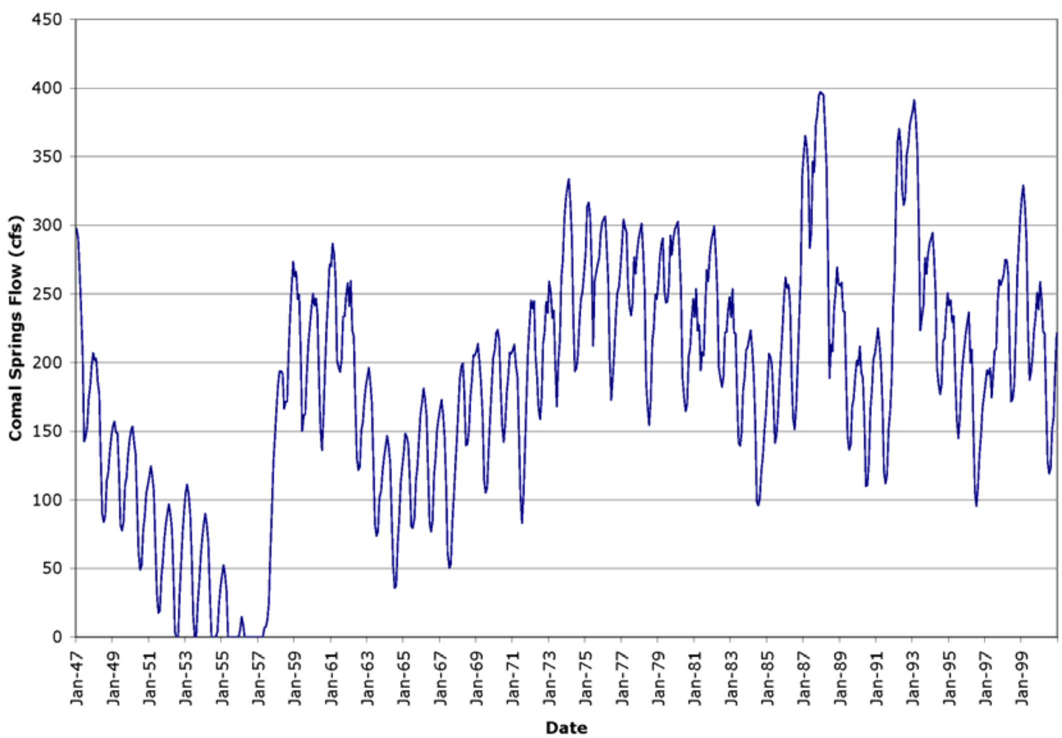
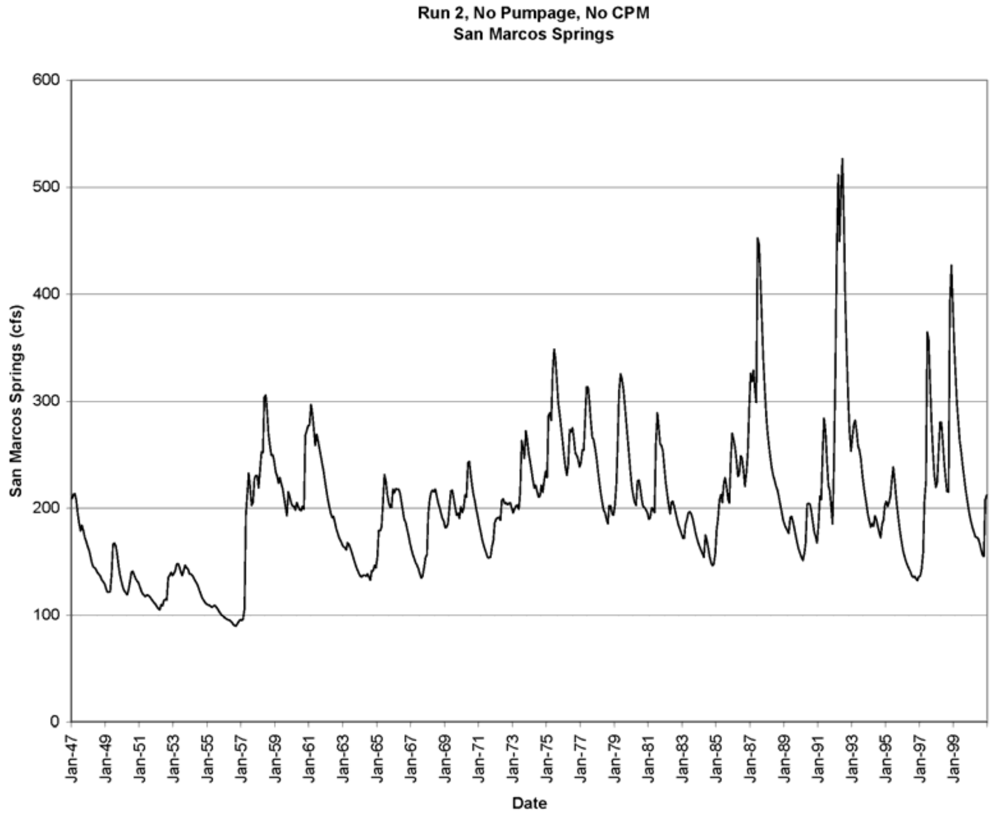
Appendix G. Plots of springflows from the Edwards Aquifer model runs

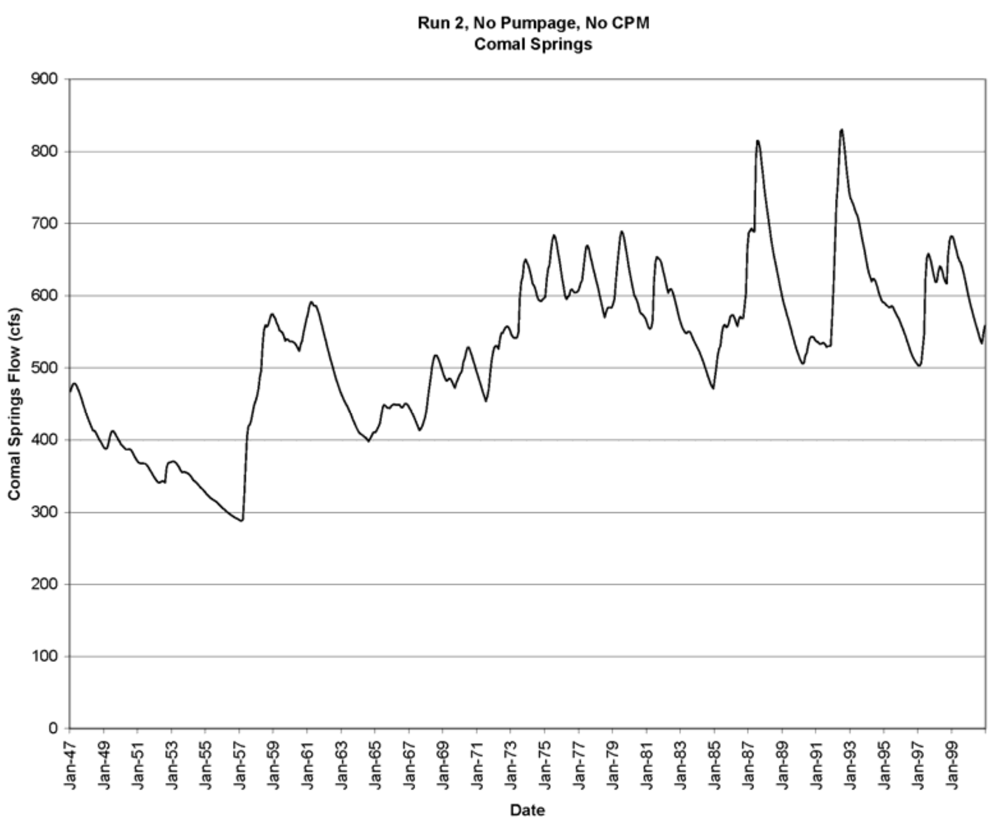
Run 1, SB 3 Criteria
San Marcos Springs



Run 1, SB 3 Criteria
Comal Springs




Run 2, No Pumpage, No CPM
San Marcos Springs
San Marcos Springs (cfs)
600
500
400
300
200
100
0
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99
Date


Run 2, No Pumpage, No CPM
Comal Springs
Comal Springs Flow (cfs)
900
800
700
600
500
400
300
200
100
0
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
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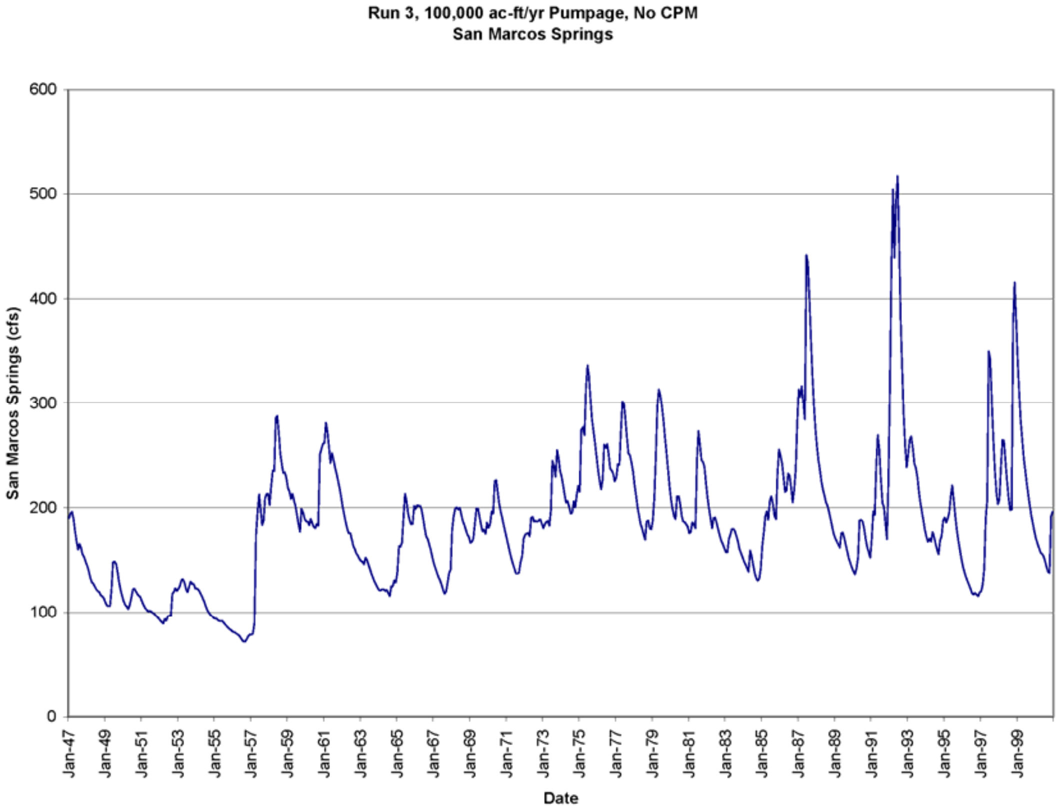
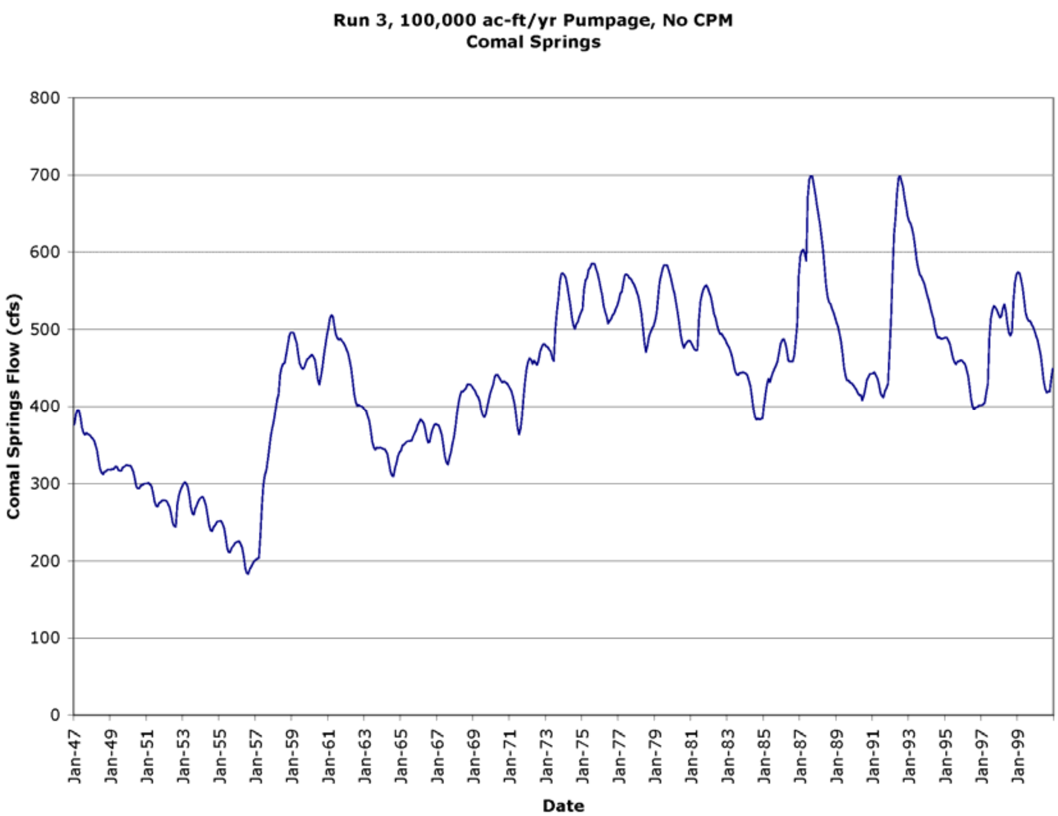
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99
Date


Run 3, 100,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs
San Marcos Springs (cfs)
600
500
400
300
200
100
0
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99
Date


Run 3, 100,000 ac-ft/yr Pumpage, No CPM
Comal Springs
Comal Springs Flow (cfs)
800
700
600
500
400
300
200
100
0
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
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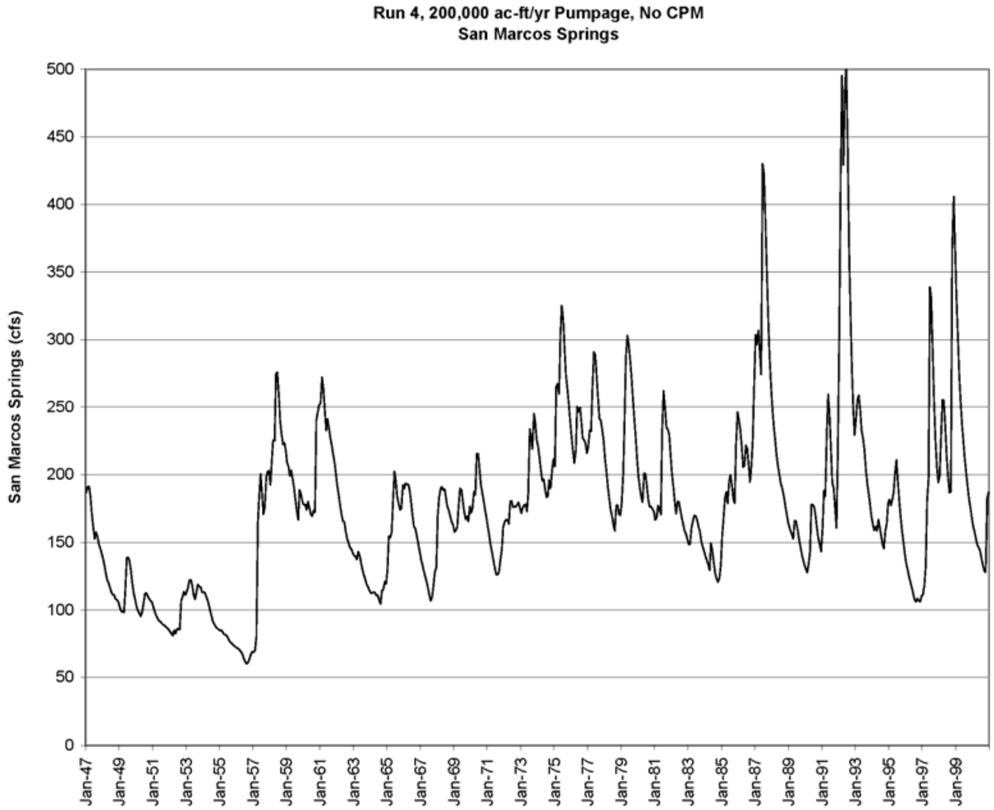
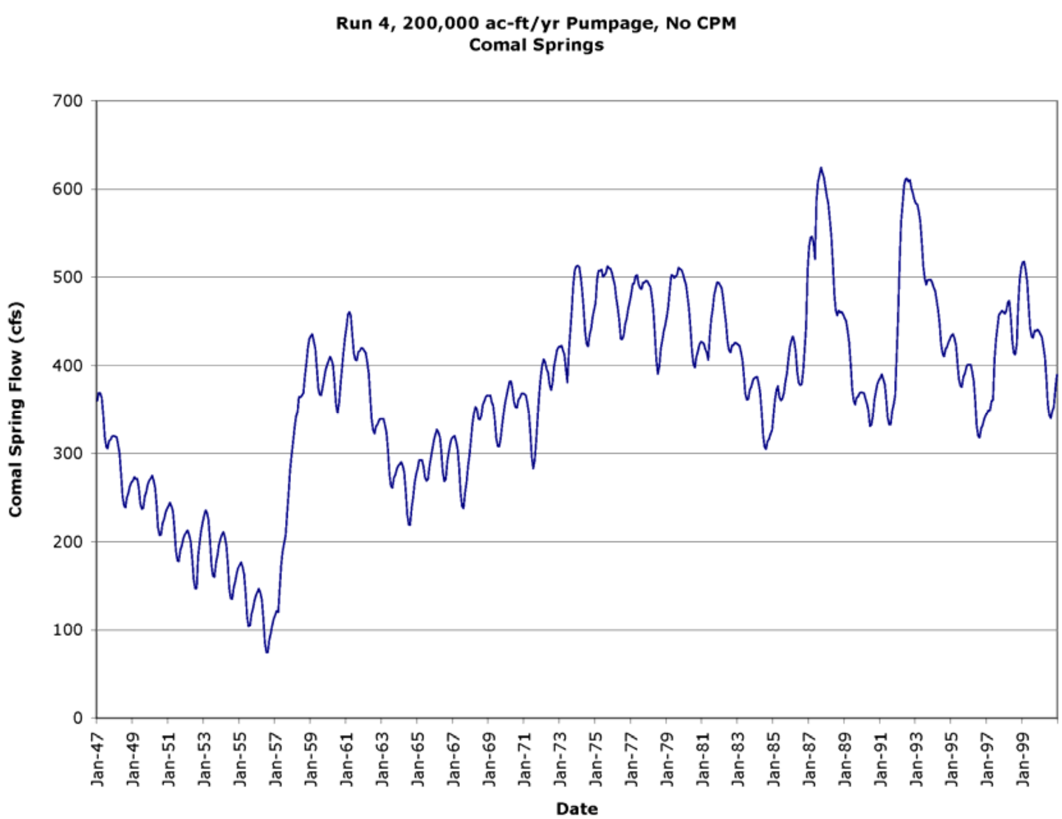
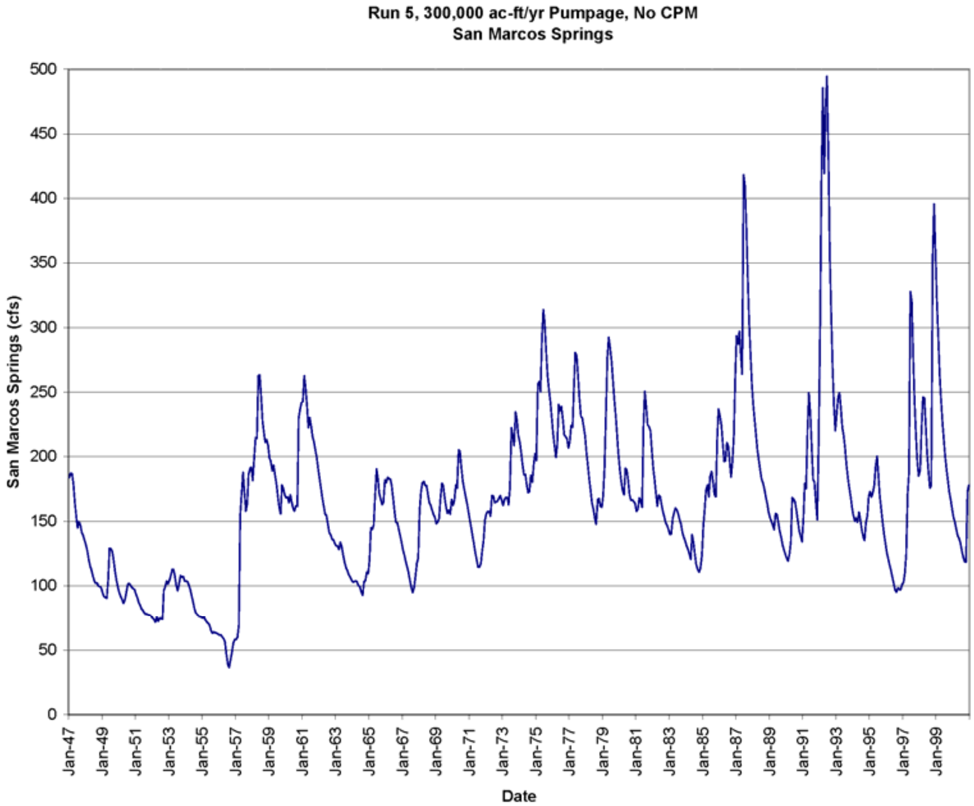
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99
Date


Run 4, 200,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs
San Marcos Springs (cfs)
500
450
400
350
300
250
200
150
100
50
0
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99


Run 4, 200,000 ac-ft/yr Pumpage, No CPM
Comal Springs
Comal Spring Flow (cfs)
700
600
500
400
300
200
100
0
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99
Date


Run 5, 300,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs
San Marcos Springs (cfs)
Date
0
50
100
150
200
250
300
350
400
450
500
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
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Jan-89
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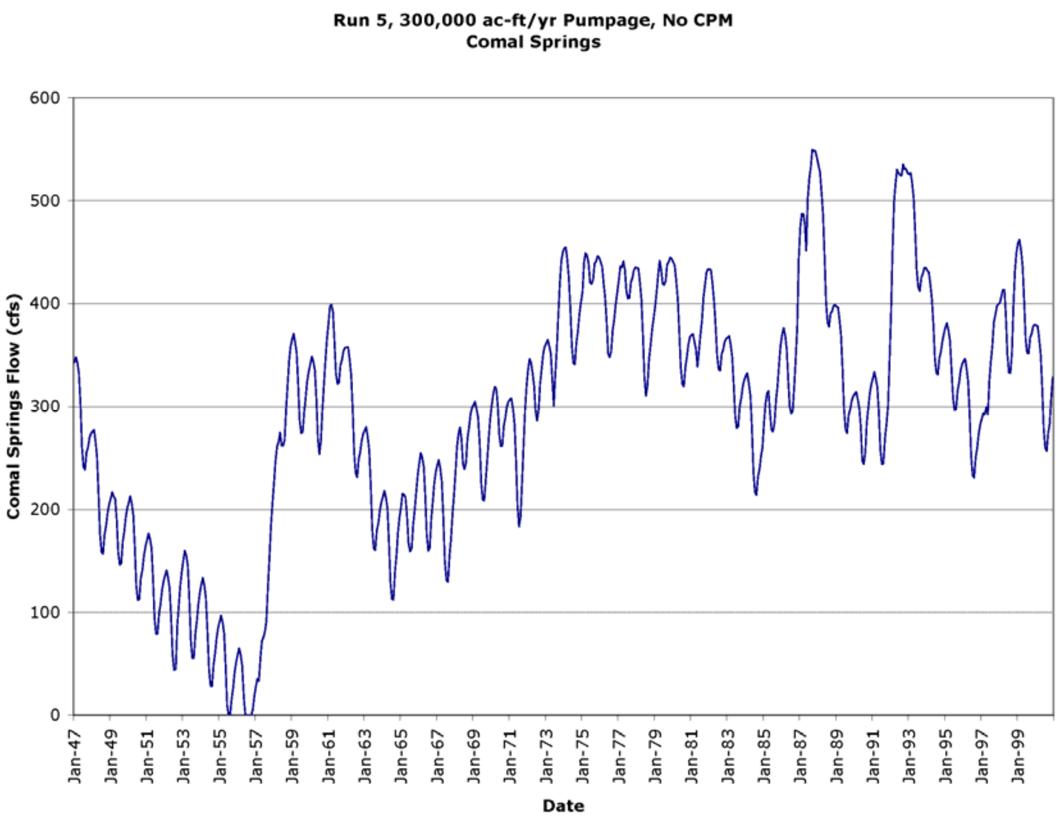
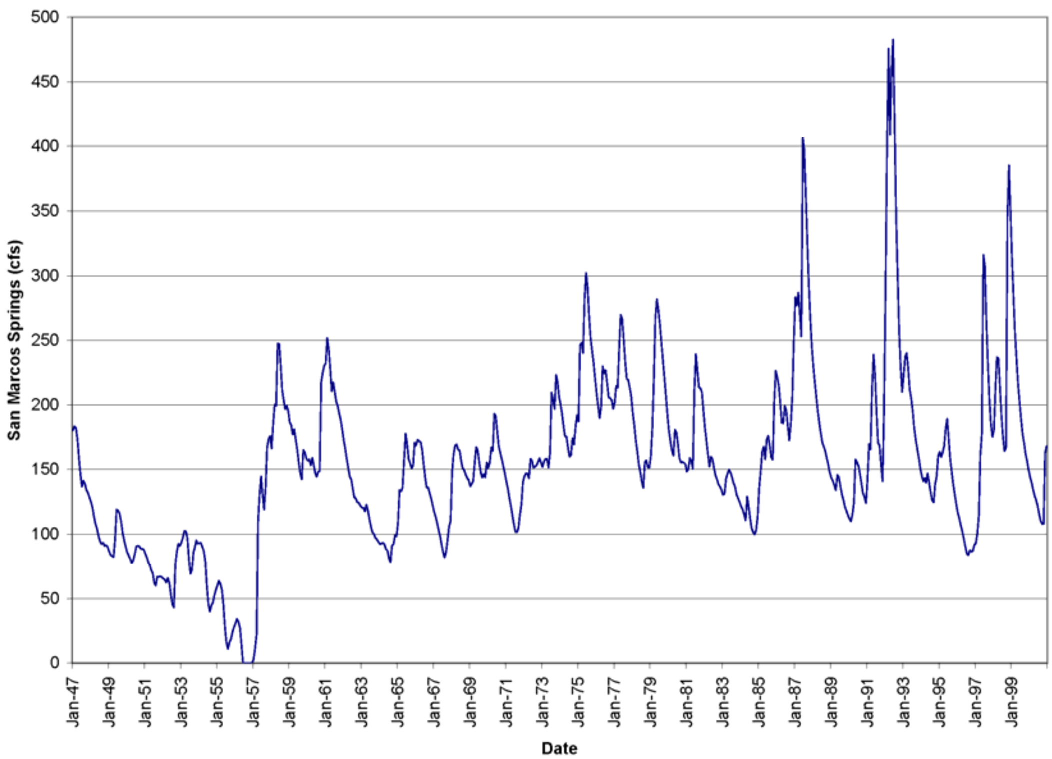
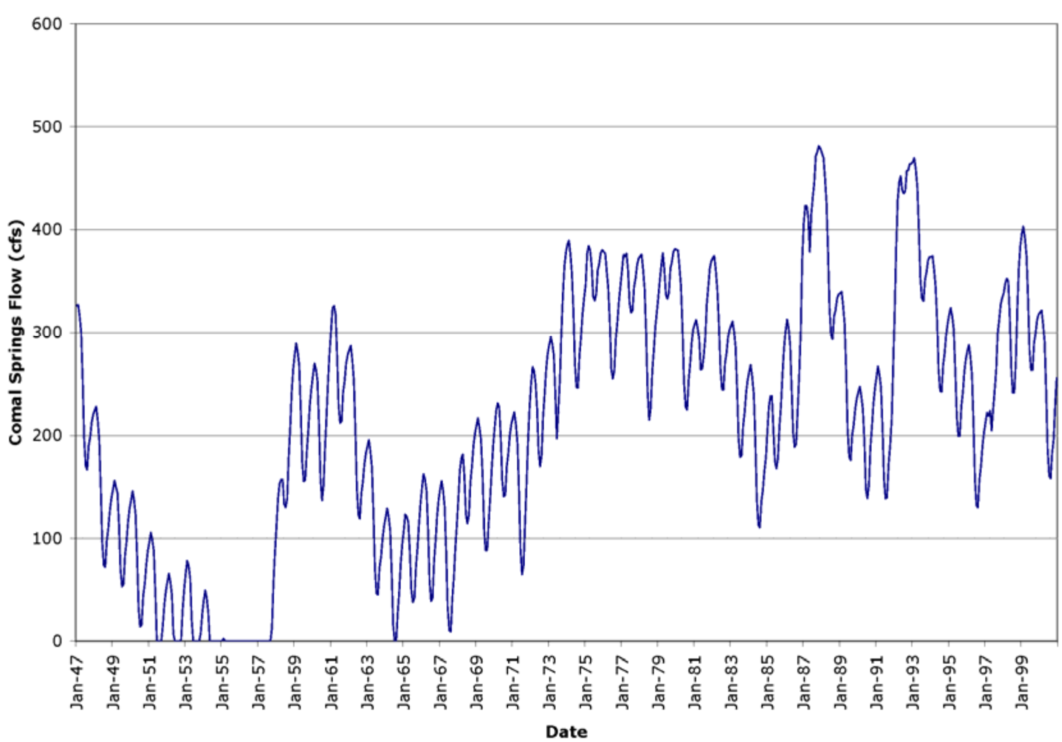
Jan-93
Jan-95
Jan-97
Jan-99


Run 5, 300,000 ac-ft/yr Pumpage, No CPM
Comal Springs
Comal Springs Flow (cfs)
Date
0
100
200
300
400
500
600
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99

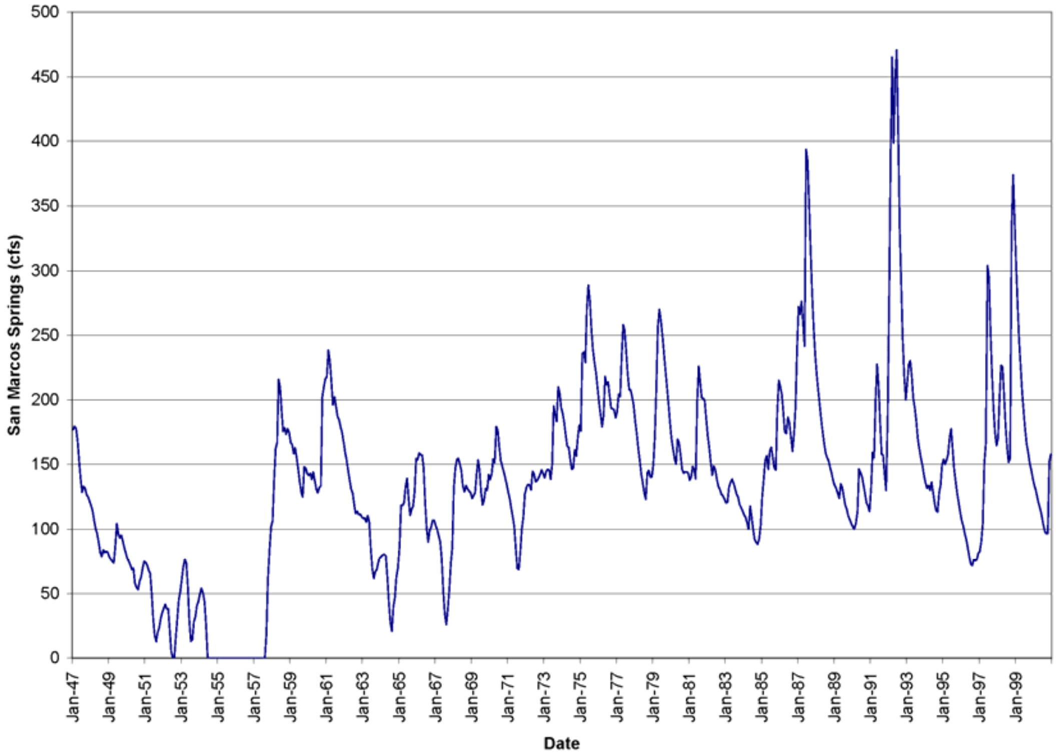
Run 6, 400,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs



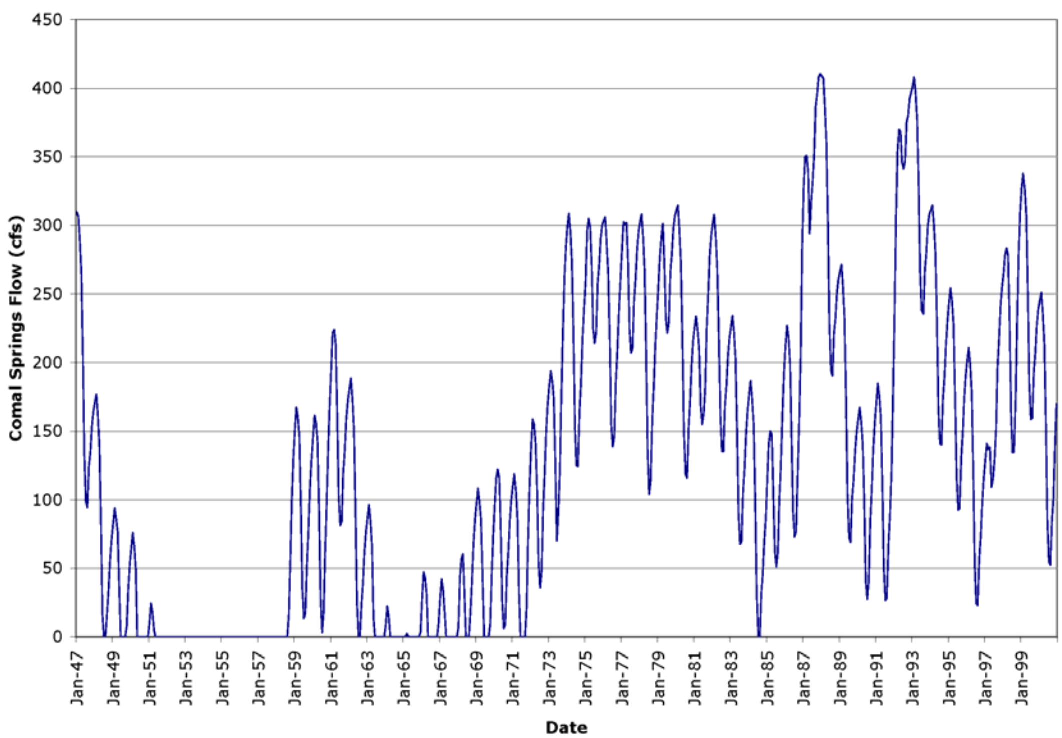
Run 6, 400,000 ac-ft/yr Pumpage, No CPM
Comal Springs

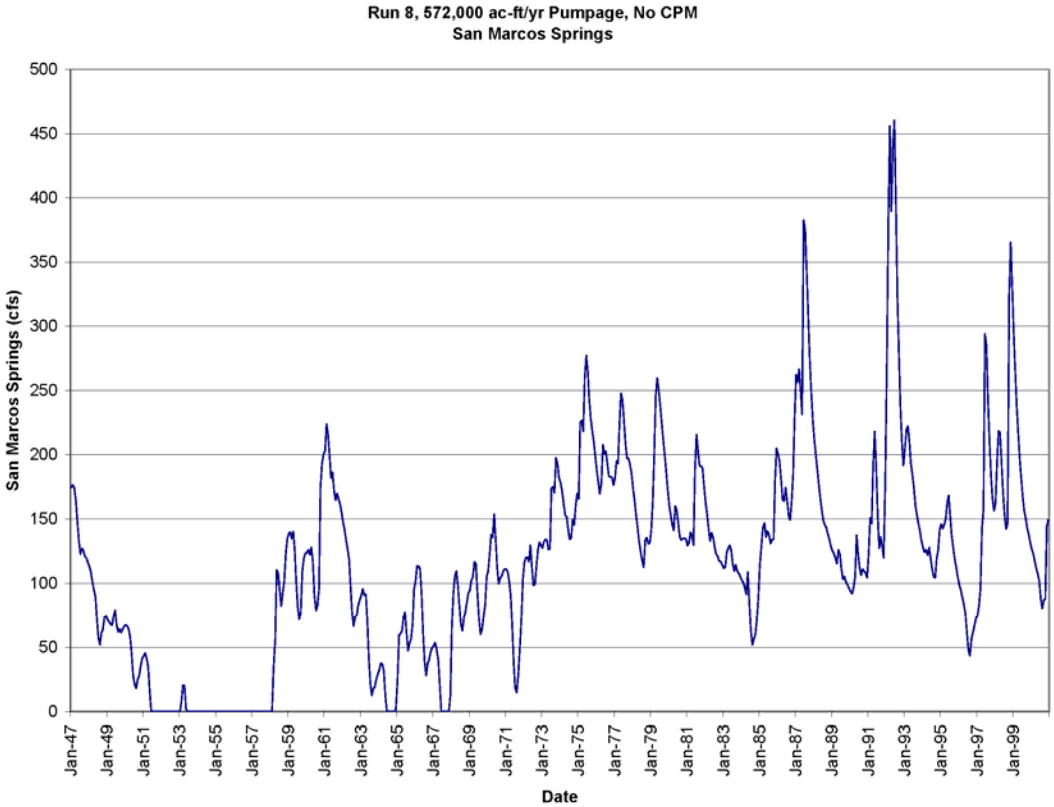


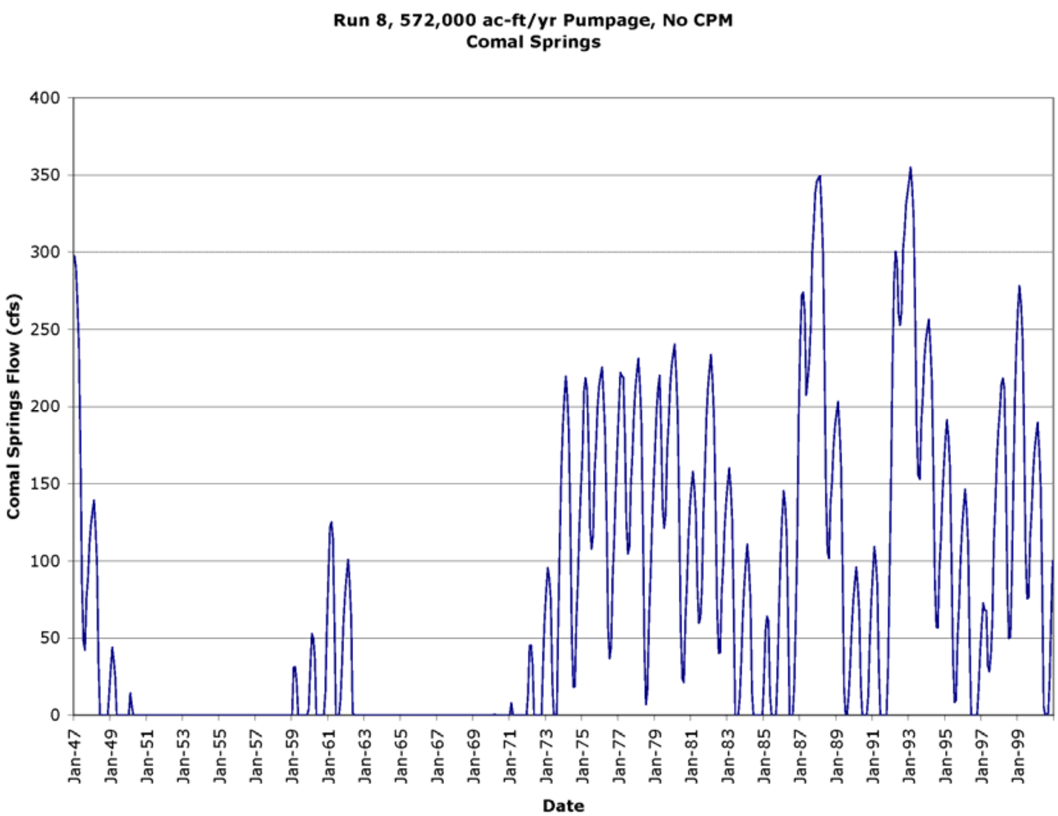
Run 7, 500,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs



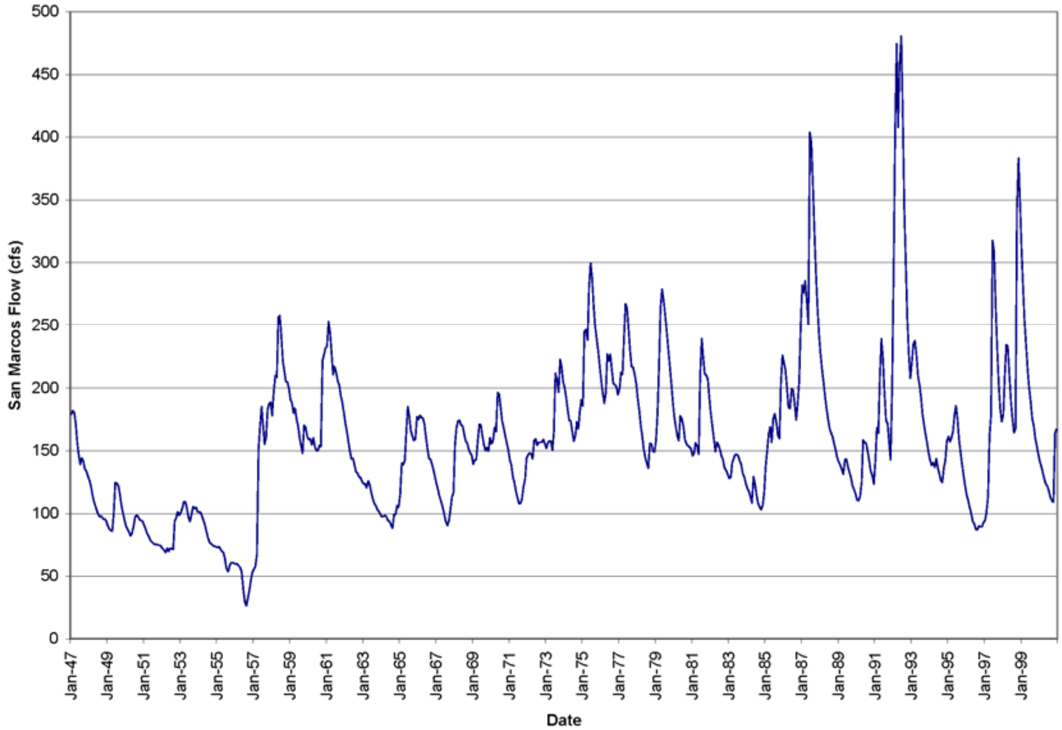
Run 7, 500,000 ac-ft/yr Pumpage, No CPM
Comal Springs



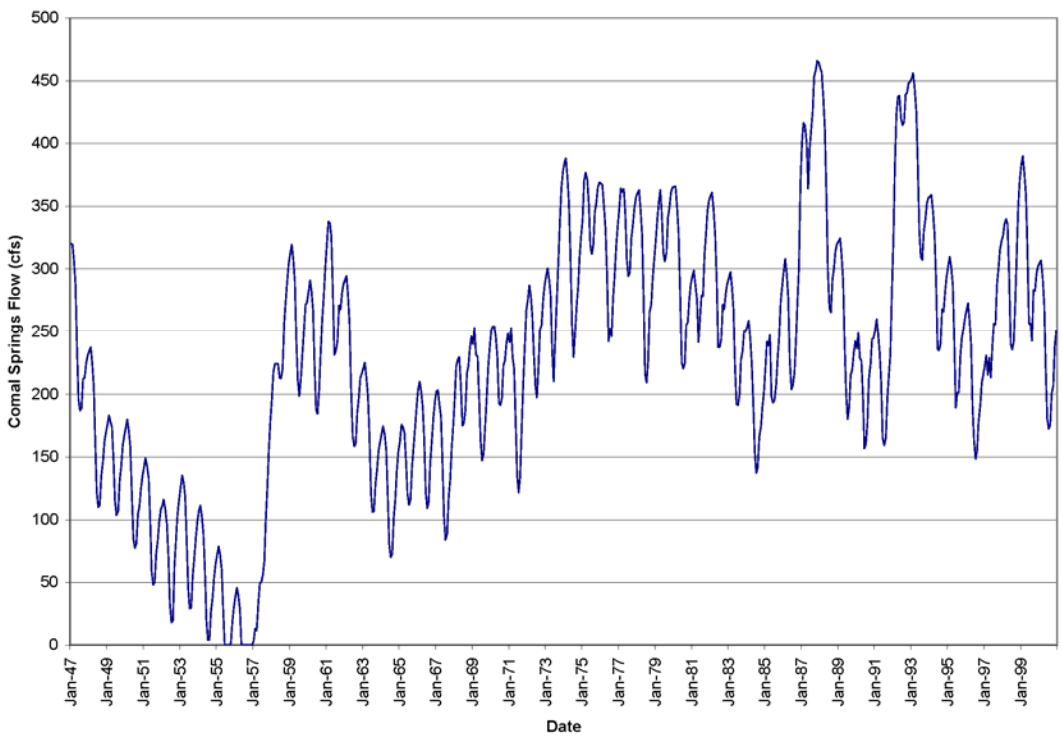

Run 8, 572,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs
San Marcos Springs (cfs)
500
450
400
350
300
250
200
150
100
50
0
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99
Date


Run 8, 572,000 ac-ft/yr Pumpage, No CPM
Comal Springs
Comal Springs Flow (cfs)
400
350
300
250
200
150
100
50
0
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99
Date

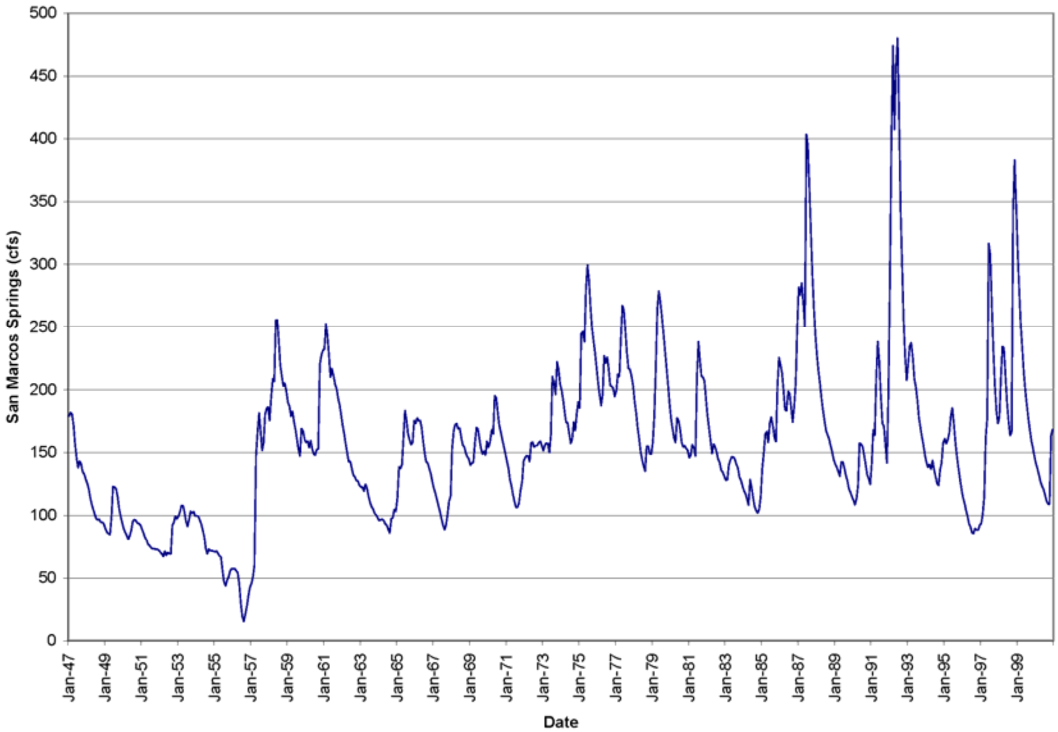
Run 9, 437,000 ac-ft/yr Pumpage, CPM Reductions: 14%, 21%, 24%, 28%
San Marcos Springs



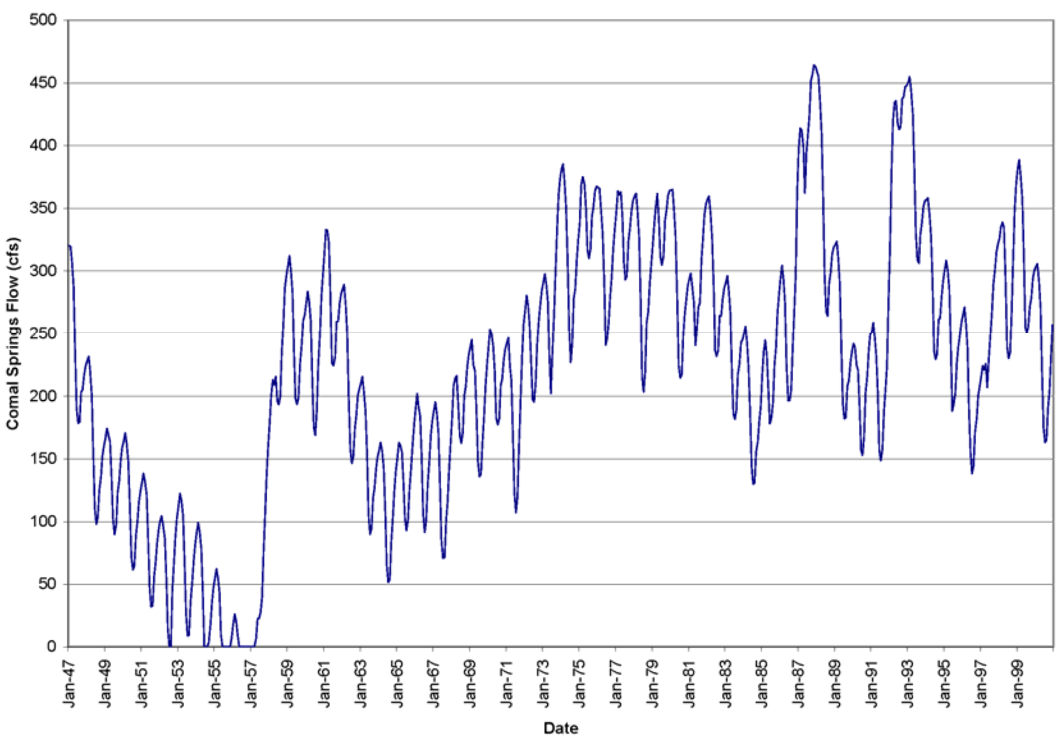
Run 9, 437,000 ac-ft/yr Pumpage, CPM Reductions: 14%, 21%, 24%, 28%
Comal Springs



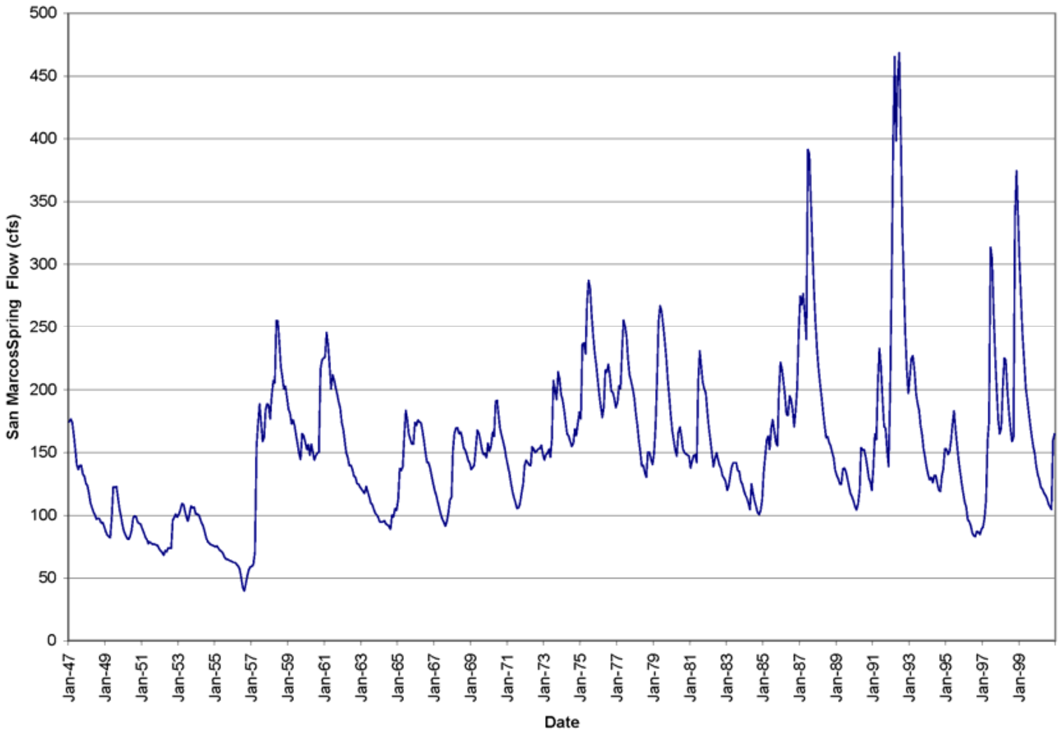
Run 10, 437,000 ac-ft/yr Pumpage, CPM Reductions: 11%, 17%, 20%, 23%
San Marcos Springs



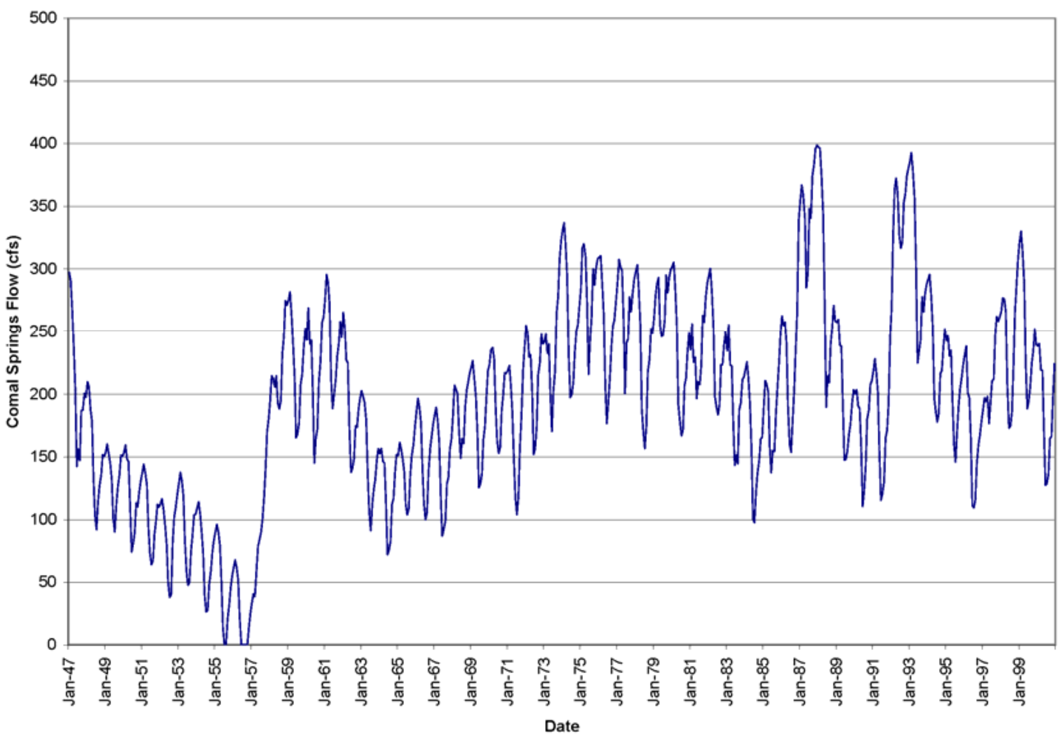
Run 10, 437,000 ac-ft/yr Pumpage, CPM Reductions: 11%, 17%, 20%, 23%
Comal Springs



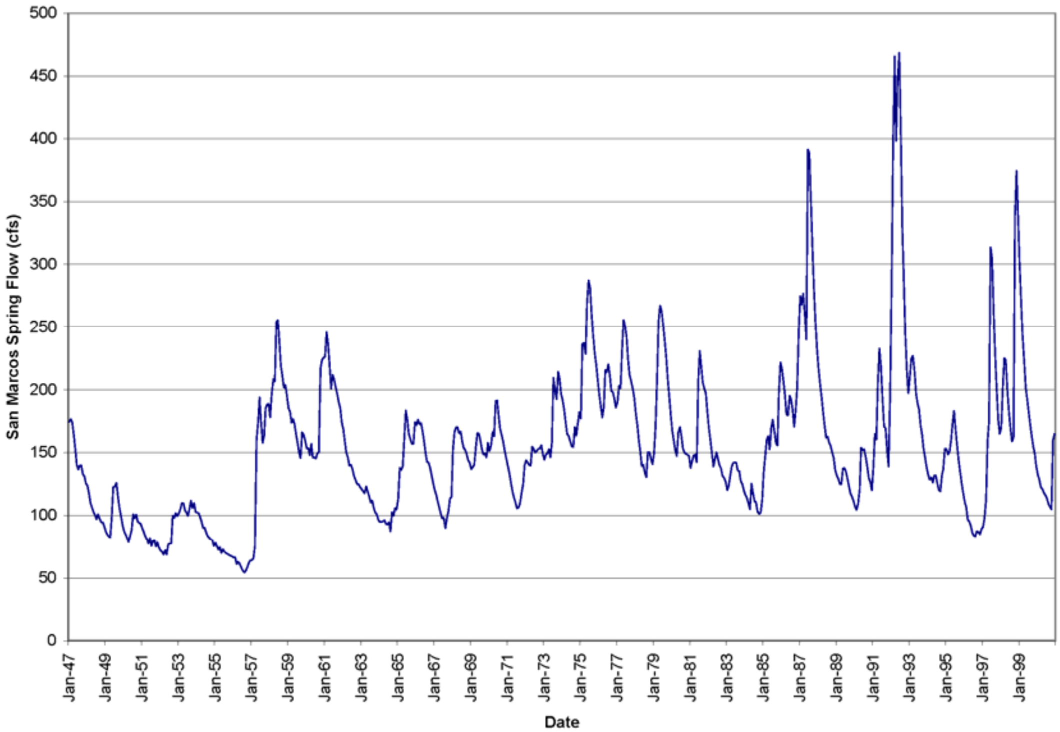
Run 11, 572,000 ac-ft/yr, CPM Reductions: 20%, 30%, 40%, 50%
San Marcos Springs



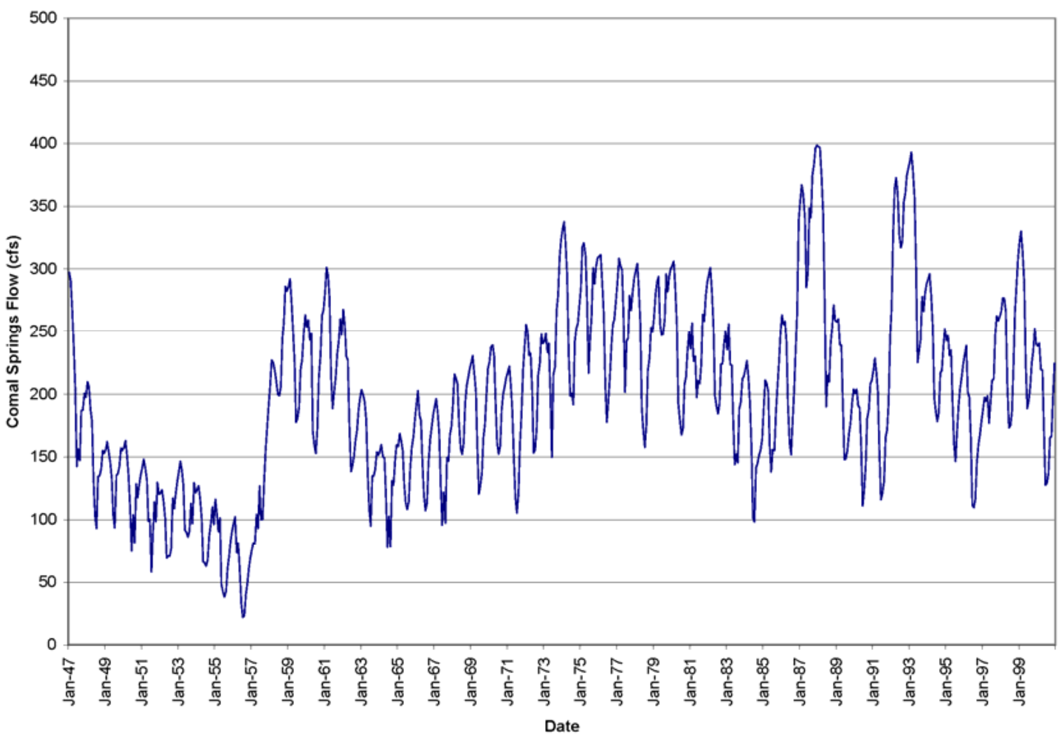
Run 11, 572,000 ac-ft/yr Pumpage, CPM Reductions: 20%, 30%, 40%, 50%
Comal Springs



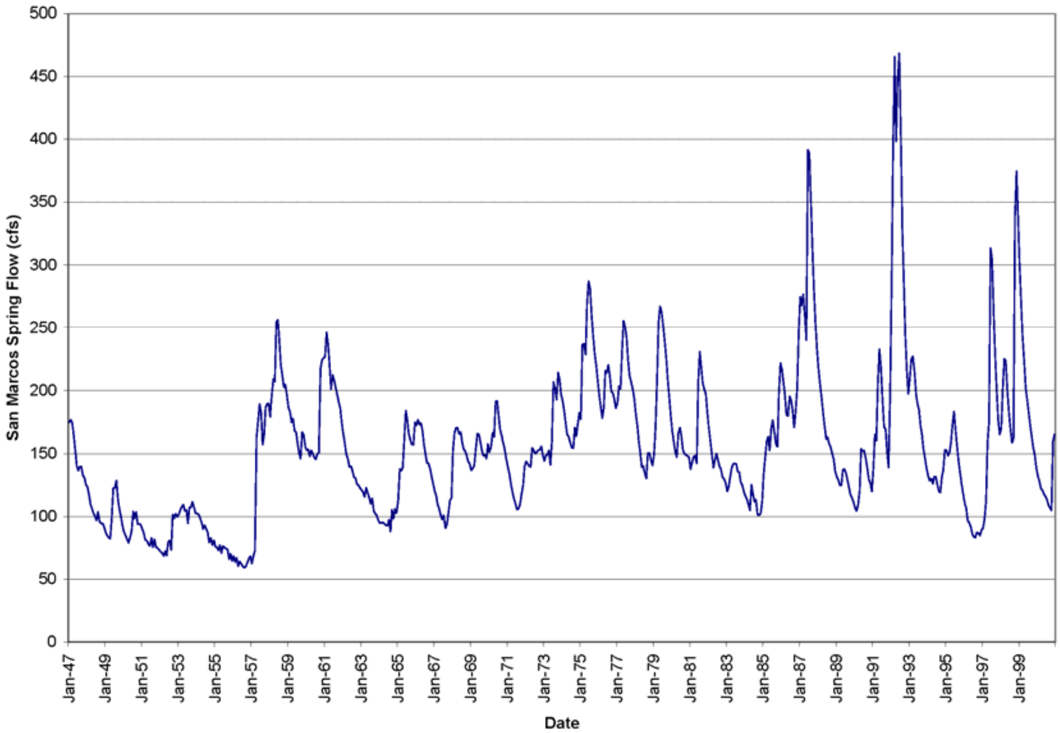
Run 12, 572 ac-ft/yr Pumpage, CPM Reductions: 20%, 30%, 40%, 60%
San Marcos Springs



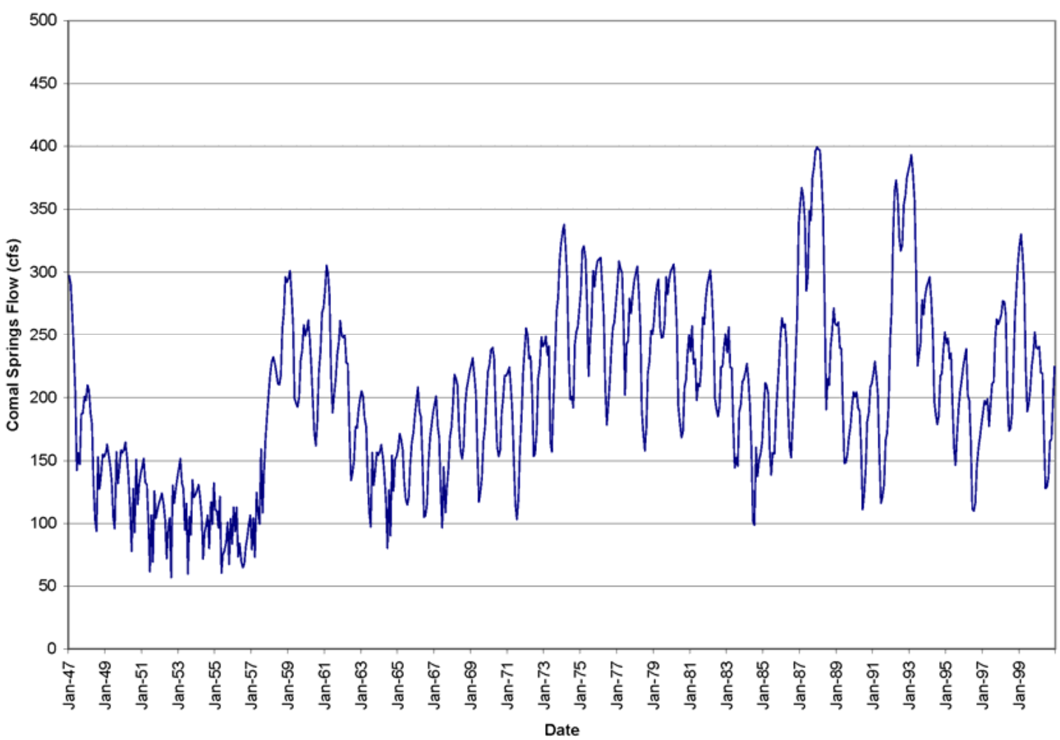
Run 12, 572,000 ac-ft/yr Pumpage, CPM Reductions: 20%, 30%, 40%, 60%
Comal Springs



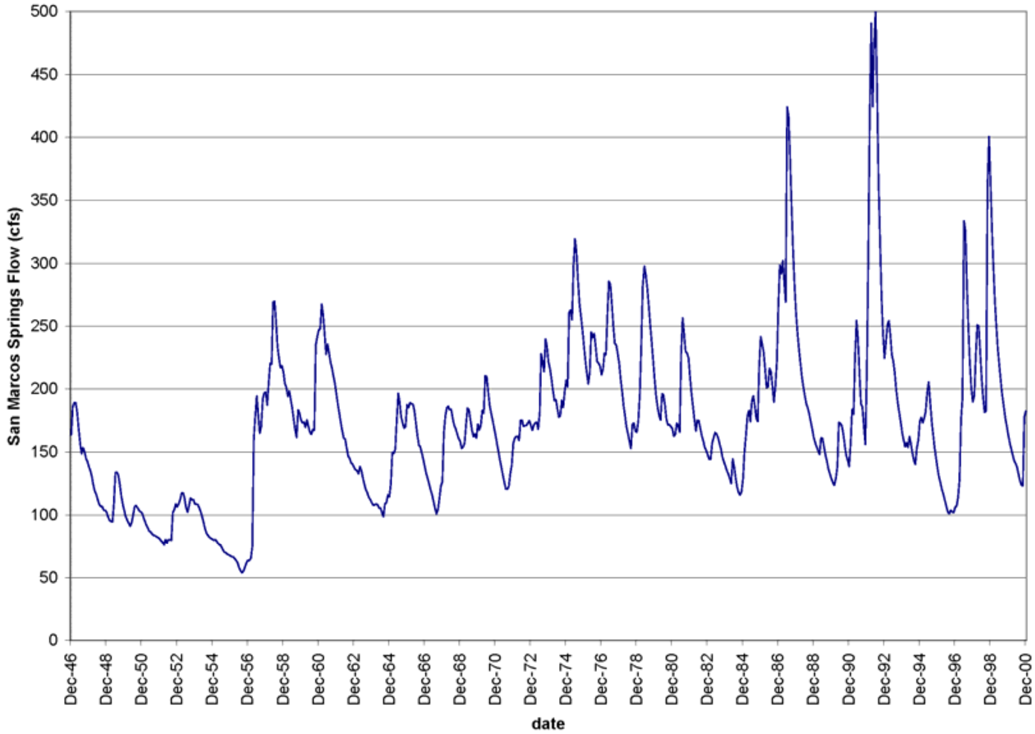
Run 13, 572,000 ac-ft/yr Pumpage, CPM Reductions: 20%, 30%, 40%, 70%
San Marcos Springs



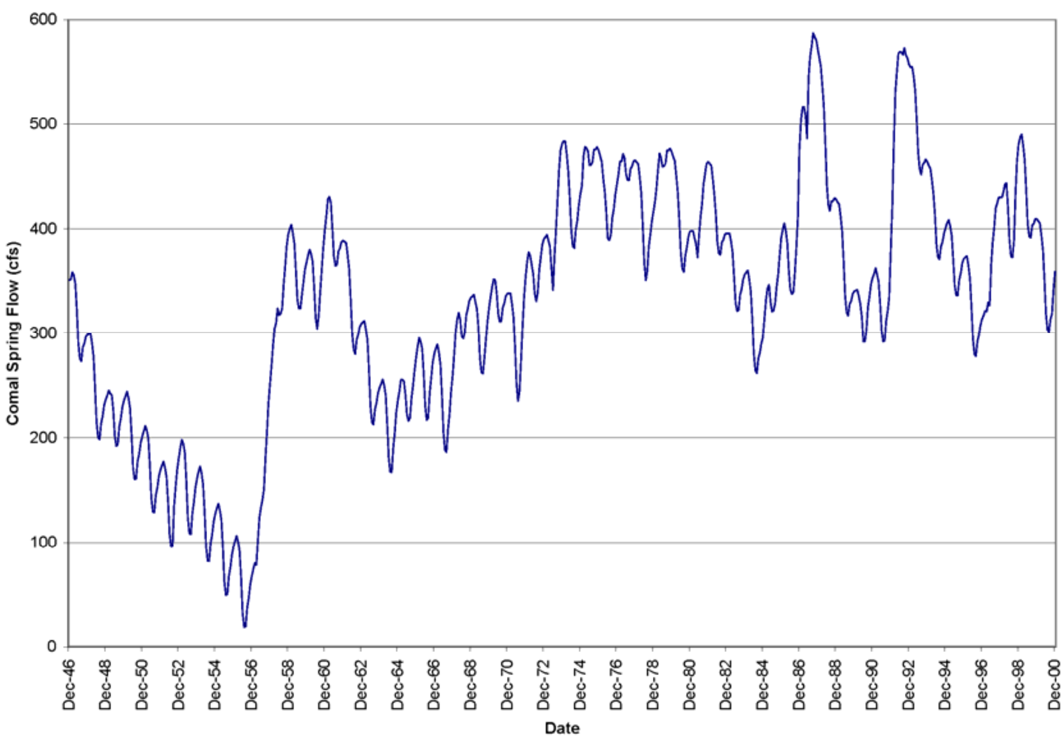
Run 13, 572,000 ac-ft/yr Pumpage, CPM Reductions: 20%, 30%, 40%, 70%
Comal Springs

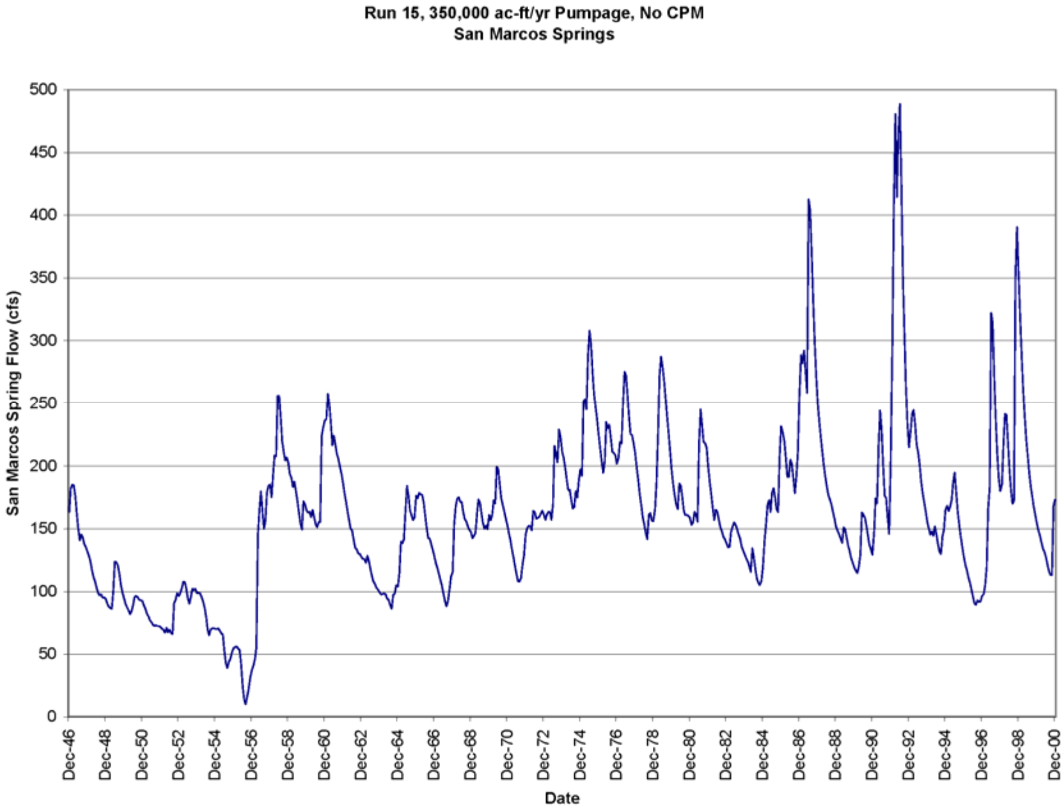


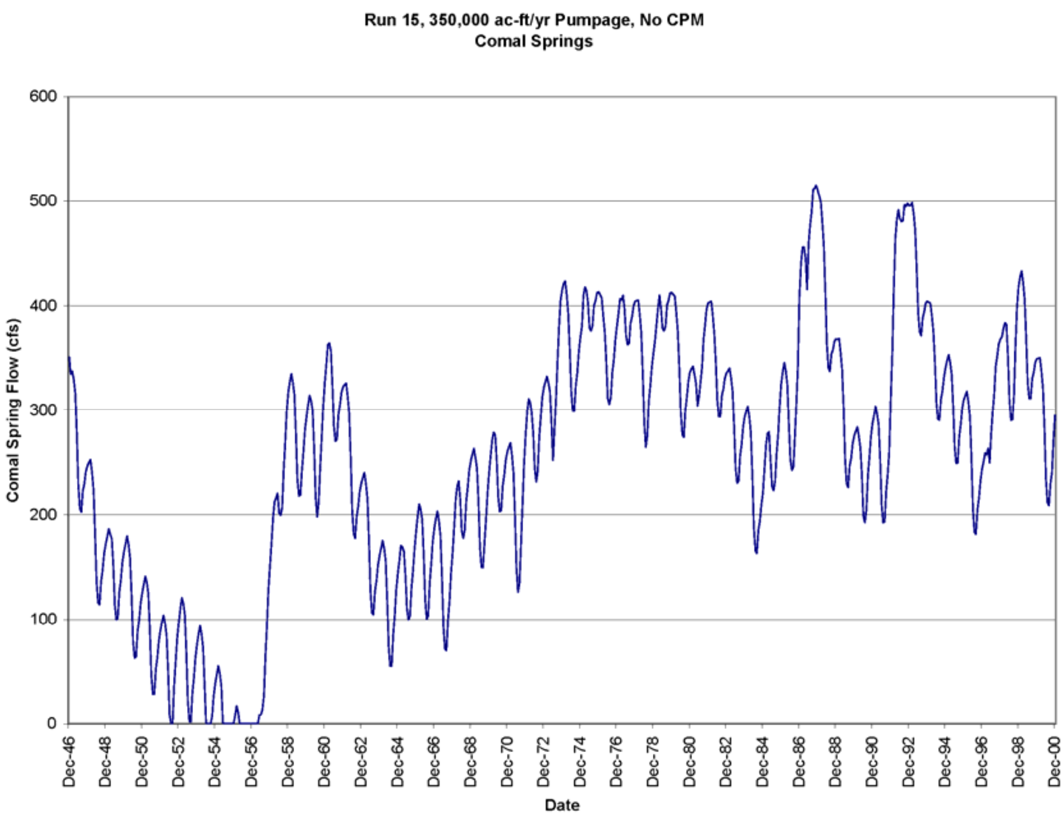
Run 14, 250,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs

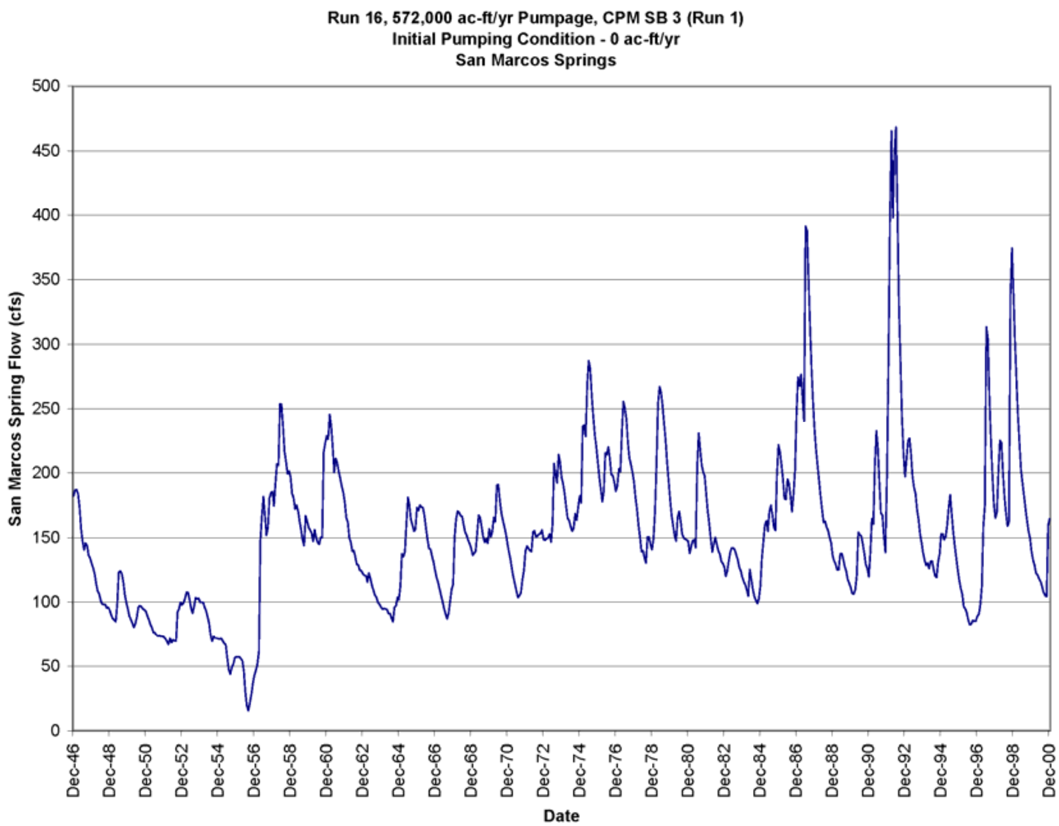


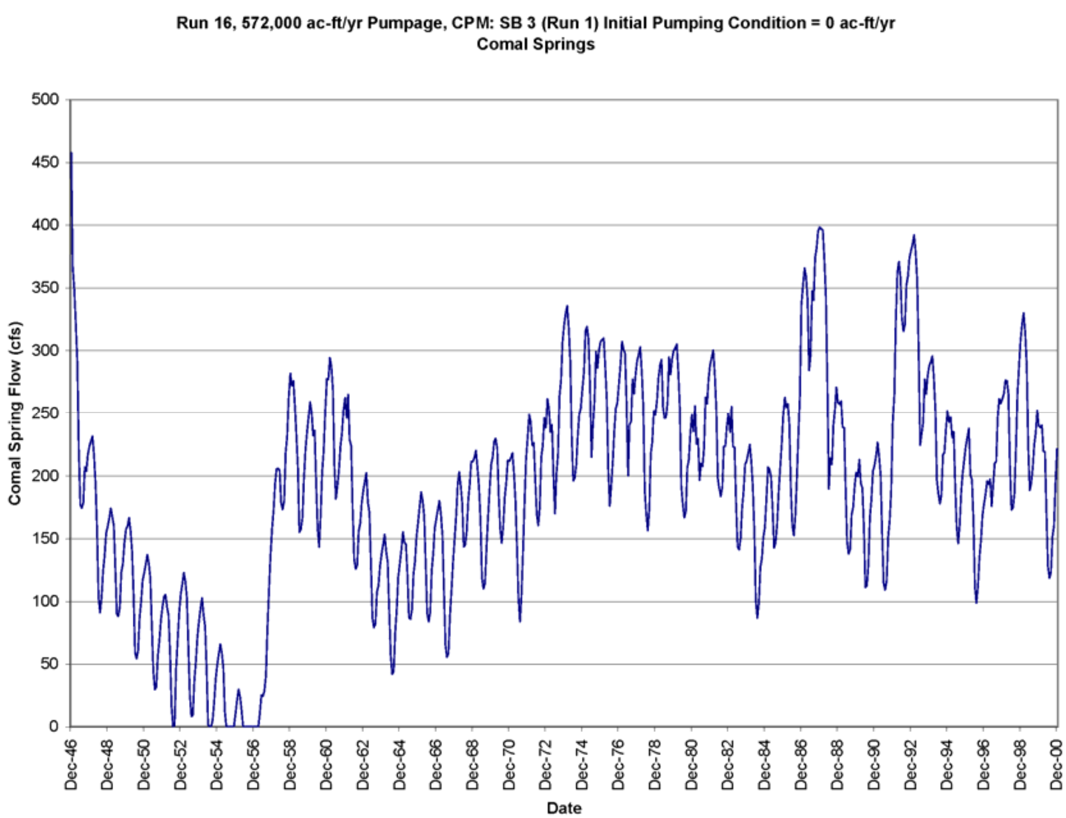
Run 14, 250,000 ac-ft/yr Pumpage, No CPM
Comal Springs

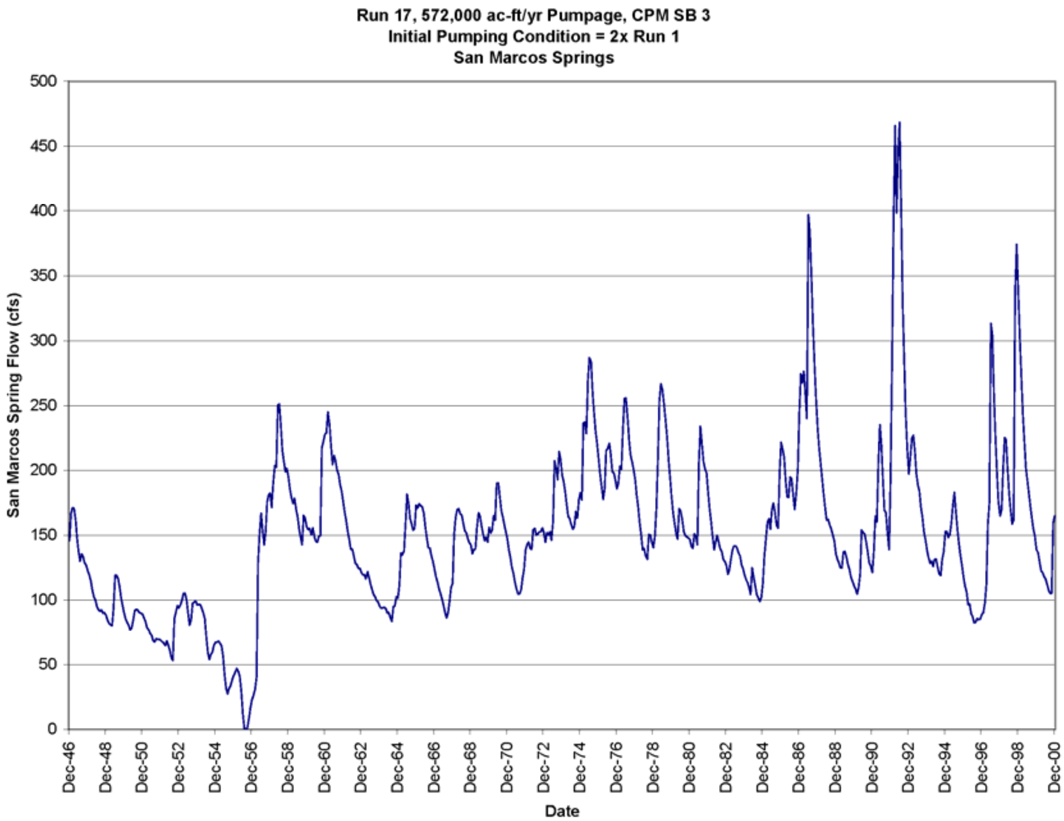


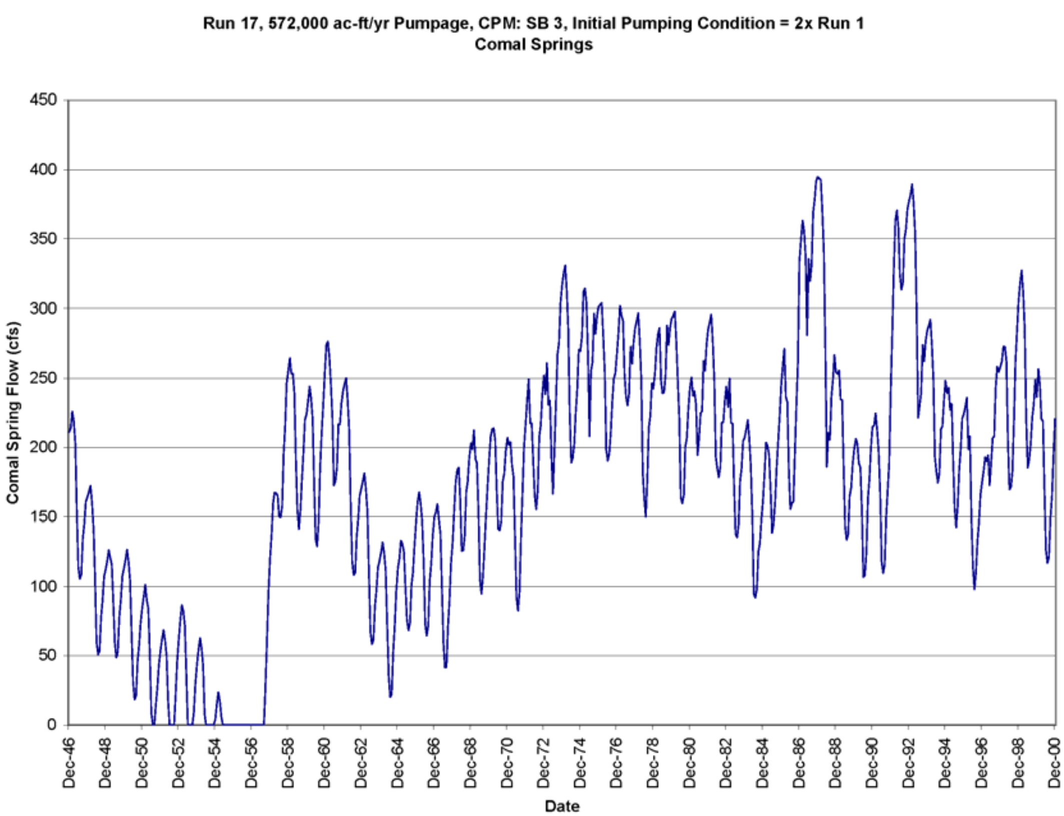

Run 15, 350,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs
San Marcos Spring Flow (cfs)
500
450
400
350
300
250
200
150
100
50
0
Dec-46
Dec-48
Dec-50
Dec-52
Dec-54
Dec-56
Dec-58
Dec-60
Dec-62
Dec-64
Dec-66
Dec-68
Dec-70
Dec-72
Dec-74
Dec-76
Dec-78
Dec-80
Dec-82
Dec-84
Dec-86
Dec-88
Dec-90
Dec-92
Dec-94
Dec-96
Dec-98
Dec-00
Date


Run 15, 350,000 ac-ft/yr Pumpage, No CPM
Comal Springs
Comal Spring Flow (cfs)
600
500
400
300
200
100
0
Dec-46
Dec-48
Dec-50
Dec-52
Dec-54
Dec-56
Dec-58
Dec-60
Dec-62
Dec-64
Dec-66
Dec-68
Dec-70
Dec-72
Dec-74
Dec-76
Dec-78
Dec-80
Dec-82
Dec-84
Dec-86
Dec-88
Dec-90
Dec-92
Dec-94
Dec-96
Dec-98
Dec-00
Date

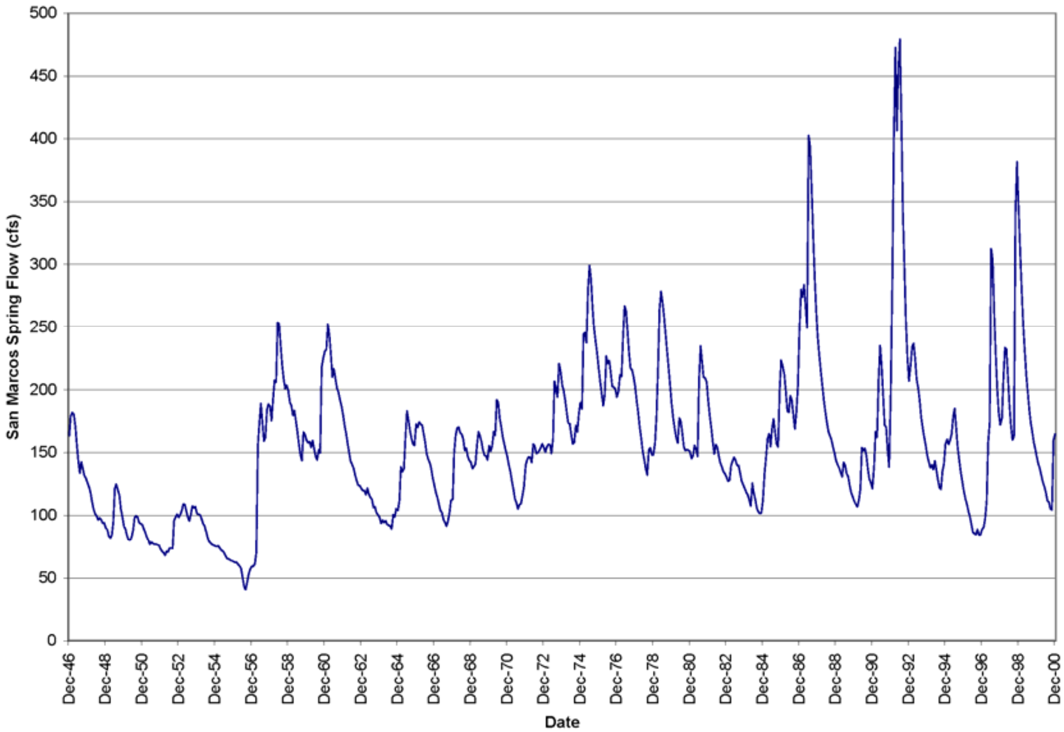

Run 16, 572,000 ac-ft/yr Pumpage, CPM SB 3 (Run 1)
Initial Pumping Condition - 0 ac-ft/yr
San Marcos Springs
San Marcos Spring Flow (cfs)
Date


Run 16, 572,000 ac-ft/yr Pumpage, CPM: SB 3 (Run 1) Initial Pumping Condition = 0 ac-ft/yr
Comal Springs
Comal Spring Flow (cfs)
Date

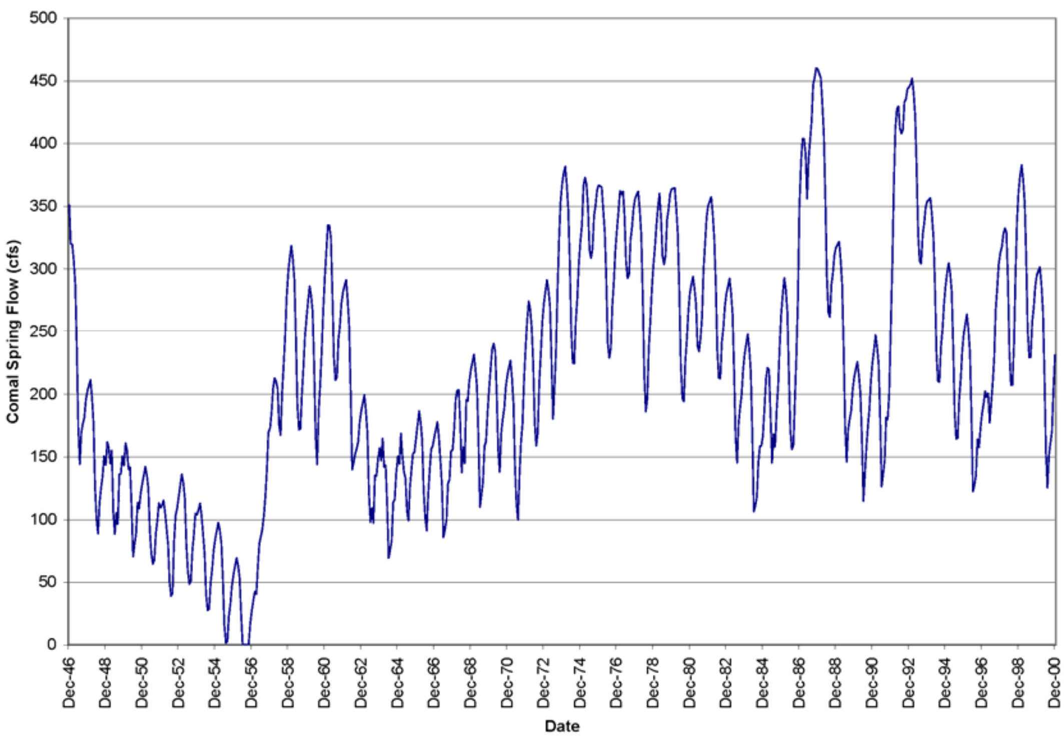

Run 17, 572,000 ac-ft/yr Pumpage, CPM SB 3
Initial Pumping Condition = 2x Run 1
San Marcos Springs
San Marcos Spring Flow (cfs)
500
450
400
350
300
250
200
150
100
50
0
Dec-46
Dec-48
Dec-50
Dec-52
Dec-54
Dec-56
Dec-58
Dec-60
Dec-62
Dec-64
Dec-66
Dec-68
Dec-70
Dec-72
Dec-74
Dec-76
Dec-78
Dec-80
Dec-82
Dec-84
Dec-86
Dec-88
Dec-90
Dec-92
Dec-94
Dec-96
Dec-98
Dec-00
Date


Run 17, 572,000 ac-ft/yr Pumpage, CPM: SB 3, Initial Pumping Condition = 2x Run 1
Comal Springs
Comal Spring Flow (cfs)
450
400
350
300
250
200
150
100
50
0
Dec-46
Dec-48
Dec-50
Dec-52
Dec-54
Dec-56
Dec-58
Dec-60
Dec-62
Dec-64
Dec-66
Dec-68
Dec-70
Dec-72
Dec-74
Dec-76
Dec-78
Dec-80
Dec-82
Dec-84
Dec-86
Dec-88
Dec-90
Dec-92
Dec-94
Dec-96
Dec-98
Dec-00
Date

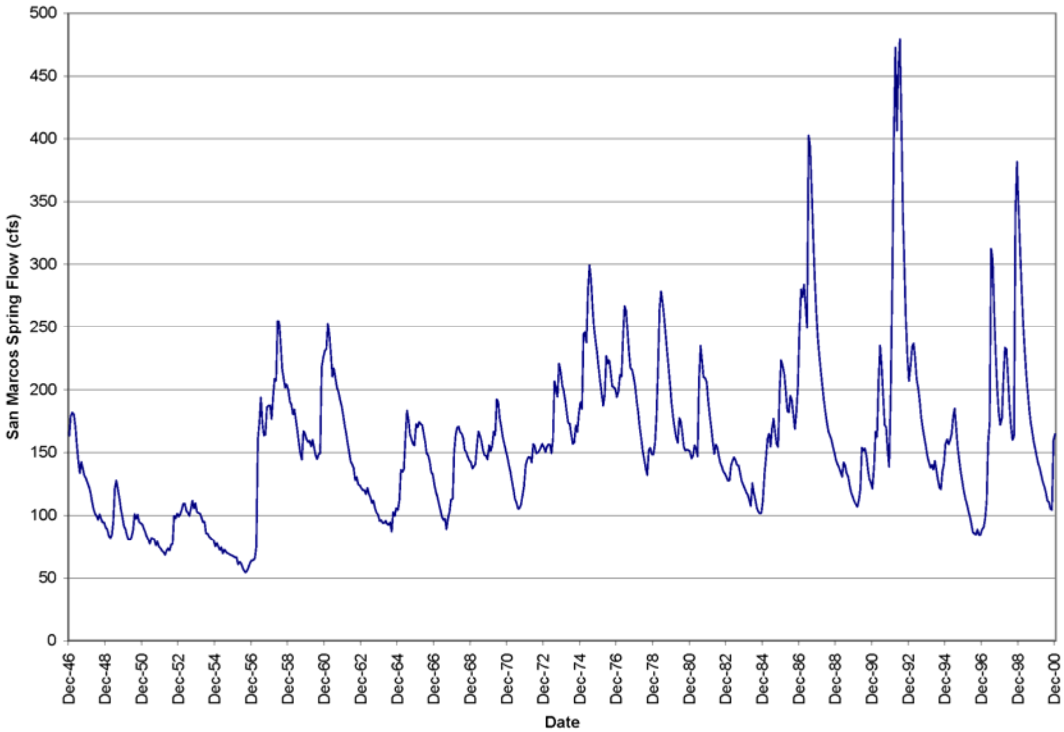
Run 18, 437,000 ac-ft/yr Pumpage, CPM Reductions: 0%, 0%, 20%, 35%
San Marcos Springs



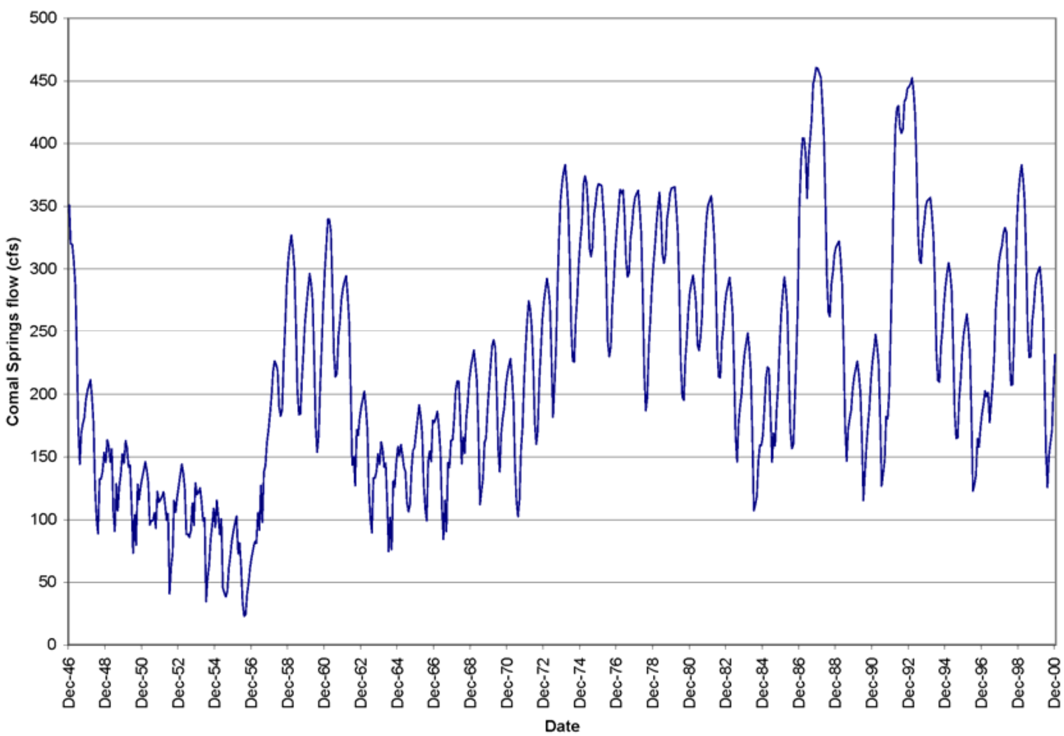
Run 18, 437 ac-ft/yr Pumpage, CPM Reductions: 0%, 0%, 20%, 35%
Comal Springs



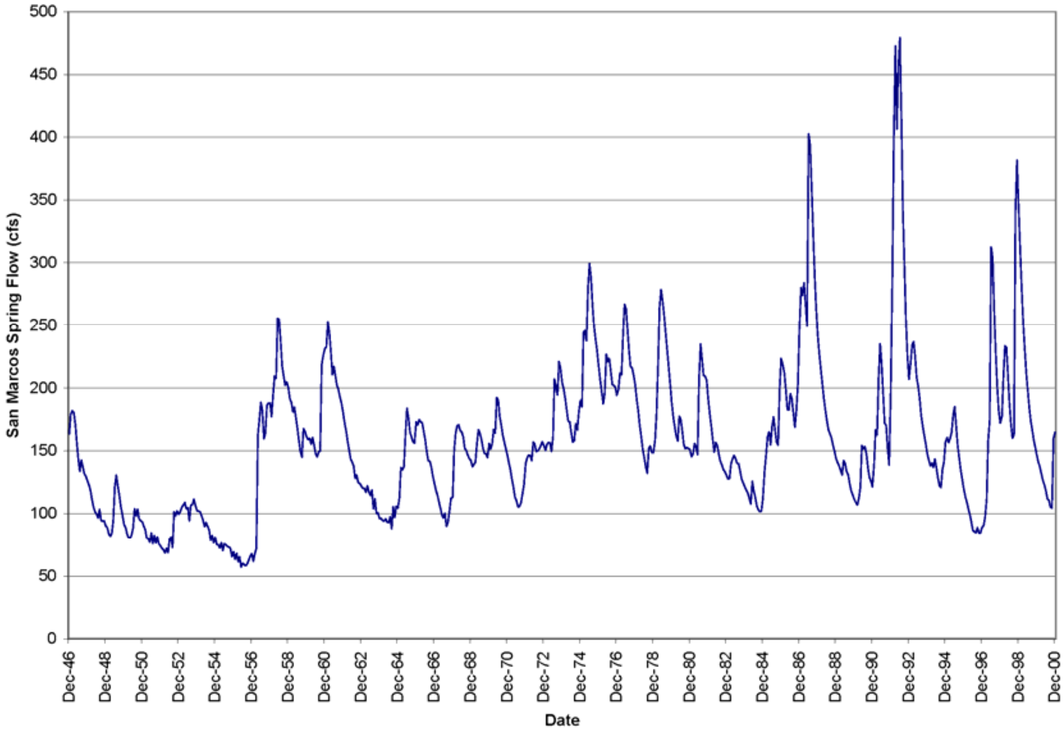
Run 19, 437,000 ac-ft/yr Pumpage, CPM Reductions: 0%, 0%, 20%, 48%
San Marcos Springs



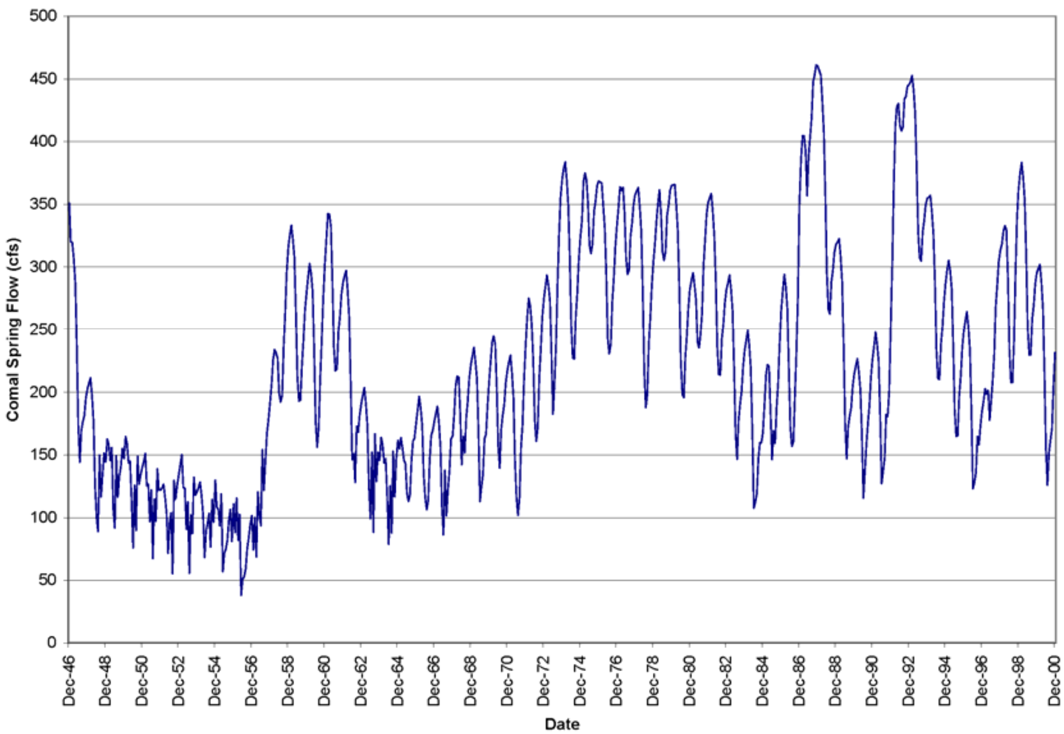
Run 19, 437,000 ac-ft/yr Pumpage, CPM Reductions: 0%, 0%, 70%, 48%
Comal Springs



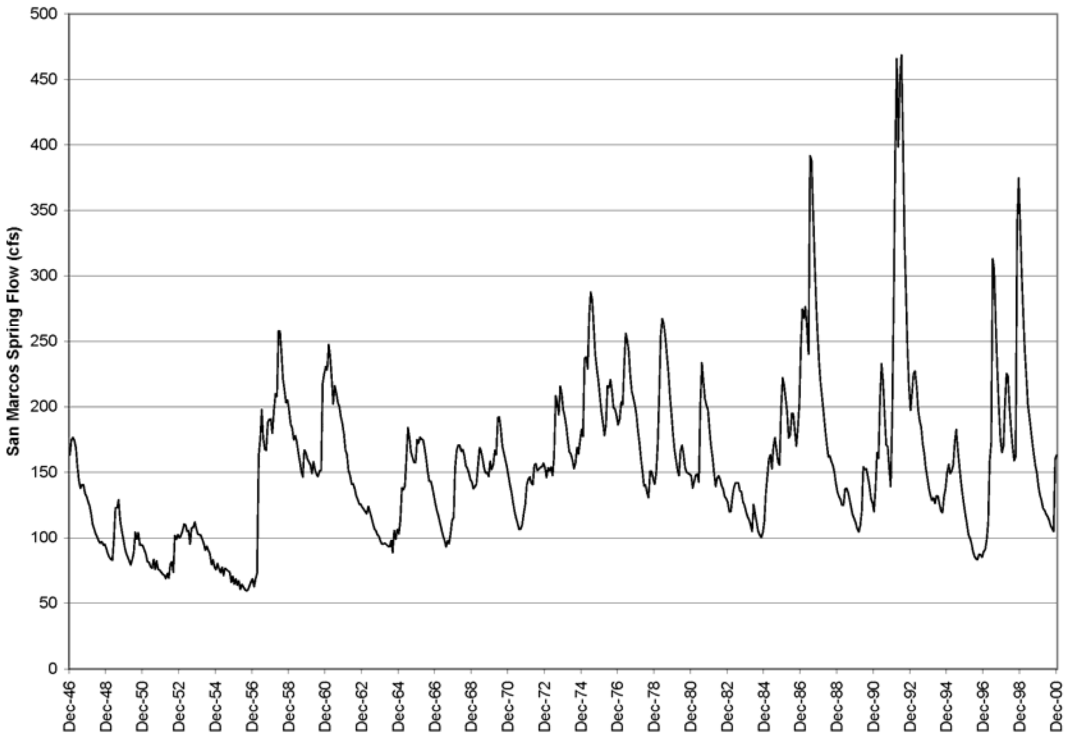
Run 20, 437,000 ac-ft/yr Pumpage, CPM Reductions: 0%, 0%, 20%, 60%
San Marcos Springs



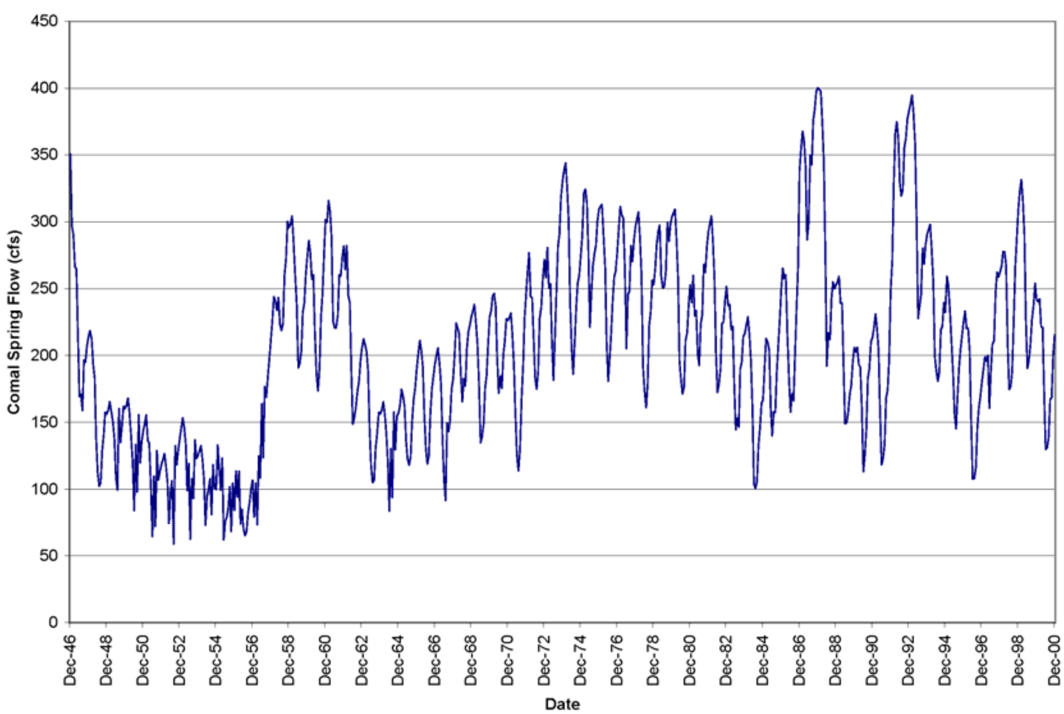
Run 20, 437,000 ac-ft/yr Pumpage, CPM Reductions: 0%, 0%, 20%, 60%
Comal Springs

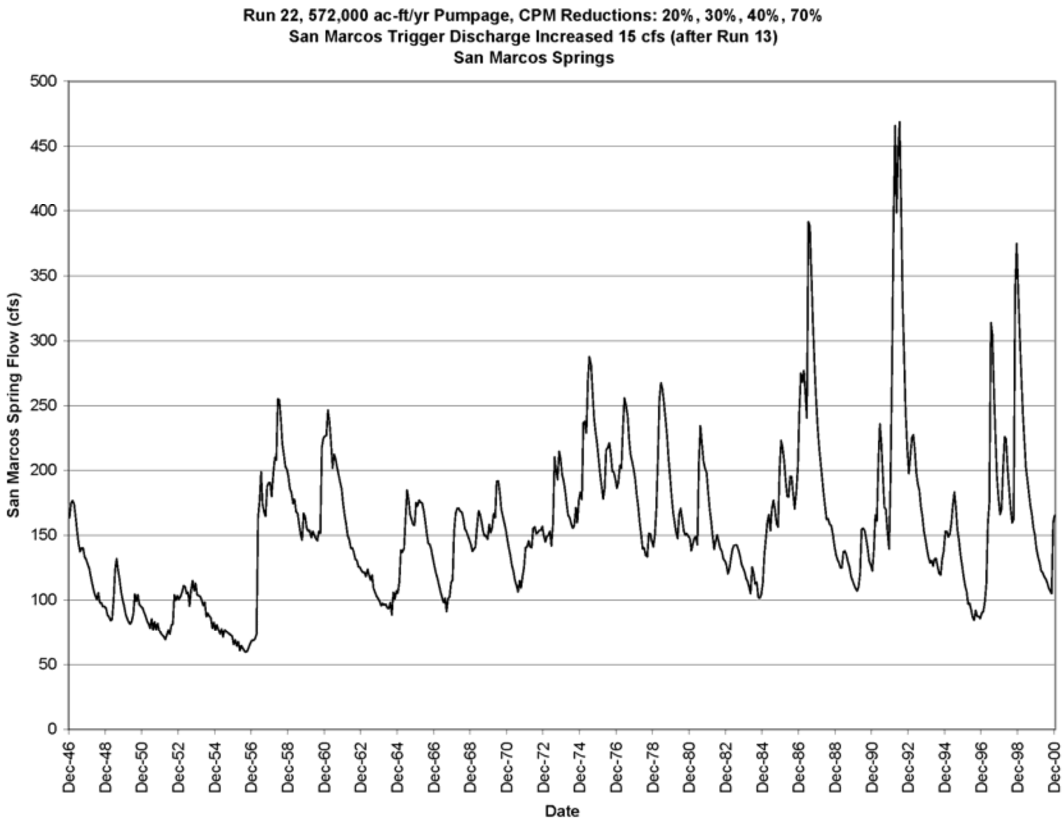


Run 21, 572,000 ac-ft/yr Pumpage, CPM Reductions: 20%, 30%, 40%, 70%
Trigger Elevations for J-17 and J-27 raised 5 ft (after Run 13)
San Marcos Springs

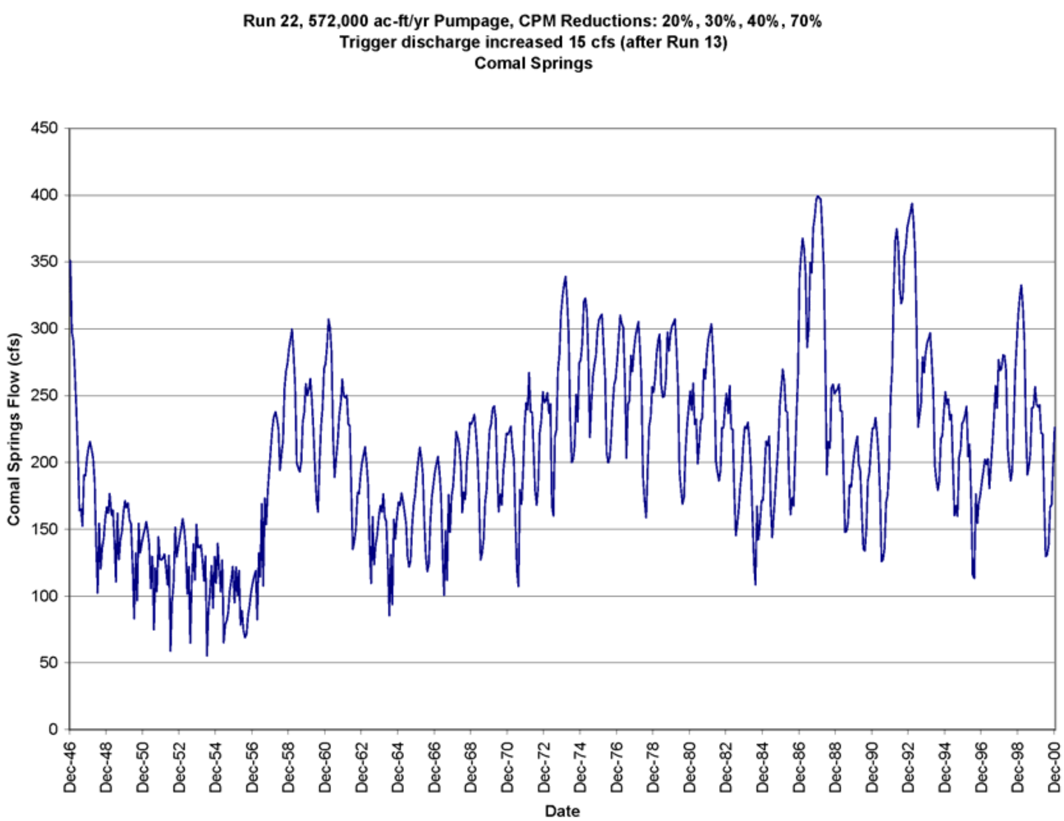


Run 21, 572,000 ac-ft/yr Pumpage, CPM Reductions: 20%, 30%, 40%, 70%,
Trigger elevations for J-17 and J-27 raised 5 ft (after Run 13)
Comal Springs

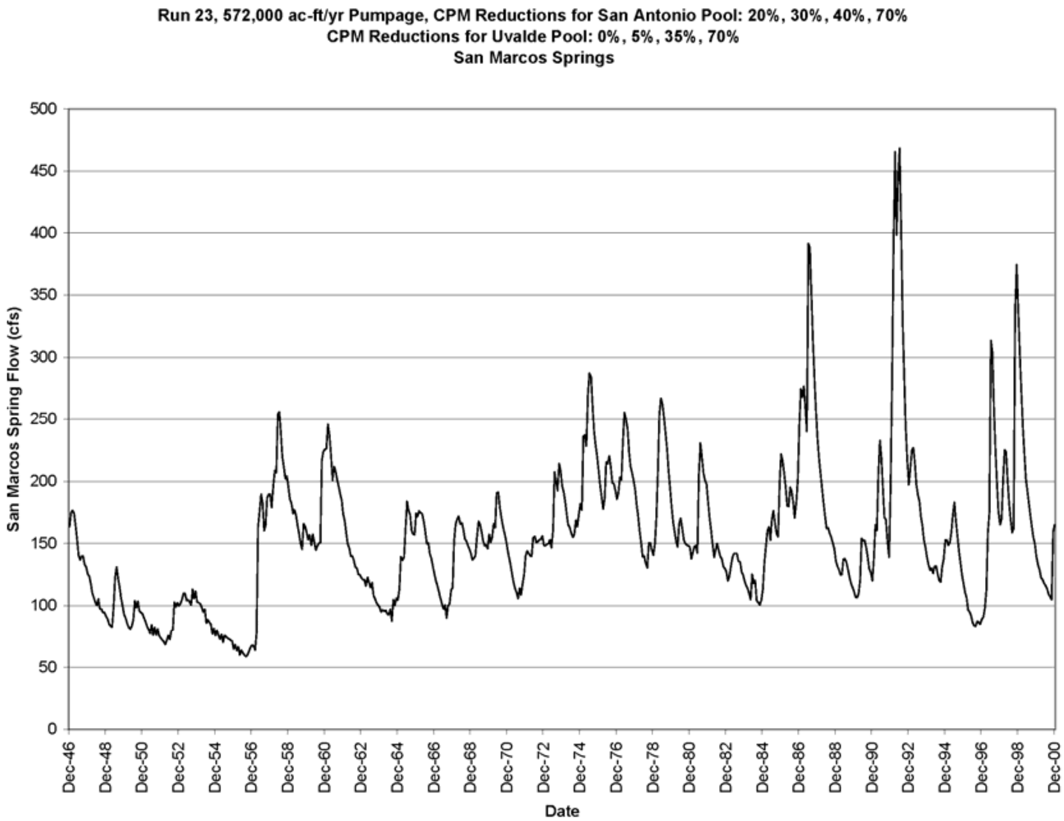


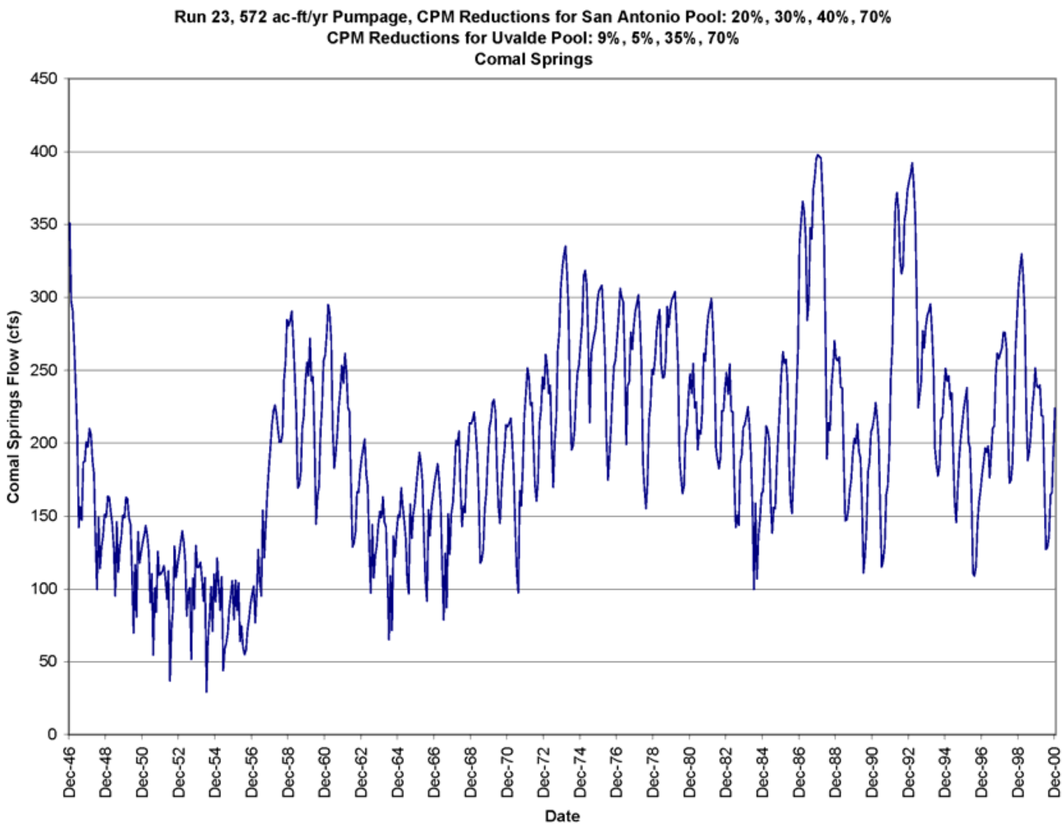


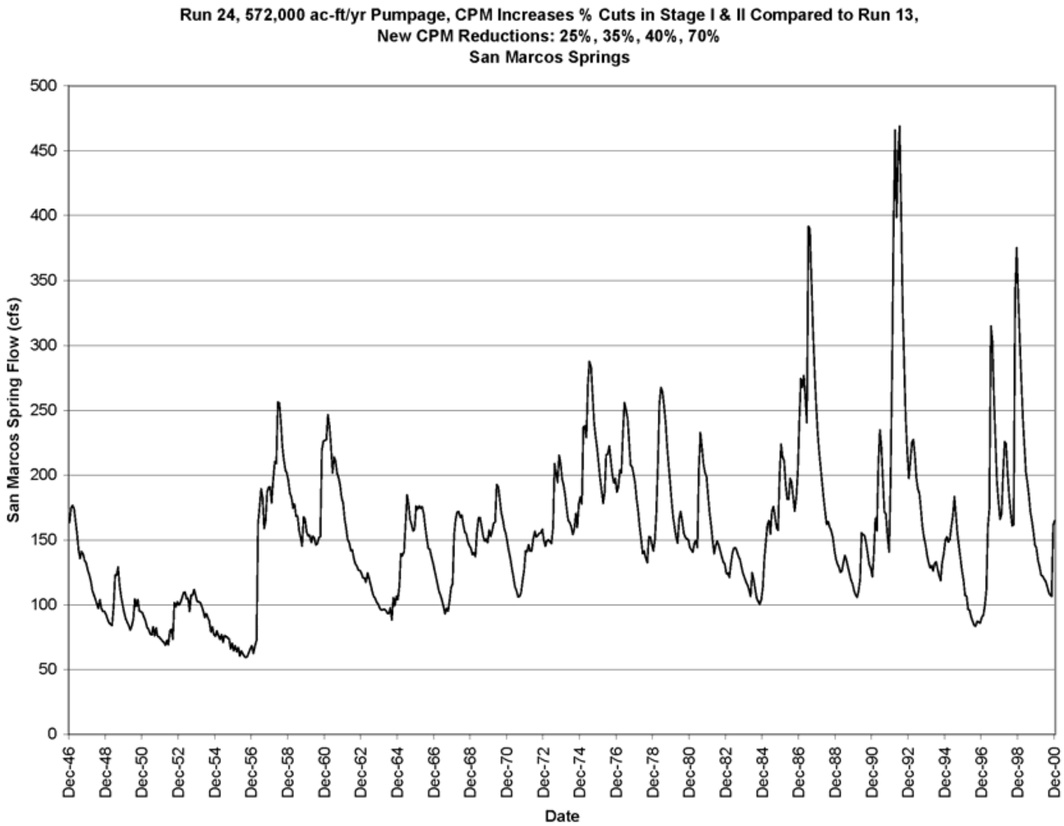
Run 22, 572,000 ac-ft/yr Pumpage, CPM Reductions: 20%, 30%, 40%, 70%
San Marcos Trigger Discharge Increased 15 cfs (after Run 13)
San Marcos Springs
San Marcos Spring Flow (cfs)
500
450
400
350
300
250
200
150
100
50
0
Dec-46
Dec-48
Dec-50
Dec-52
Dec-54
Dec-56
Dec-58
Dec-60
Dec-62
Dec-64
Dec-66
Dec-68
Dec-70
Dec-72
Dec-74
Dec-76
Dec-78
Dec-80
Dec-82
Dec-84
Dec-86
Dec-88
Dec-90
Dec-92
Dec-94
Dec-96
Dec-98
Dec-00
Date

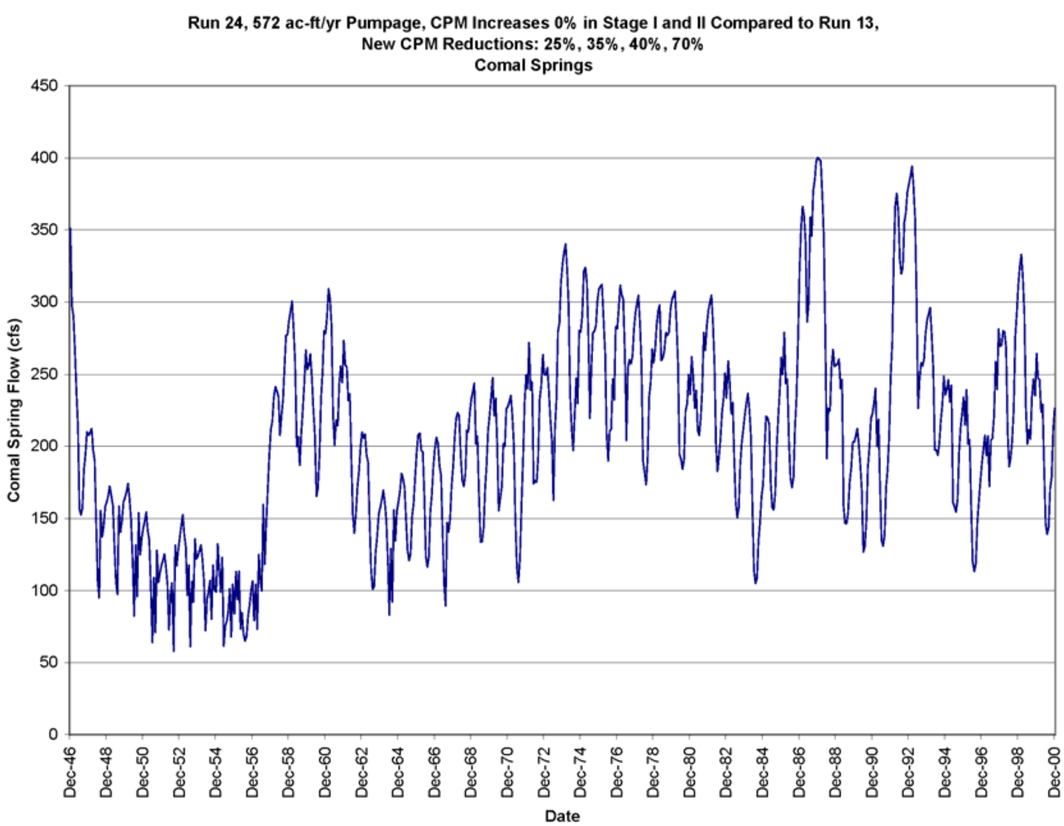


Run 22, 572,000 ac-ft/yr Pumpage, CPM Reductions: 20%, 30%, 40%, 70%
Trigger discharge increased 15 cfs (after Run 13)
Comal Springs
Comal Springs Flow (cfs)
450
400
350
300
250
200
150
100
50
0
Dec-46
Dec-48
Dec-50
Dec-52
Dec-54
Dec-56
Dec-58
Dec-60
Dec-62
Dec-64
Dec-66
Dec-68
Dec-70
Dec-72
Dec-74
Dec-76
Dec-78
Dec-80
Dec-82
Dec-84
Dec-86
Dec-88
Dec-90
Dec-92
Dec-94
Dec-96
Dec-98
Dec-00
Date

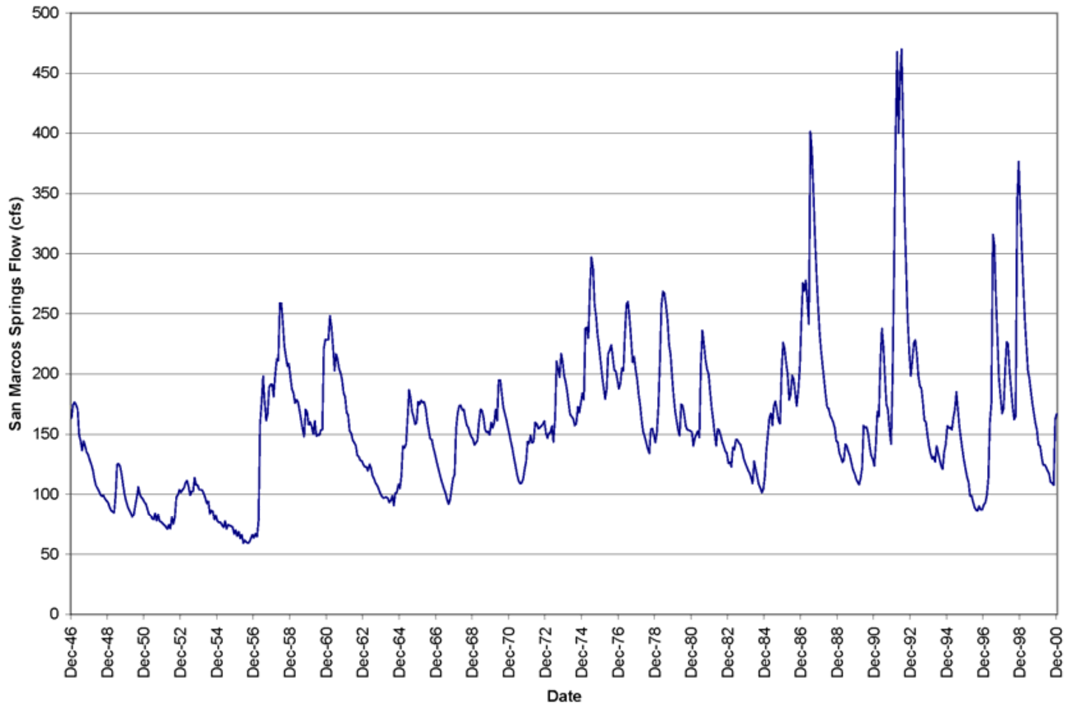

Run 23, 572,000 ac-ft/yr Pumpage, CPM Reductions for San Antonio Pool: 20%, 30%, 40%, 70%
CPM Reductions for Uvalde Pool: 0%, 5%, 35%, 70%
San Marcos Springs
San Marcos Spring Flow (cfs)
Date
Dec-46
Dec-48
Dec-50
Dec-52
Dec-54
Dec-56
Dec-58
Dec-60
Dec-62
Dec-64
Dec-66
Dec-68
Dec-70
Dec-72
Dec-74
Dec-76
Dec-78
Dec-80
Dec-82
Dec-84
Dec-86
Dec-88
Dec-90
Dec-92
Dec-94
Dec-96
Dec-98
Dec-00


Run 23, 572 ac-ft/yr Pumpage, CPM Reductions for San Antonio Pool: 20%, 30%, 40%, 70%
CPM Reductions for Uvalde Pool: 9%, 5%, 35%, 70%
Comal Springs
Comal Springs Flow (cfs)
Date
Dec-46
Dec-48
Dec-50
Dec-52
Dec-54
Dec-56
Dec-58
Dec-60
Dec-62
Dec-64
Dec-66
Dec-68
Dec-70
Dec-72
Dec-74
Dec-76
Dec-78
Dec-80
Dec-82
Dec-84
Dec-86
Dec-88
Dec-90
Dec-92
Dec-94
Dec-96
Dec-98
Dec-00

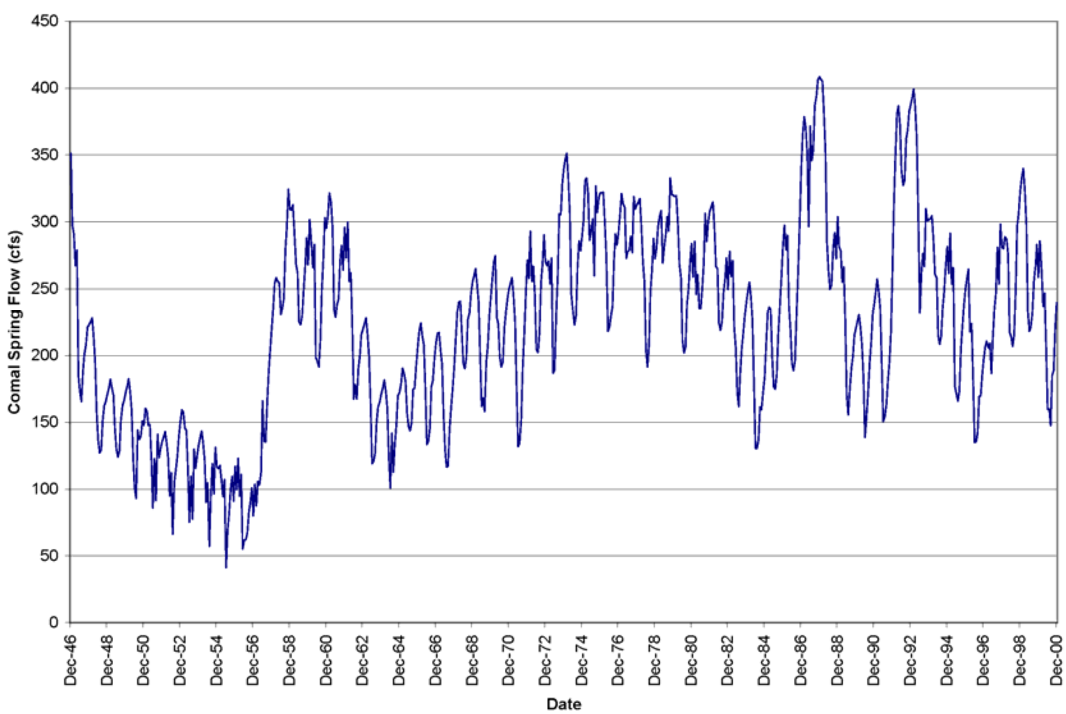

Run 24, 572,000 ac-ft/yr Pumpage, CPM Increases % Cuts in Stage I & II Compared to Run 13,
New CPM Reductions: 25%, 35%, 40%, 70%
San Marcos Springs
San Marcos Spring Flow (cfs)
500
450
400
350
300
250
200
150
100
50
0
Dec-46
Dec-48
Dec-50
Dec-52
Dec-54
Dec-56
Dec-58
Dec-60
Dec-62
Dec-64
Dec-66
Dec-68
Dec-70
Dec-72
Dec-74
Dec-76
Dec-78
Dec-80
Dec-82
Dec-84
Dec-86
Dec-88
Dec-90
Dec-92
Dec-94
Dec-96
Dec-98
Dec-00
Date


Run 24, 572 ac-ft/yr Pumpage, CPM Increases 0% in Stage I and II Compared to Run 13,
New CPM Reductions: 25%, 35%, 40%, 70%
Comal Springs
Comal Spring Flow (cfs)
450
400
350
300
250
200
150
100
50
0
Dec-46
Dec-48
Dec-50
Dec-52
Dec-54
Dec-56
Dec-58
Dec-60
Dec-62
Dec-64
Dec-66
Dec-68
Dec-70
Dec-72
Dec-74
Dec-76
Dec-78
Dec-80
Dec-82
Dec-84
Dec-86
Dec-88
Dec-90
Dec-92
Dec-94
Dec-96
Dec-98
Dec-00
Date

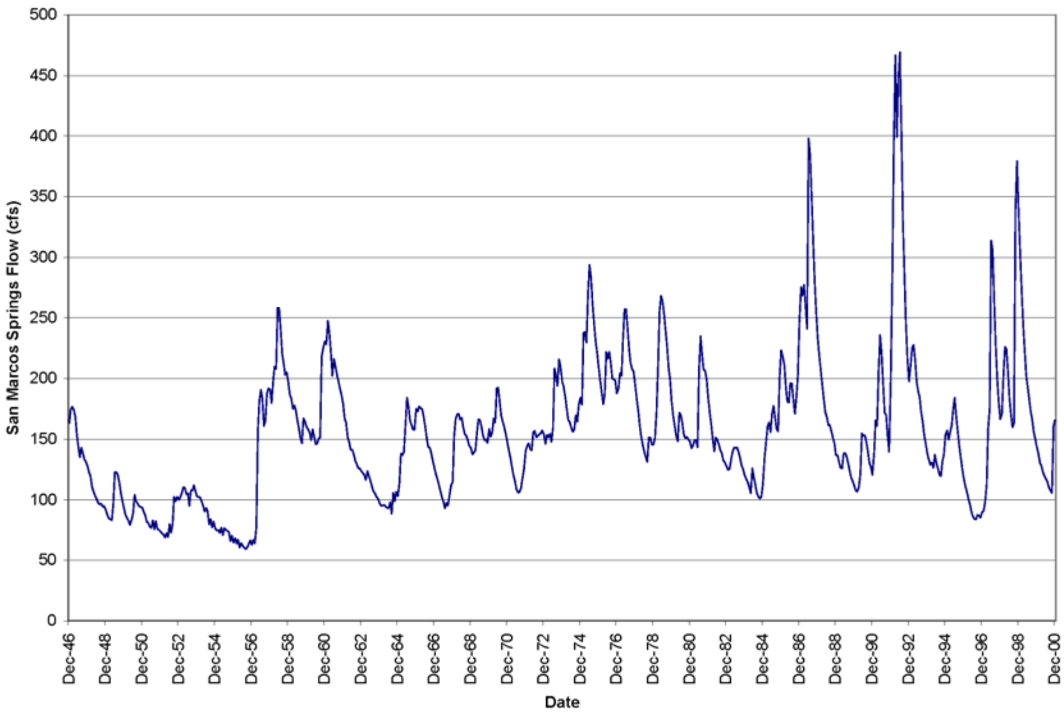
Run 28, 572,000 ac-ft/yr Pumpage, CPM Reductions to test sensitivity of higher percent reductions and higher triggers at earlier stages. (See appendix for description)
San Marcos Springs



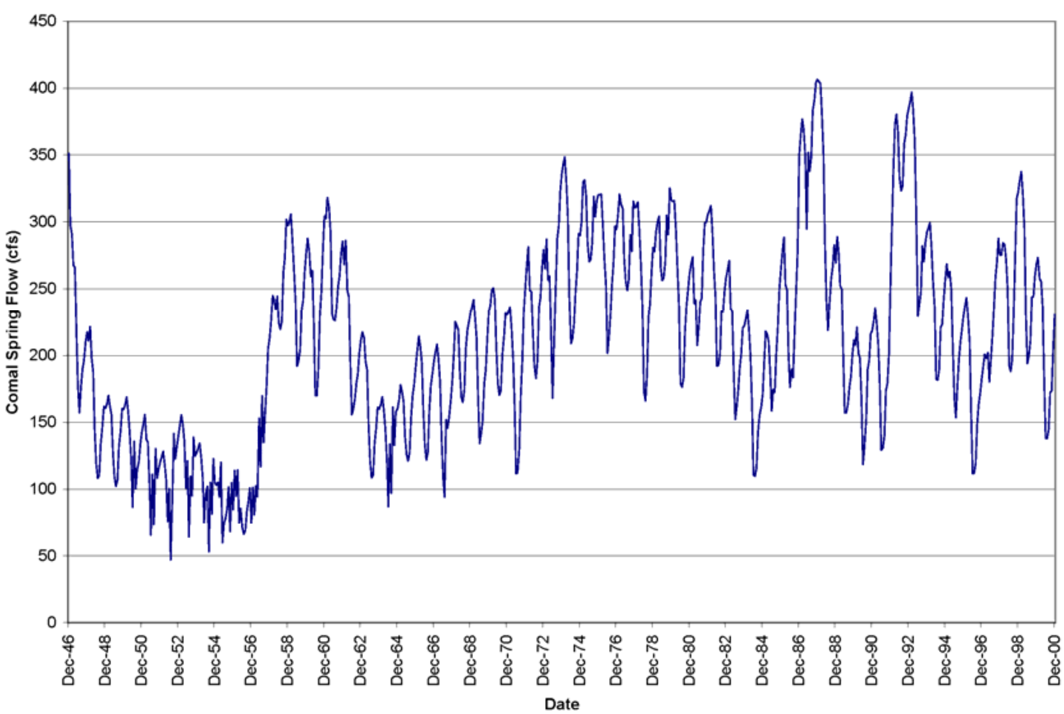
Run 28, 572,000 ac-ft/yr Pumpage, CPM Reductions to test sensitivity of higher percent reductions and higher triggers at earlier stages. (See appendix for description)
Comal Springs

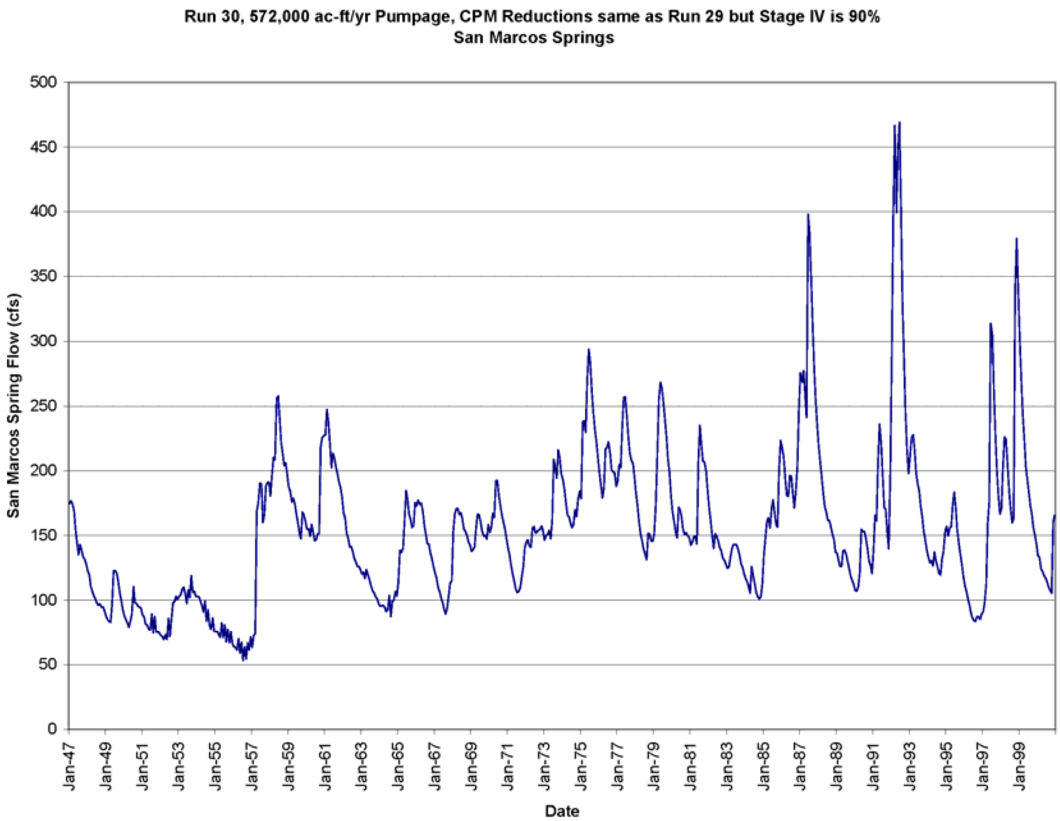


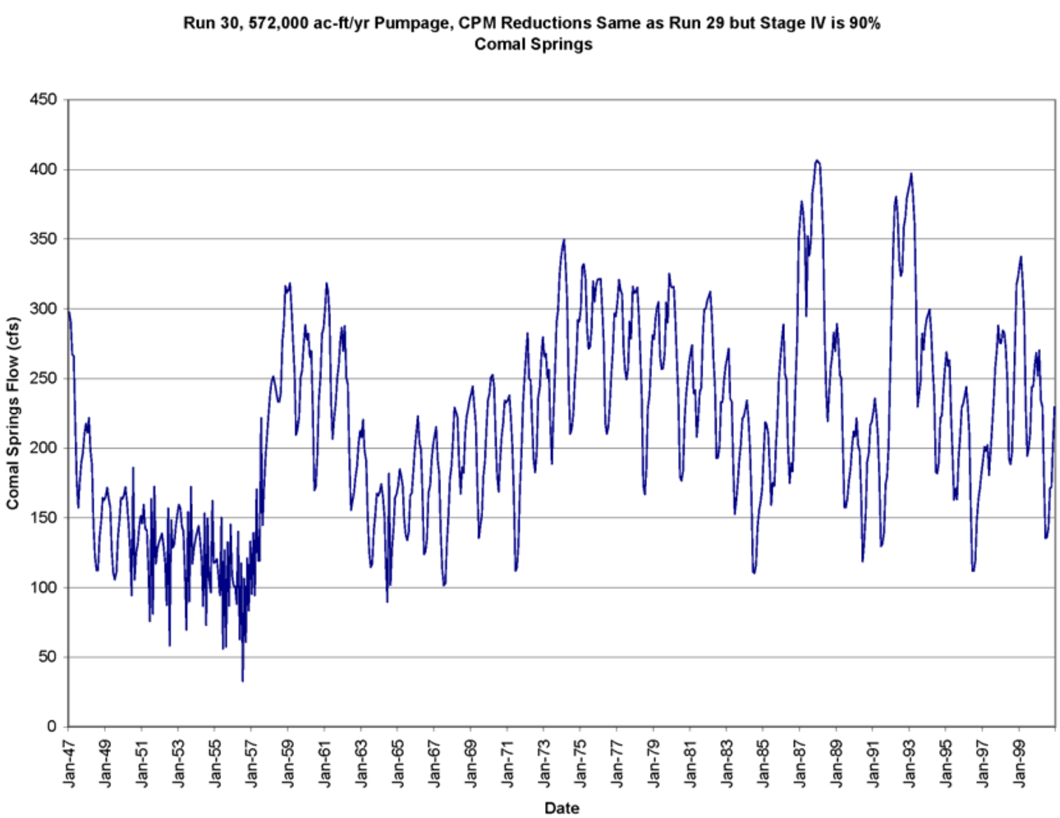
Run 29, 572,000 ac-ft/yr Pumpage, CPM Reduction increases for higher triggers, higher percentages and earlier stages. (See appendix for description)
San Marcos Springs



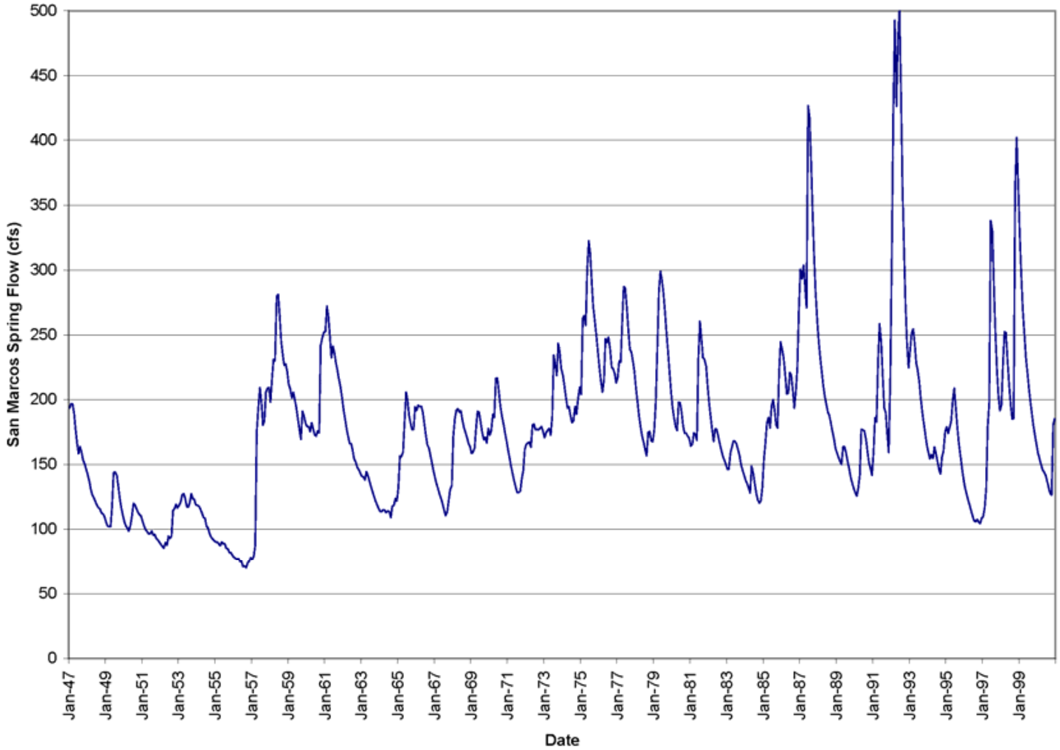
Run 29, 572,000 ac-ft/yr Pumpage, CPM reduction increase for higher triggers, higher percentages and earlier stages. (See appendix for description)
Comal Springs



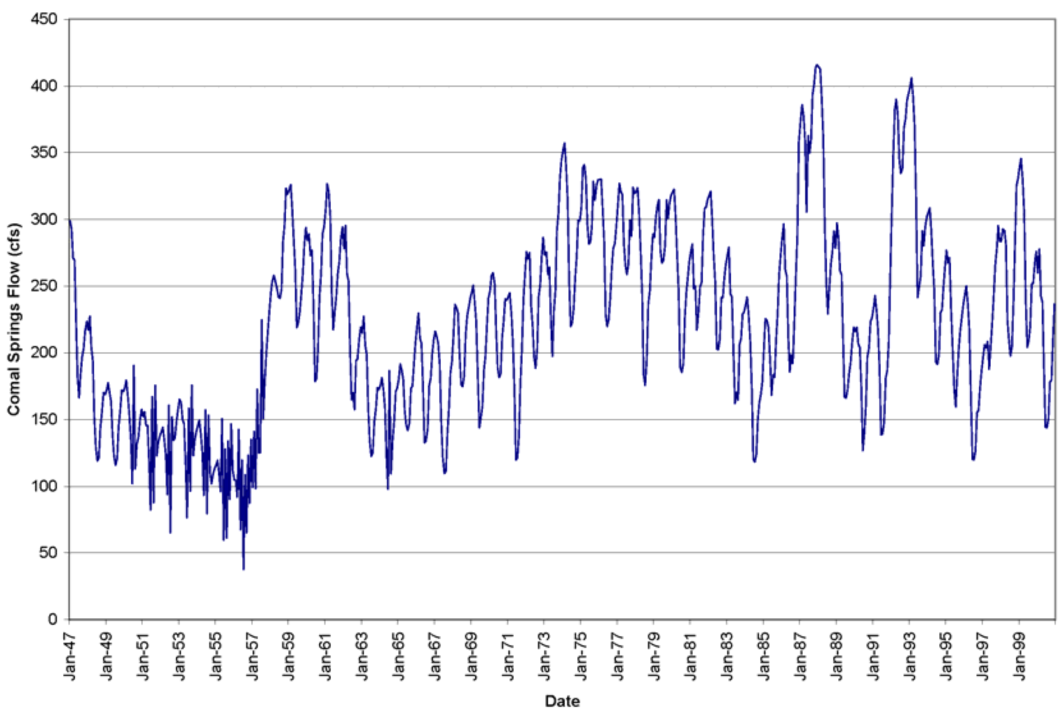

Run 30, 572,000 ac-ft/yr Pumpage, CPM Reductions same as Run 29 but Stage IV is 90%
San Marcos Springs
San Marcos Spring Flow (cfs)
Date
0
50
100
150
200
250
300
350
400
450
500
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99


Run 30, 572,000 ac-ft/yr Pumpage, CPM Reductions Same as Run 29 but Stage IV is 90%
Comal Springs
Comal Springs Flow (cfs)
Date
0
50
100
150
200
250
300
350
400
450
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99

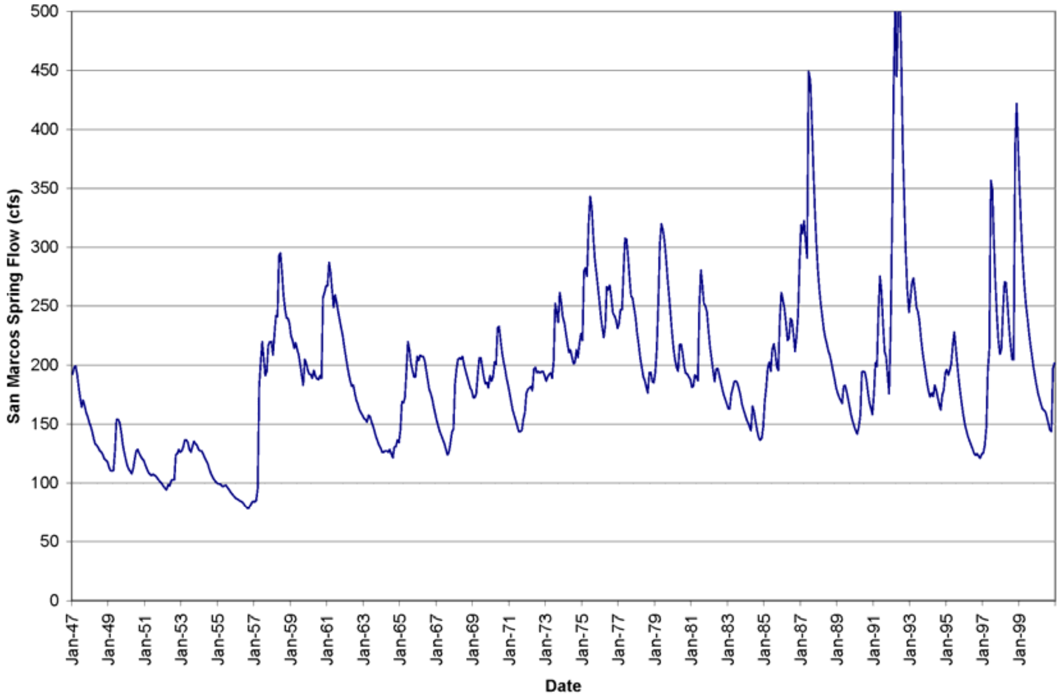
Run 31, 572,000 ac-ft/yr Pumpage, CPM Reductions same as Run 30, but 0 Pumpage in Comal and Hays Counties
San Marcos Springs



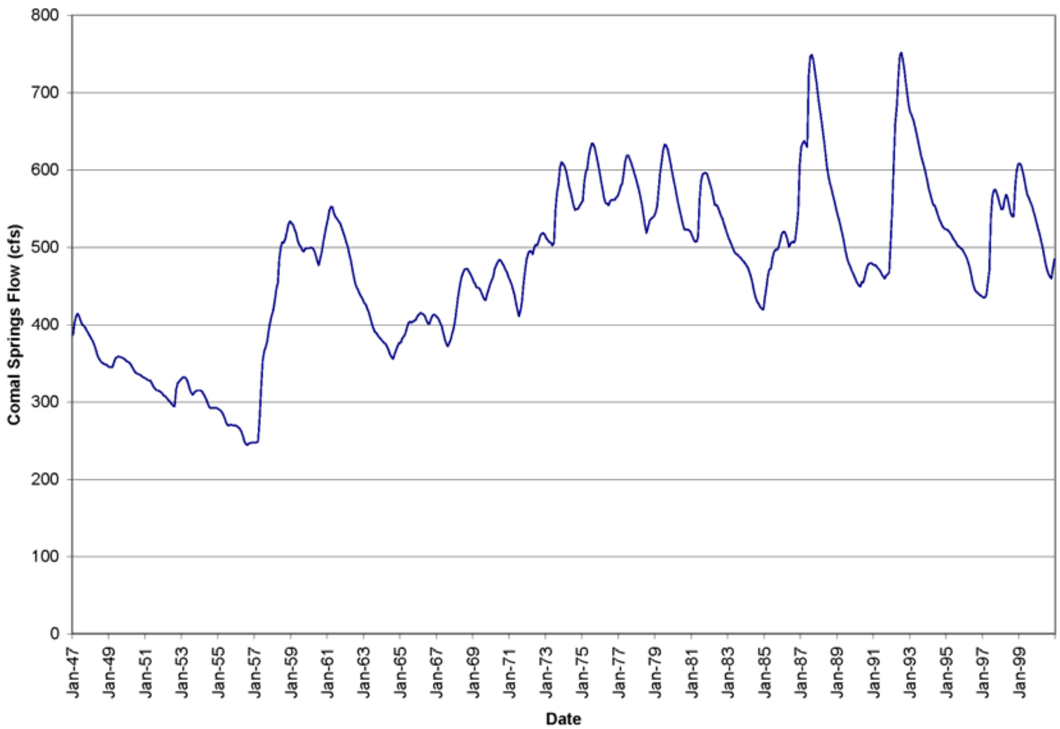
Run 31, 572,000 ac-ft/yr Pumpage, CPM Reductions
Same as Run 30 but 0 Pumpage in Comal and Hays Counties
Comal Springs



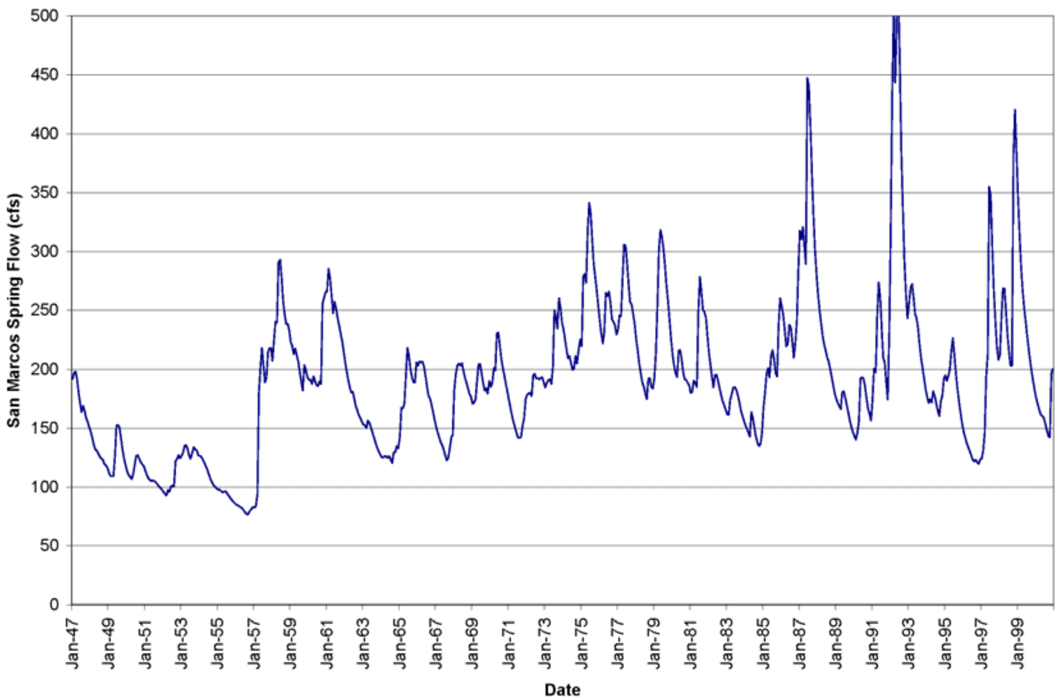
Run 32, 40,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs



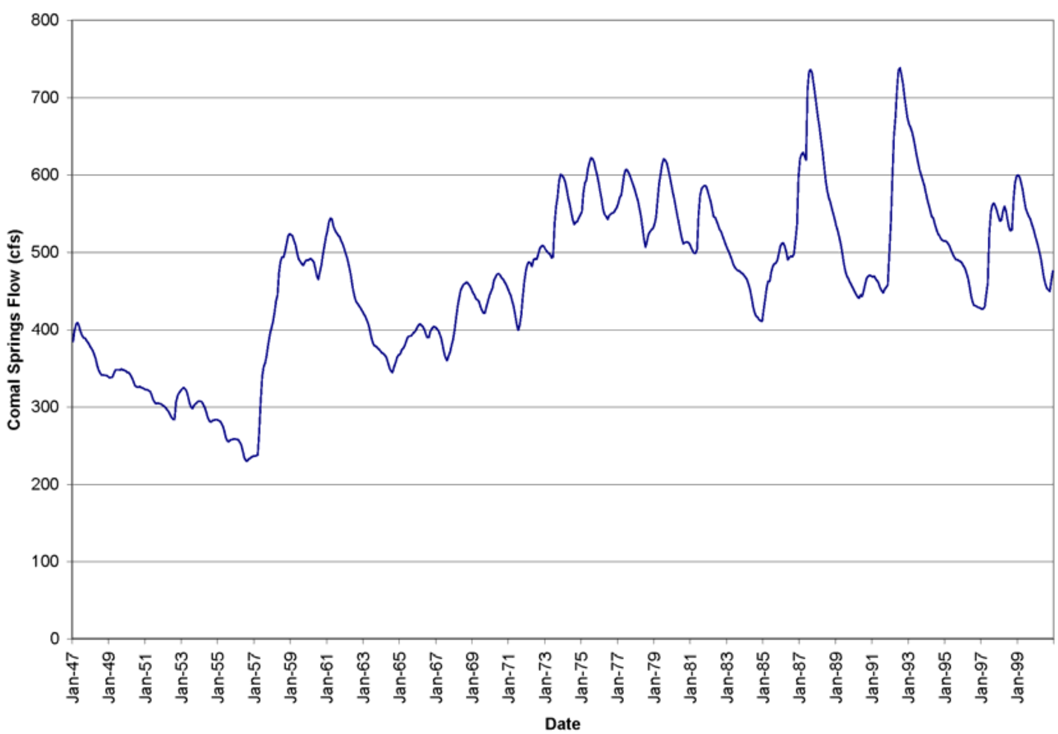
Run 32, 40,000 ac-ft/yr Pumpage, No CPM
Comal Springs

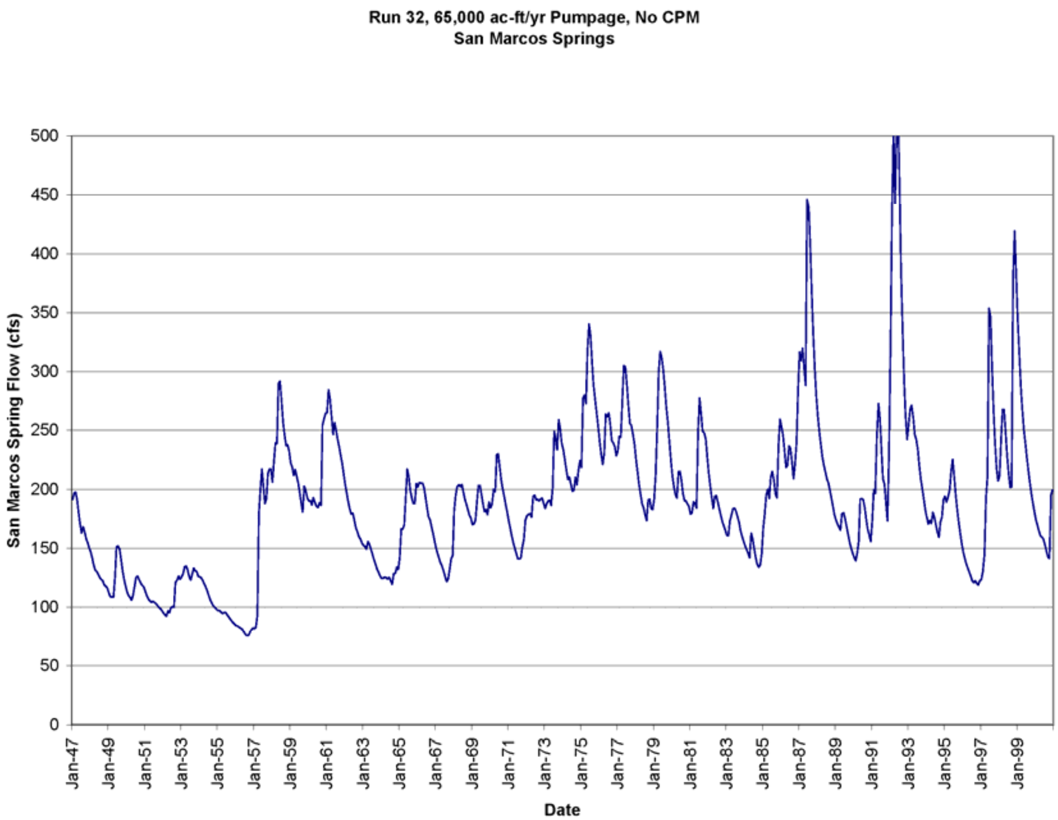


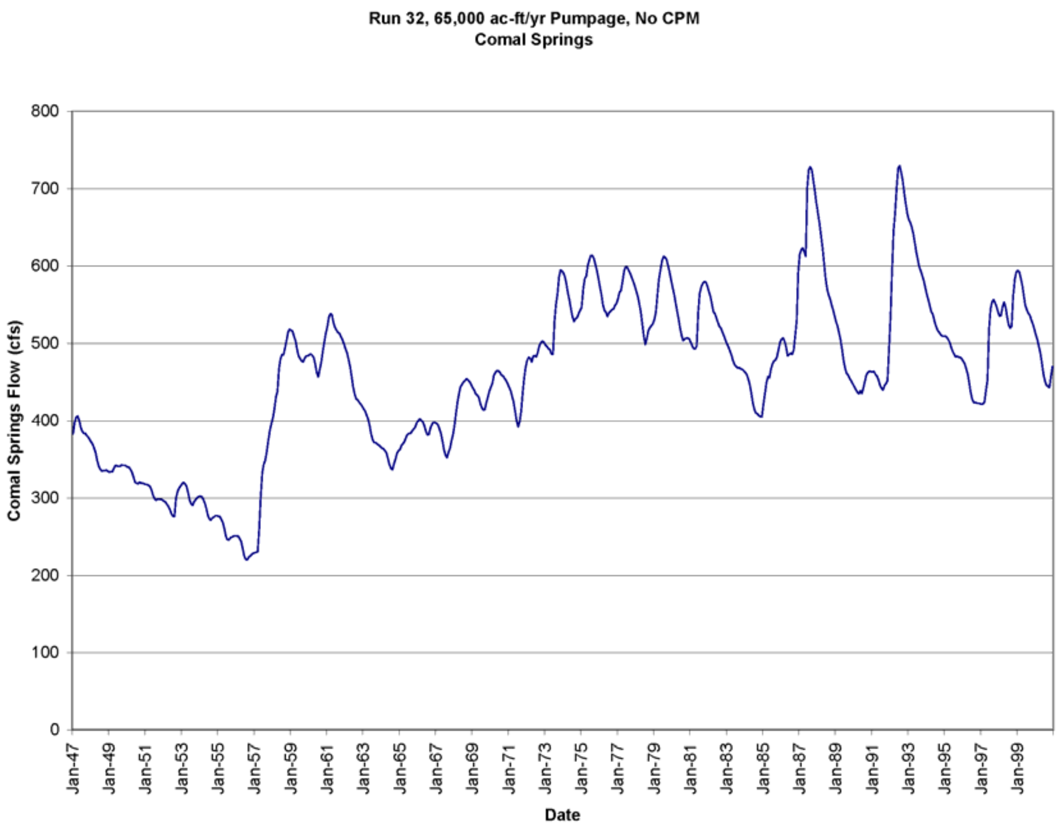
Run 32, 55,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs



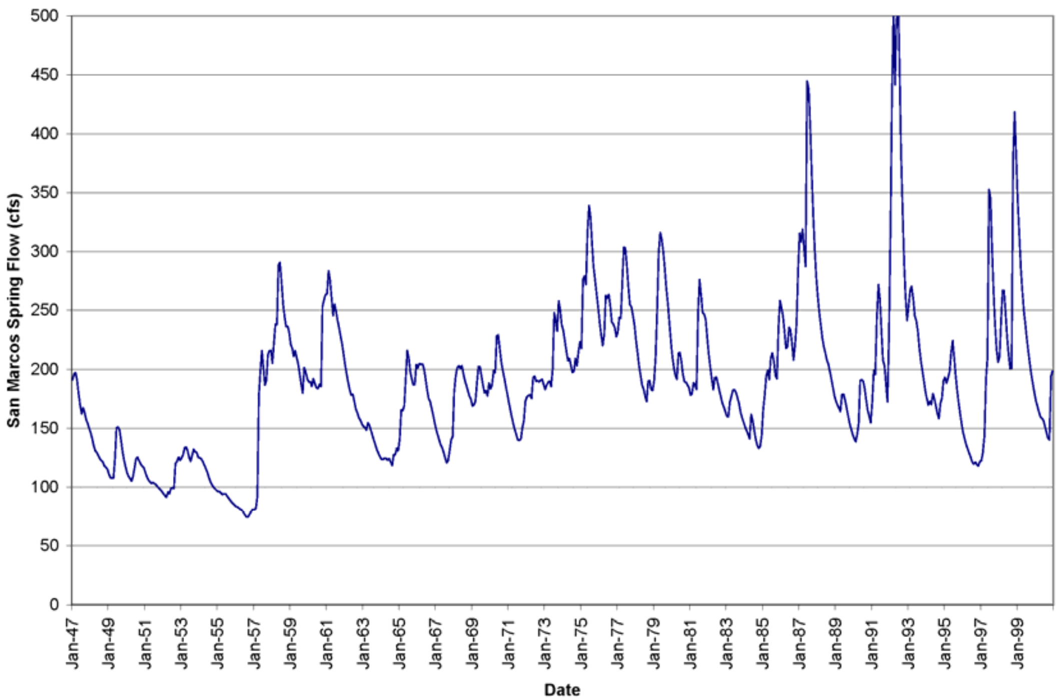
Run 32, 55,000 ac-ft/yr Pumpage, No CPM
Comal Springs



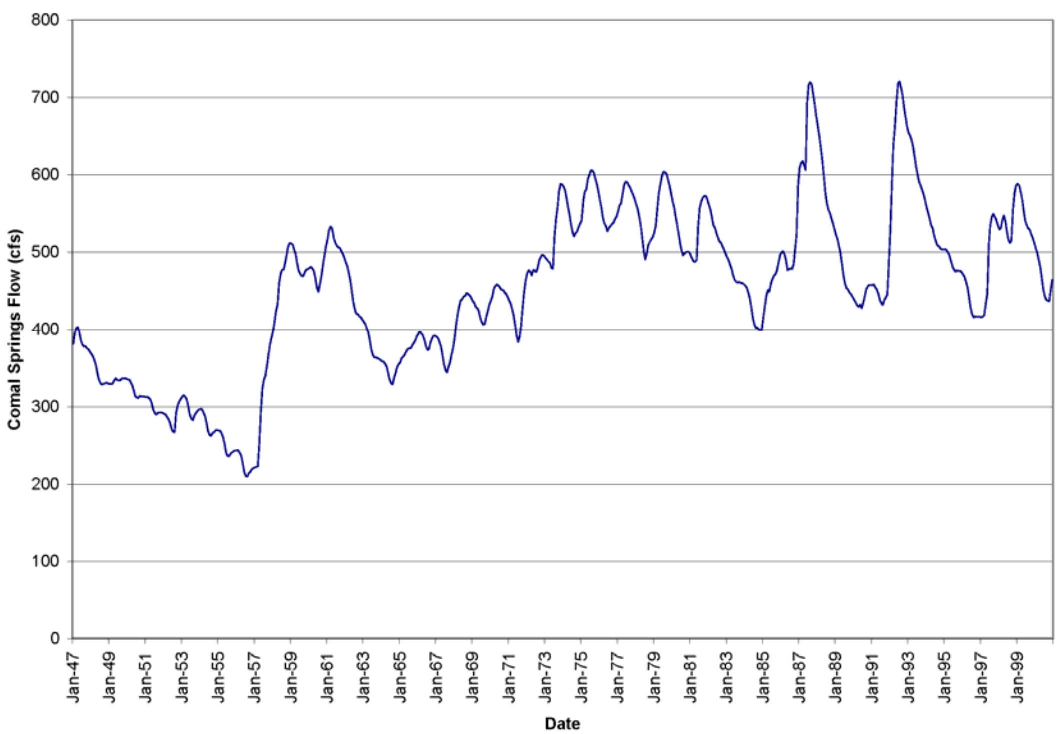

Run 32, 65,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs
San Marcos Spring Flow (cfs)
Date


Run 32, 65,000 ac-ft/yr Pumpage, No CPM
Comal Springs
Comal Springs Flow (cfs)
Date

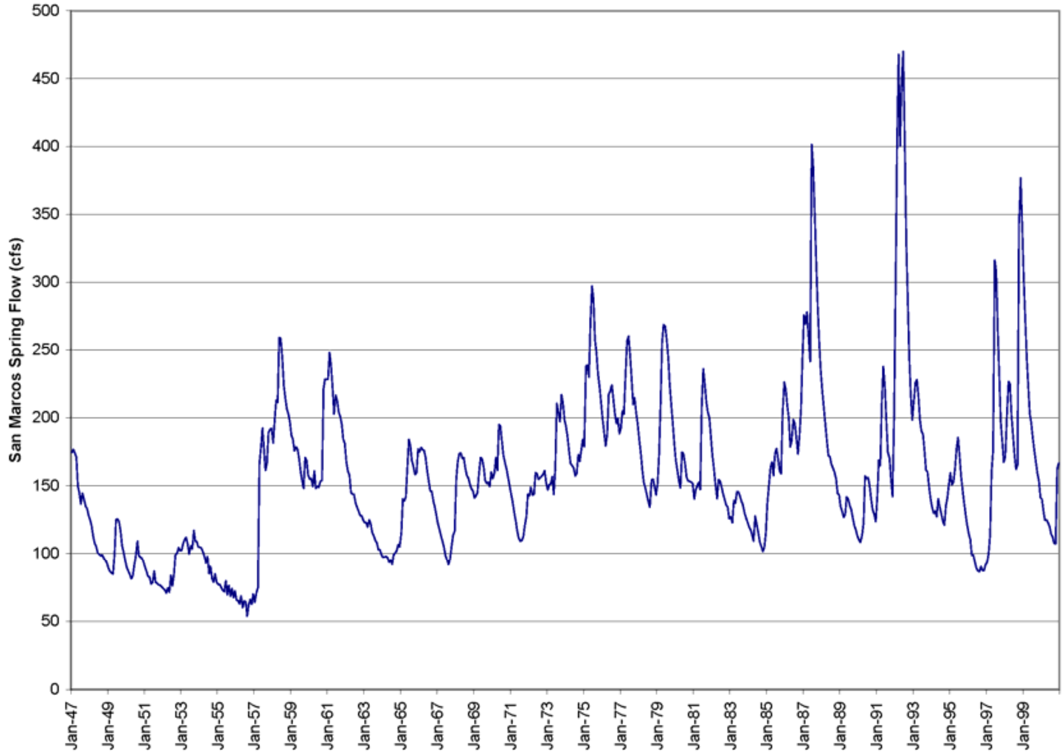
Run 32, 75,000 ac-ft/yr Pumpage, No CPM
San Marcos Springs



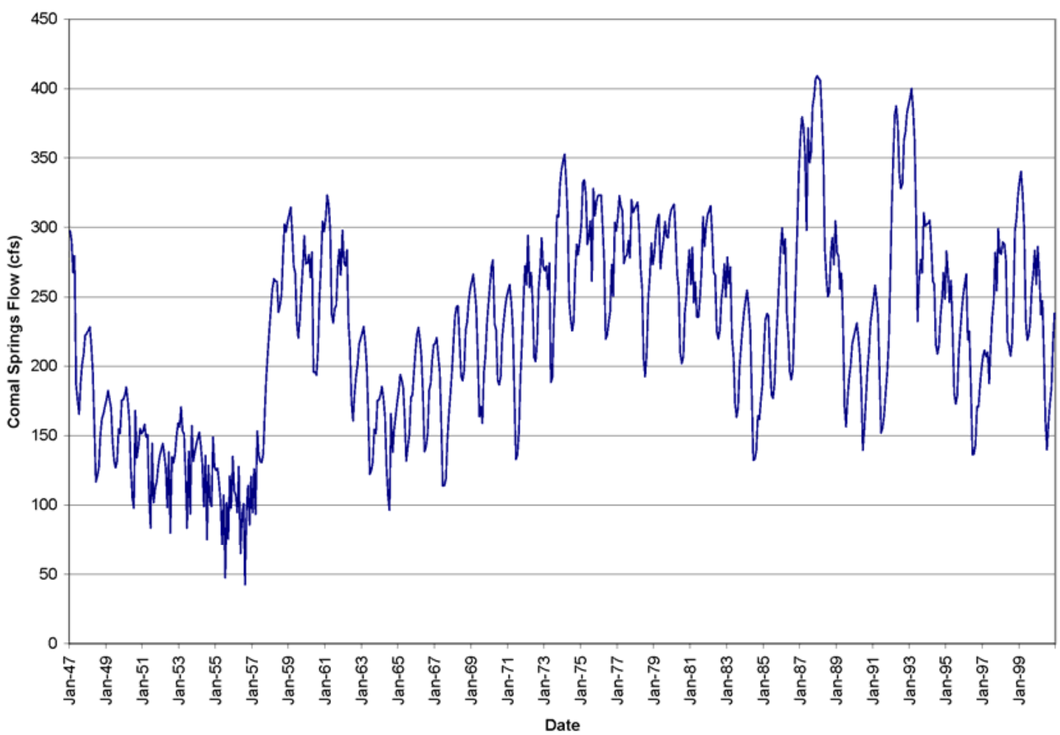
Run 32, 75,000 ac-ft/yr Pumpage, No CPM
Comal Springs

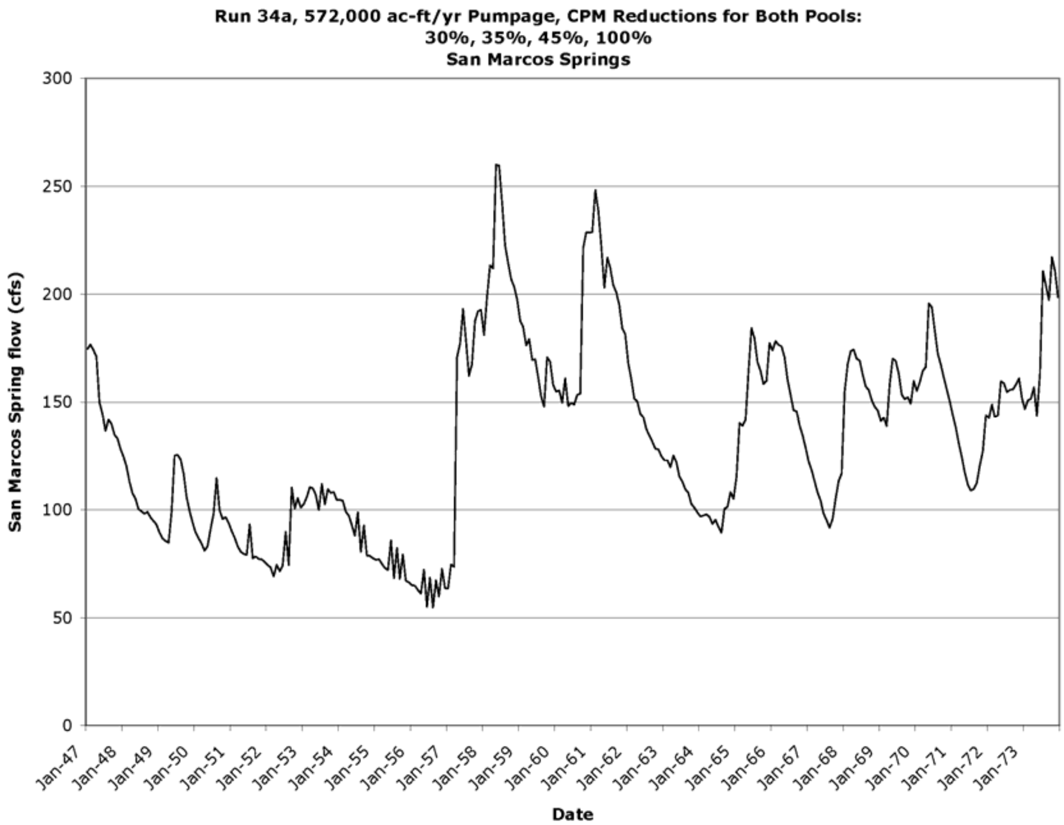


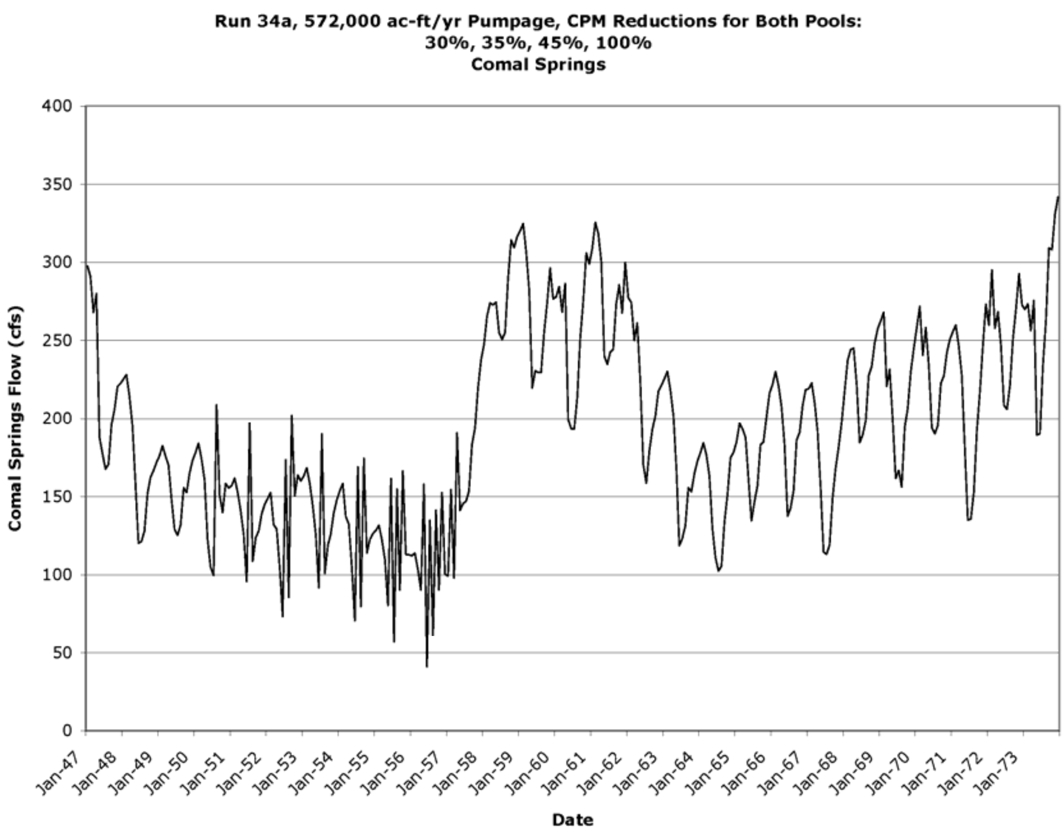
Run 33, 572,000 ac-ft/yr Pumpage, CPM Reductions are combined Run 28 and Run 29
Stage IV Reductions for both pools: 80%
San Marcos Springs

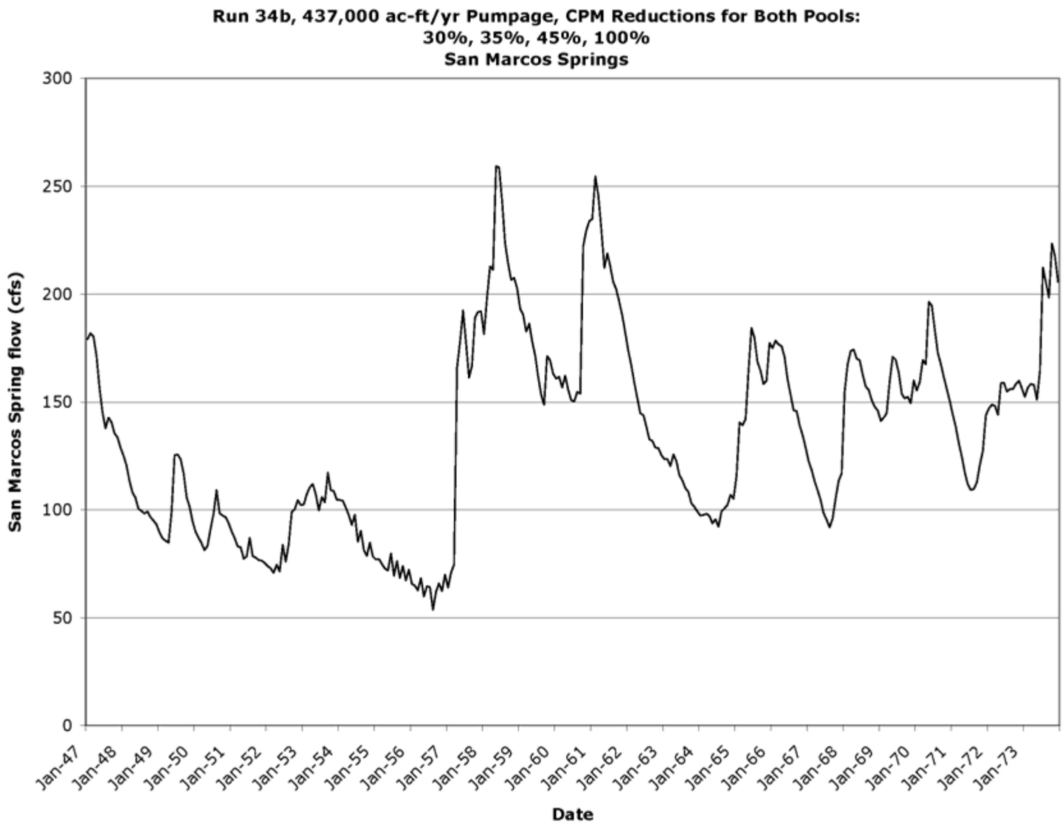


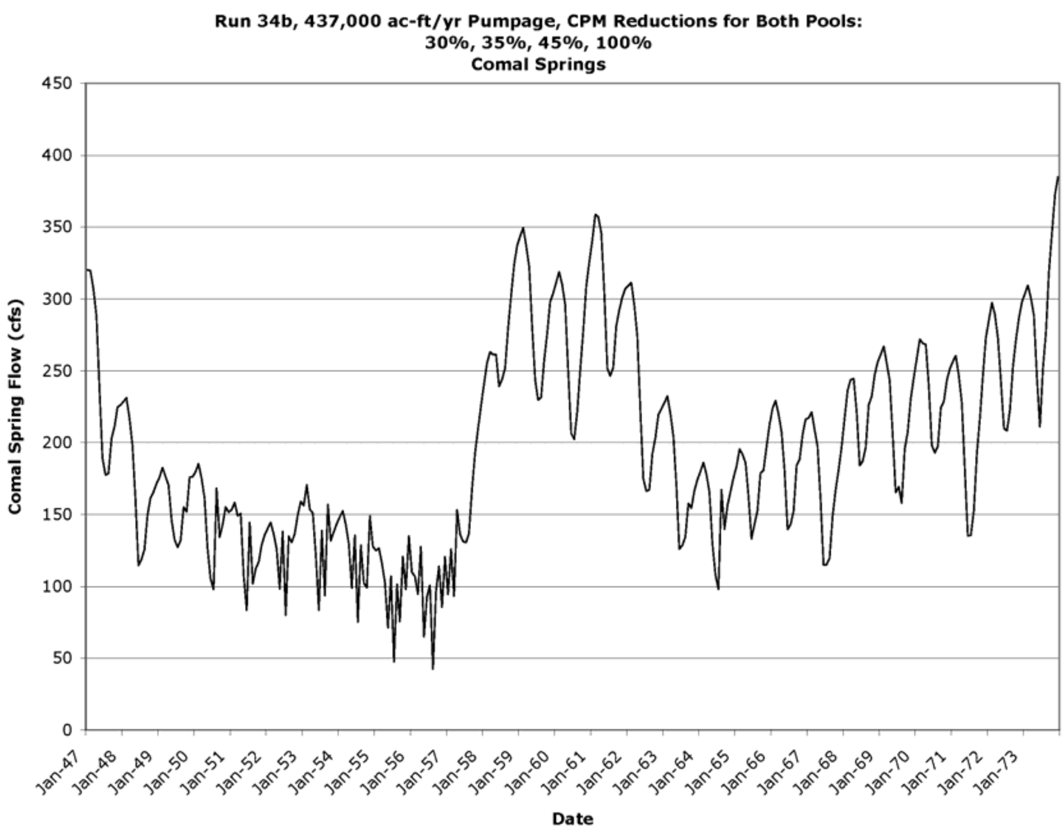
Run 33, 572,000 ac-ft/yr Pumpage, CPM Reductions are Combined Run 28 and Run 29
Stage IV Reductions for Both Pools: 80%
Comal Springs

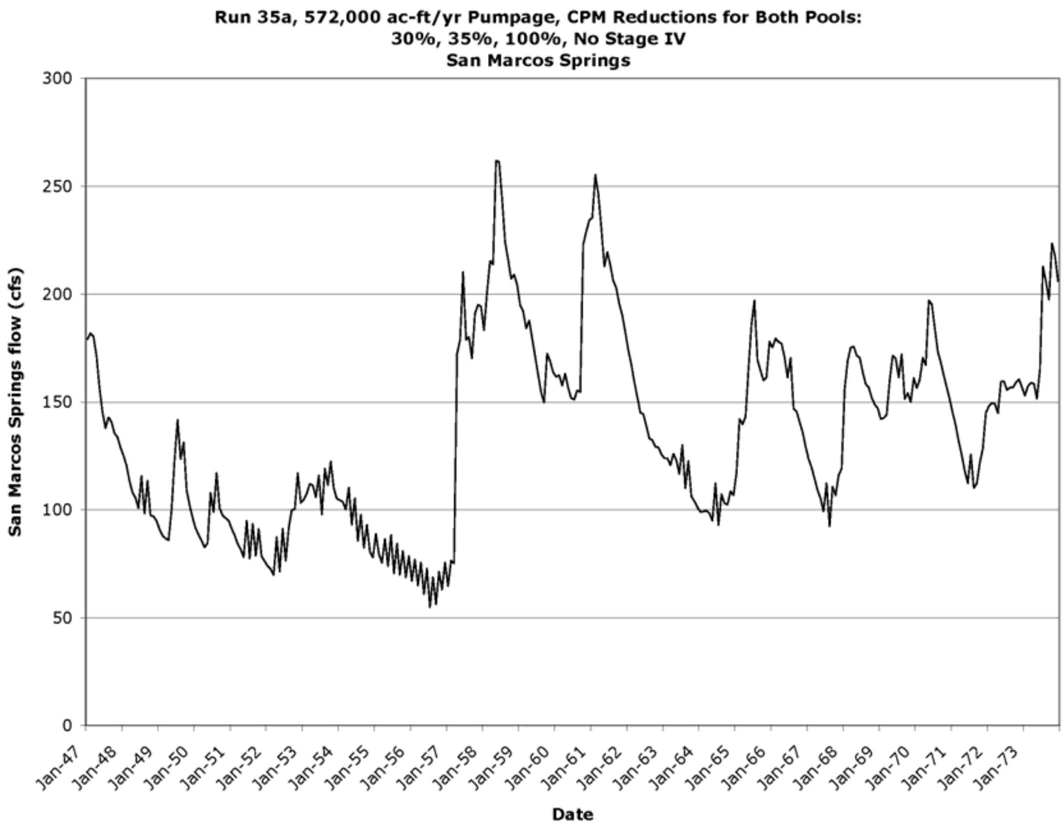


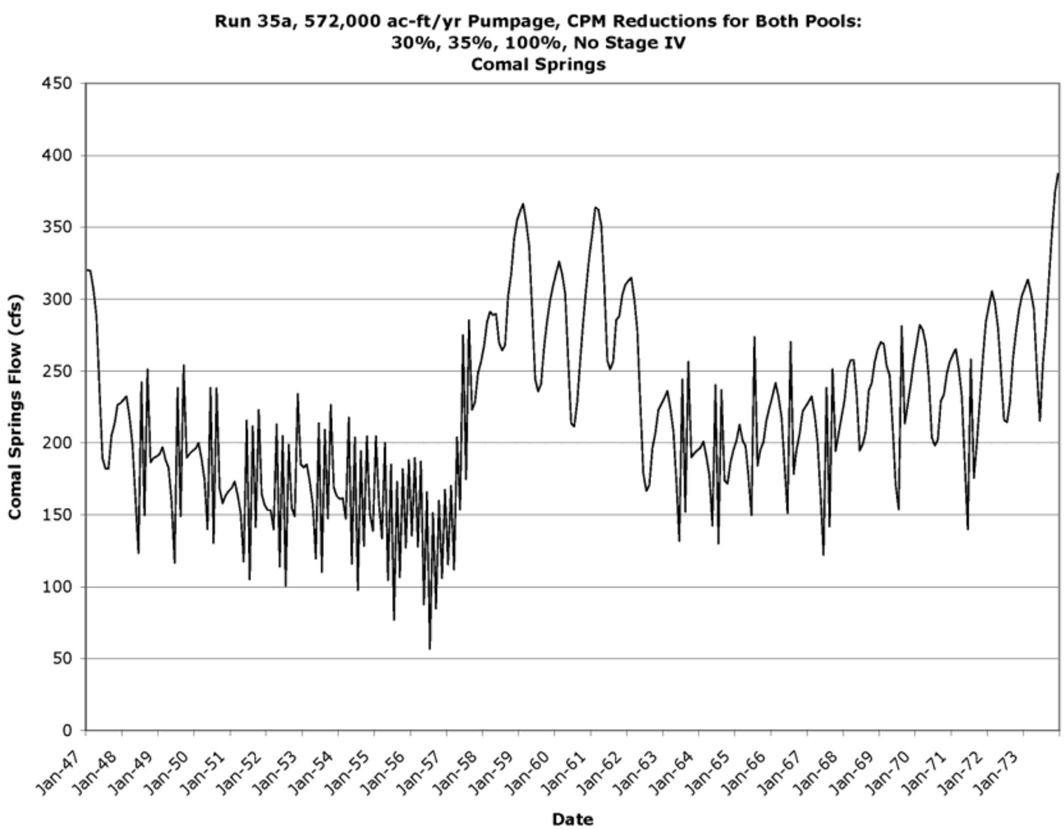

Run 34a, 572,000 ac-ft/yr Pumpage, CPM Reductions for Both Pools:
30%, 35%, 45%, 100%
San Marcos Springs
San Marcos Spring flow (cfs)
300
250
200
150
100
50
0
Jan-47
Jan-48
Jan-49
Jan-50
Jan-51
Jan-52
Jan-53
Jan-54
Jan-55
Jan-56
Jan-57
Jan-58
Jan-59
Jan-60
Jan-61
Jan-62
Jan-63
Jan-64
Jan-65
Jan-66
Jan-67
Jan-68
Jan-69
Jan-70
Jan-71
Jan-72
Jan-73
Date

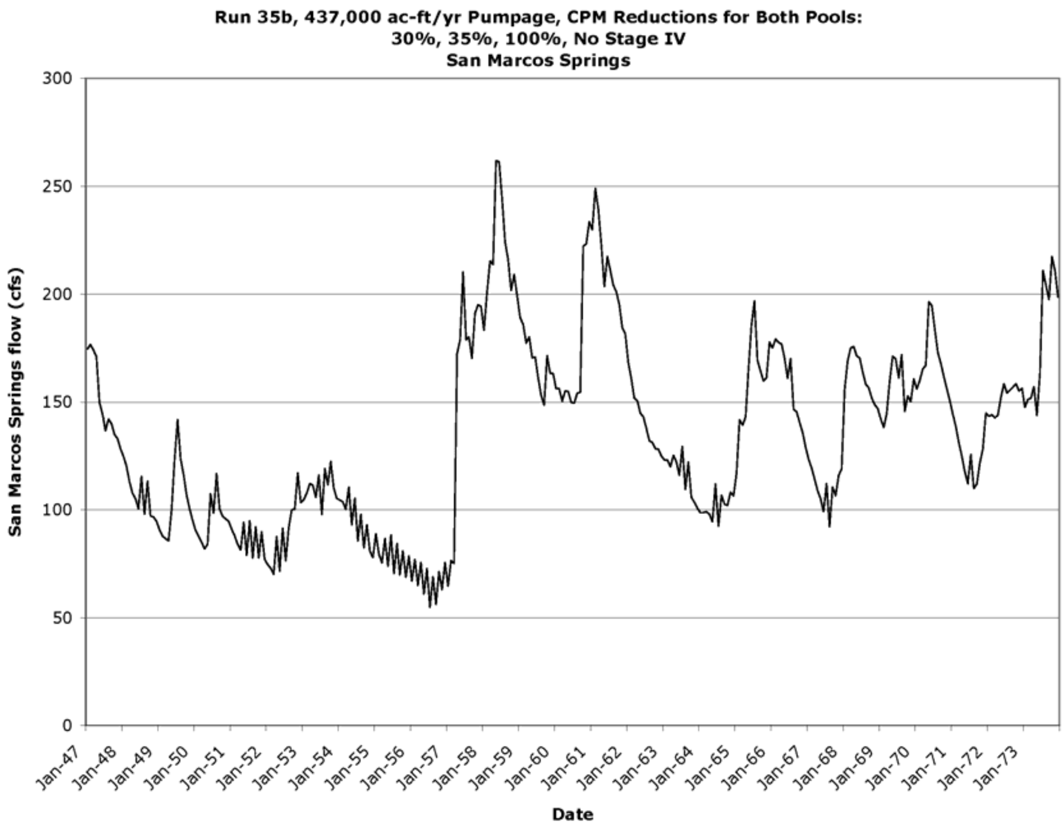

Run 34a, 572,000 ac-ft/yr Pumpage, CPM Reductions for Both Pools:
30%, 35%, 45%, 100%
Comal Springs
Comal Springs Flow (cfs)
400
350
300
250
200
150
100
50
0
Jan-47
Jan-48
Jan-49
Jan-50
Jan-51
Jan-52
Jan-53
Jan-54
Jan-55
Jan-56
Jan-57
Jan-58
Jan-59
Jan-60
Jan-61
Jan-62
Jan-63
Jan-64
Jan-65
Jan-66
Jan-67
Jan-68
Jan-69
Jan-70
Jan-71
Jan-72
Jan-73
Date

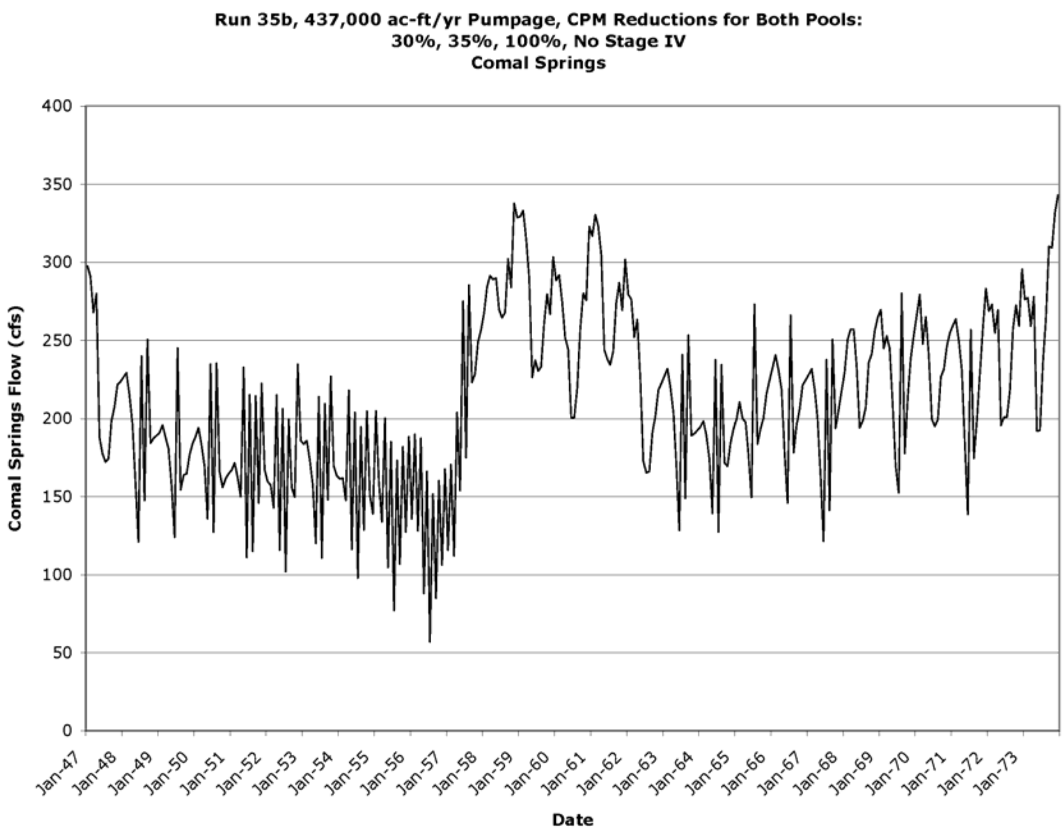

Run 34b, 437,000 ac-ft/yr Pumpage, CPM Reductions for Both Pools:
30%, 35%, 45%, 100%
San Marcos Springs
San Marcos Spring flow (cfs)
0
50
100
150
200
250
300
Jan-47
Jan-48
Jan-49
Jan-50
Jan-51
Jan-52
Jan-53
Jan-54
Jan-55
Jan-56
Jan-57
Jan-58
Jan-59
Jan-60
Jan-61
Jan-62
Jan-63
Jan-64
Jan-65
Jan-66
Jan-67
Jan-68
Jan-69
Jan-70
Jan-71
Jan-72
Jan-73
Date

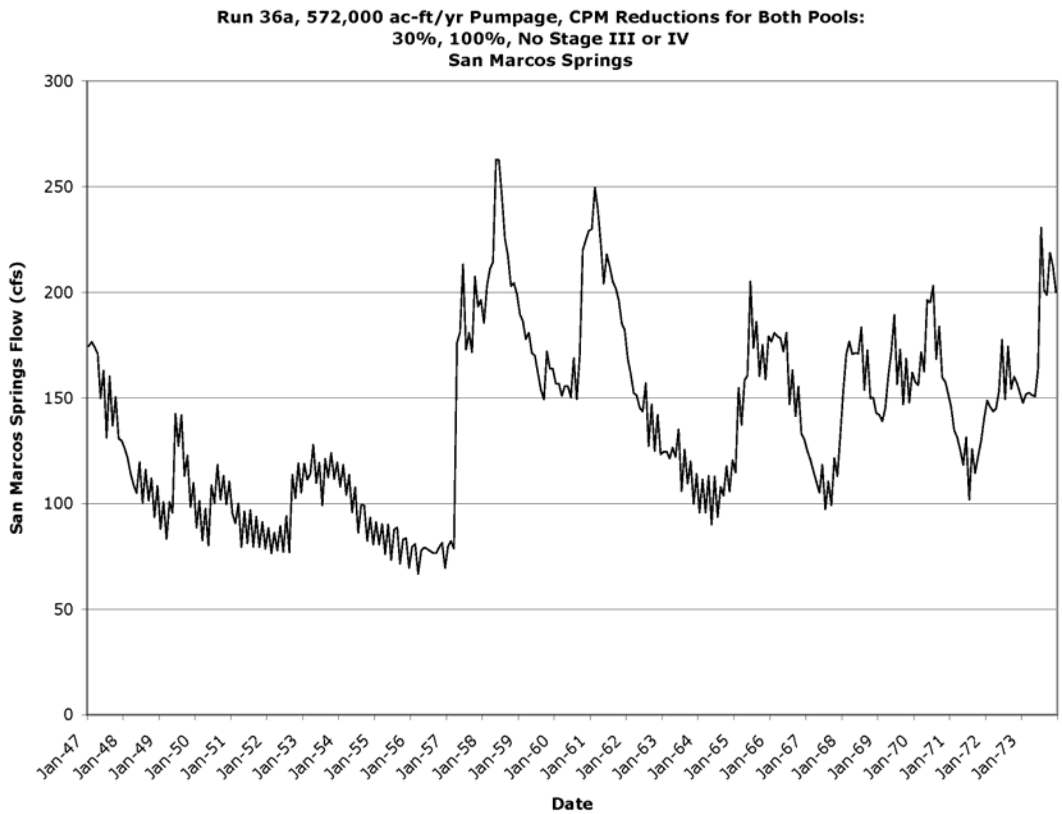

Run 34b, 437,000 ac-ft/yr Pumpage, CPM Reductions for Both Pools:
30%, 35%, 45%, 100%
Comal Springs
Comal Spring Flow (cfs)
0
50
100
150
200
250
300
350
400
450
Jan-47
Jan-48
Jan-49
Jan-50
Jan-51
Jan-52
Jan-53
Jan-54
Jan-55
Jan-56
Jan-57
Jan-58
Jan-59
Jan-60
Jan-61
Jan-62
Jan-63
Jan-64
Jan-65
Jan-66
Jan-67
Jan-68
Jan-69
Jan-70
Jan-71
Jan-72
Jan-73
Date

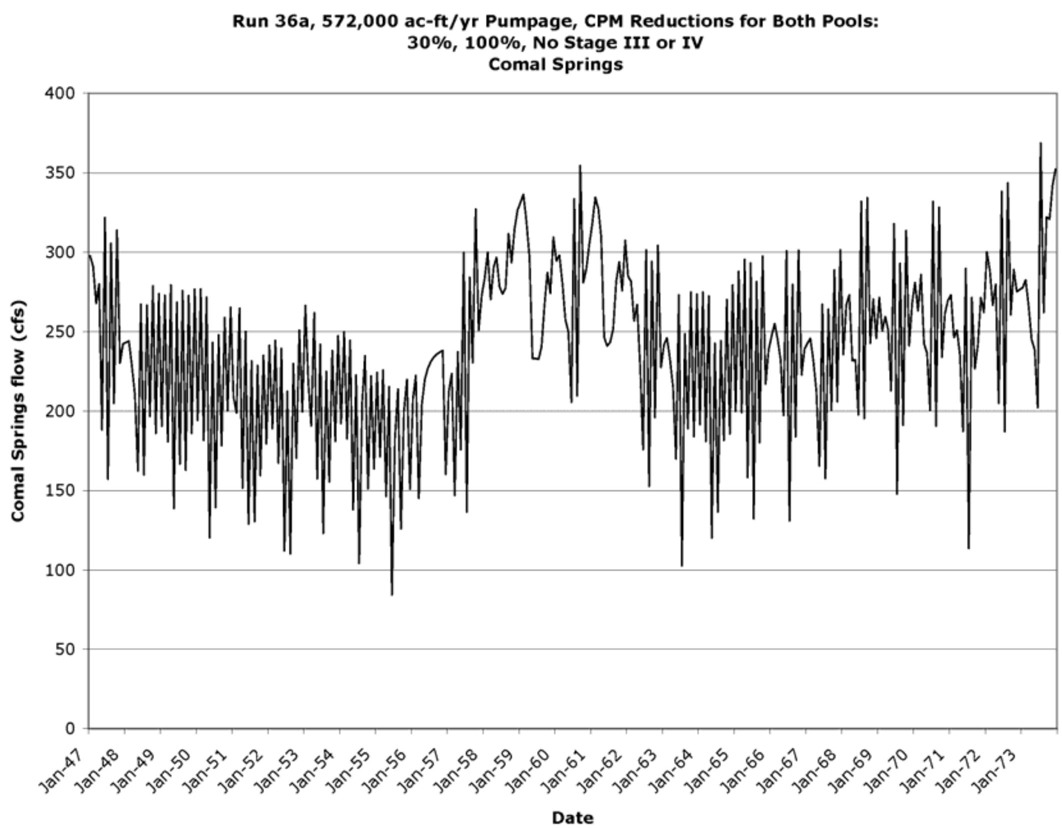

Run 35a, 572,000 ac-ft/yr Pumpage, CPM Reductions for Both Pools:
30%, 35%, 100%, No Stage IV
San Marcos Springs
San Marcos Springs flow (cfs)
0
50
100
150
200
250
300
Jan-47
Jan-48
Jan-49
Jan-50
Jan-51
Jan-52
Jan-53
Jan-54
Jan-55
Jan-56
Jan-57
Jan-58
Jan-59
Jan-60
Jan-61
Jan-62
Jan-63
Jan-64
Jan-65
Jan-66
Jan-67
Jan-68
Jan-69
Jan-70
Jan-71
Jan-72
Jan-73
Date


Run 35a, 572,000 ac-ft/yr Pumpage, CPM Reductions for Both Pools:
30%, 35%, 100%, No Stage IV
Comal Springs
Comal Springs Flow (cfs)
0
50
100
150
200
250
300
350
400
450
Jan-47
Jan-48
Jan-49
Jan-50
Jan-51
Jan-52
Jan-53
Jan-54
Jan-55
Jan-56
Jan-57
Jan-58
Jan-59
Jan-60
Jan-61
Jan-62
Jan-63
Jan-64
Jan-65
Jan-66
Jan-67
Jan-68
Jan-69
Jan-70
Jan-71
Jan-72
Jan-73
Date

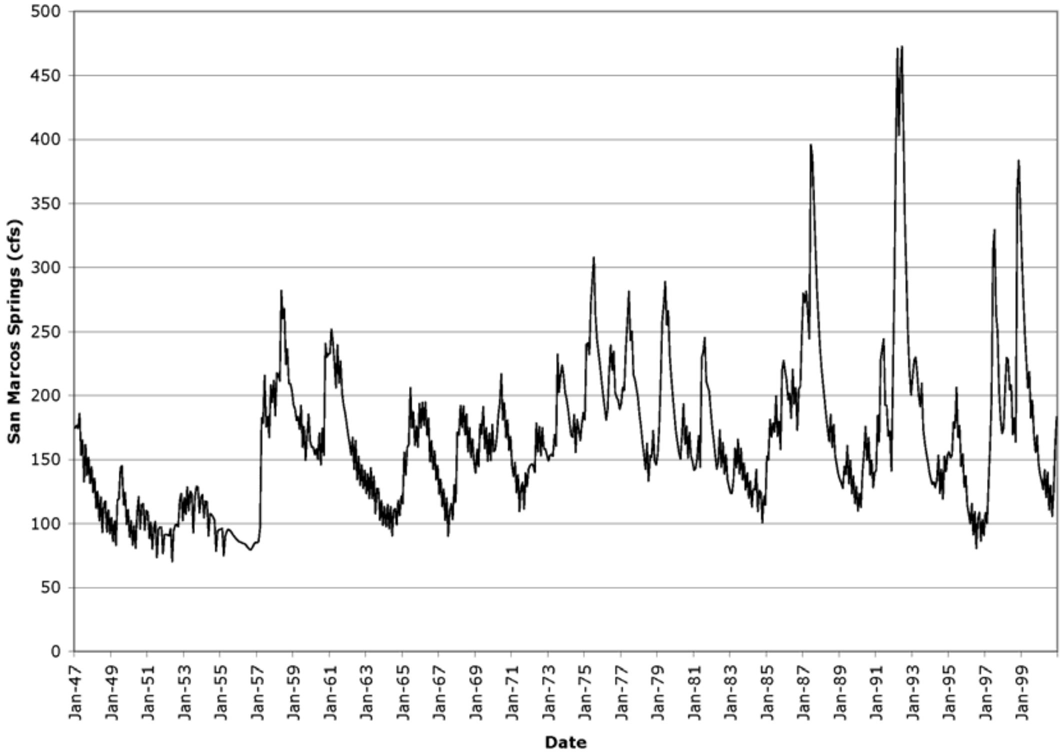

Run 35b, 437,000 ac-ft/yr Pumpage, CPM Reductions for Both Pools:
30%, 35%, 100%, No Stage IV
San Marcos Springs
San Marcos Springs flow (cfs)
300
250
200
150
100
50
0
Jan-47
Jan-48
Jan-49
Jan-50
Jan-51
Jan-52
Jan-53
Jan-54
Jan-55
Jan-56
Jan-57
Jan-58
Jan-59
Jan-60
Jan-61
Jan-62
Jan-63
Jan-64
Jan-65
Jan-66
Jan-67
Jan-68
Jan-69
Jan-70
Jan-71
Jan-72
Jan-73
Date


Run 35b, 437,000 ac-ft/yr Pumpage, CPM Reductions for Both Pools:
30%, 35%, 100%, No Stage IV
Comal Springs
Comal Springs Flow (cfs)
400
350
300
250
200
150
100
50
0
Jan-47
Jan-48
Jan-49
Jan-50
Jan-51
Jan-52
Jan-53
Jan-54
Jan-55
Jan-56
Jan-57
Jan-58
Jan-59
Jan-60
Jan-61
Jan-62
Jan-63
Jan-64
Jan-65
Jan-66
Jan-67
Jan-68
Jan-69
Jan-70
Jan-71
Jan-72
Jan-73
Date

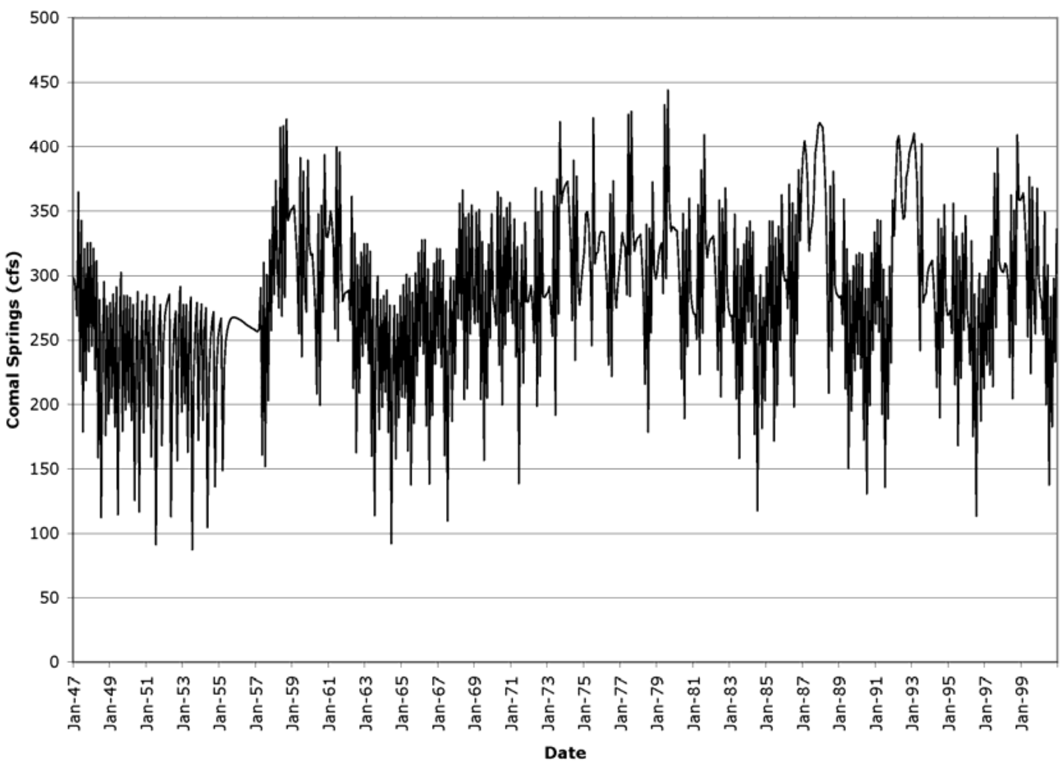

Run 36a, 572,000 ac-ft/yr Pumpage, CPM Reductions for Both Pools:
30%, 100%, No Stage III or IV
San Marcos Springs
San Marcos Springs Flow (cfs)
300
250
200
150
100
50
0
Jan-47
Jan-48
Jan-49
Jan-50
Jan-51
Jan-52
Jan-53
Jan-54
Jan-55
Jan-56
Jan-57
Jan-58
Jan-59
Jan-60
Jan-61
Jan-62
Jan-63
Jan-64
Jan-65
Jan-66
Jan-67
Jan-68
Jan-69
Jan-70
Jan-71
Jan-72
Jan-73
Date

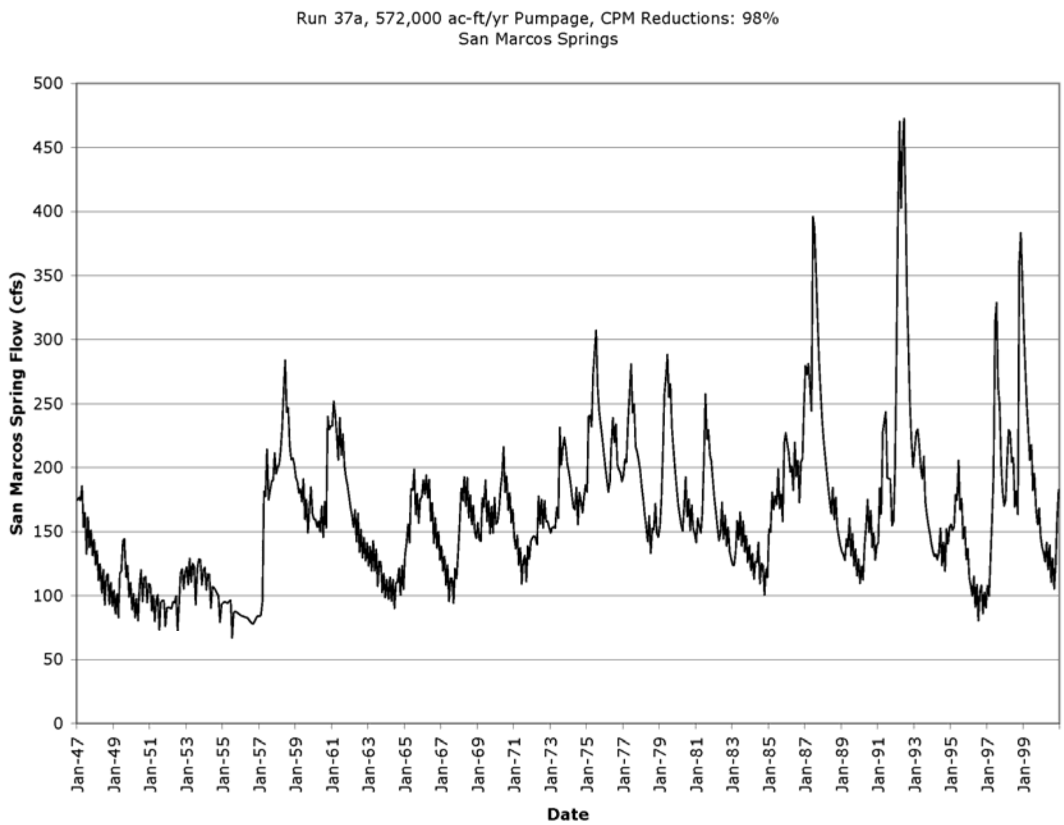

Run 36a, 572,000 ac-ft/yr Pumpage, CPM Reductions for Both Pools:
30%, 100%, No Stage III or IV
Comal Springs
Comal Springs flow (cfs)
400
350
300
250
200
150
100
50
0
Jan-47
Jan-48
Jan-49
Jan-50
Jan-51
Jan-52
Jan-53
Jan-54
Jan-55
Jan-56
Jan-57
Jan-58
Jan-59
Jan-60
Jan-61
Jan-62
Jan-63
Jan-64
Jan-65
Jan-66
Jan-67
Jan-68
Jan-69
Jan-70
Jan-71
Jan-72
Jan-73
Date

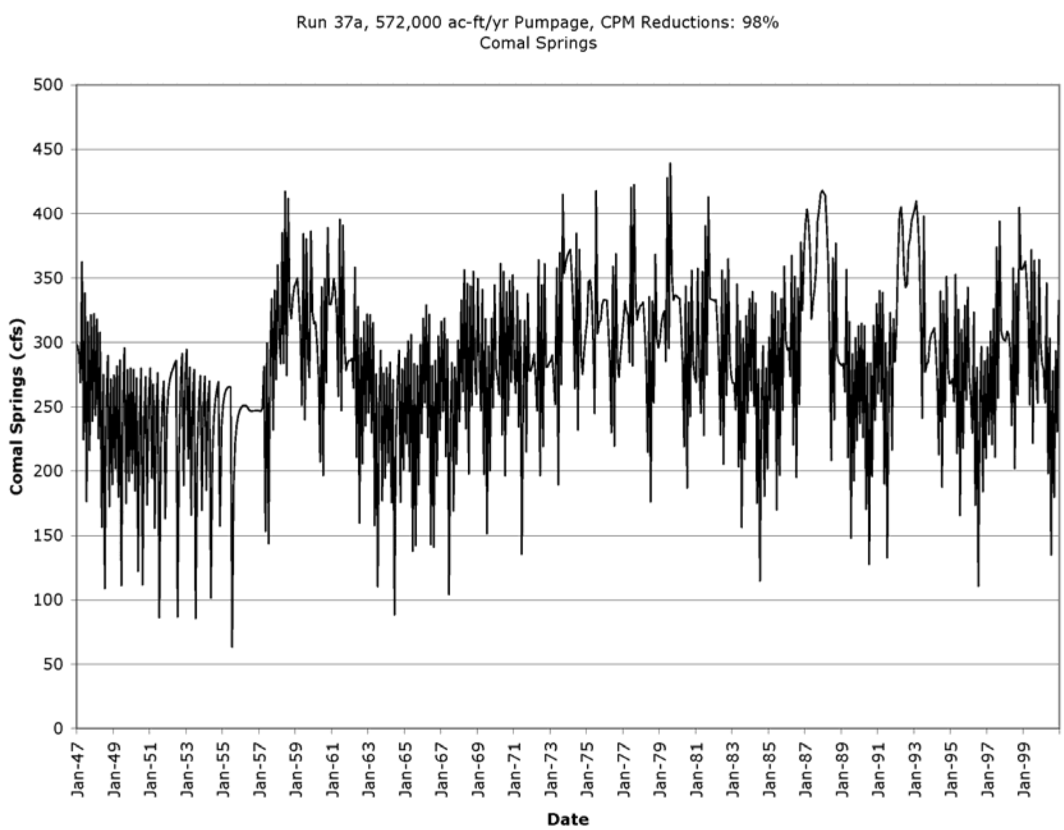
Run 37a, 572,000 ac-ft/yr Pumpage, CPM Reductions: 100%
San Marcos Springs

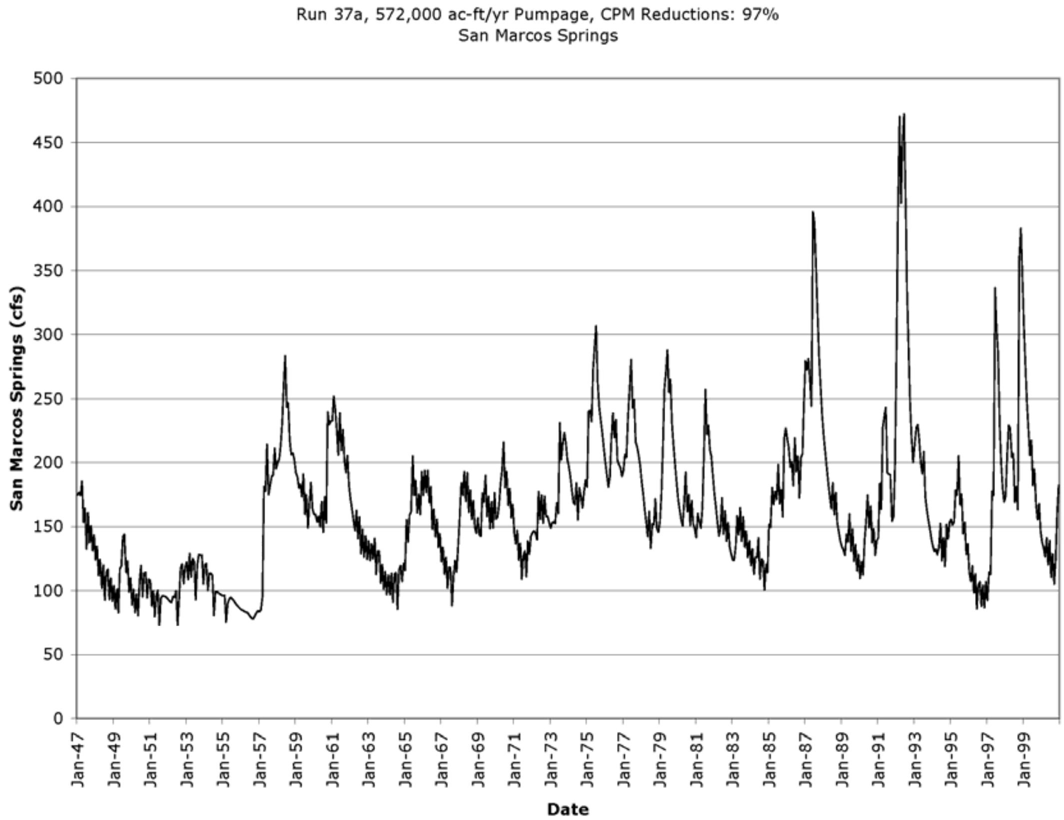


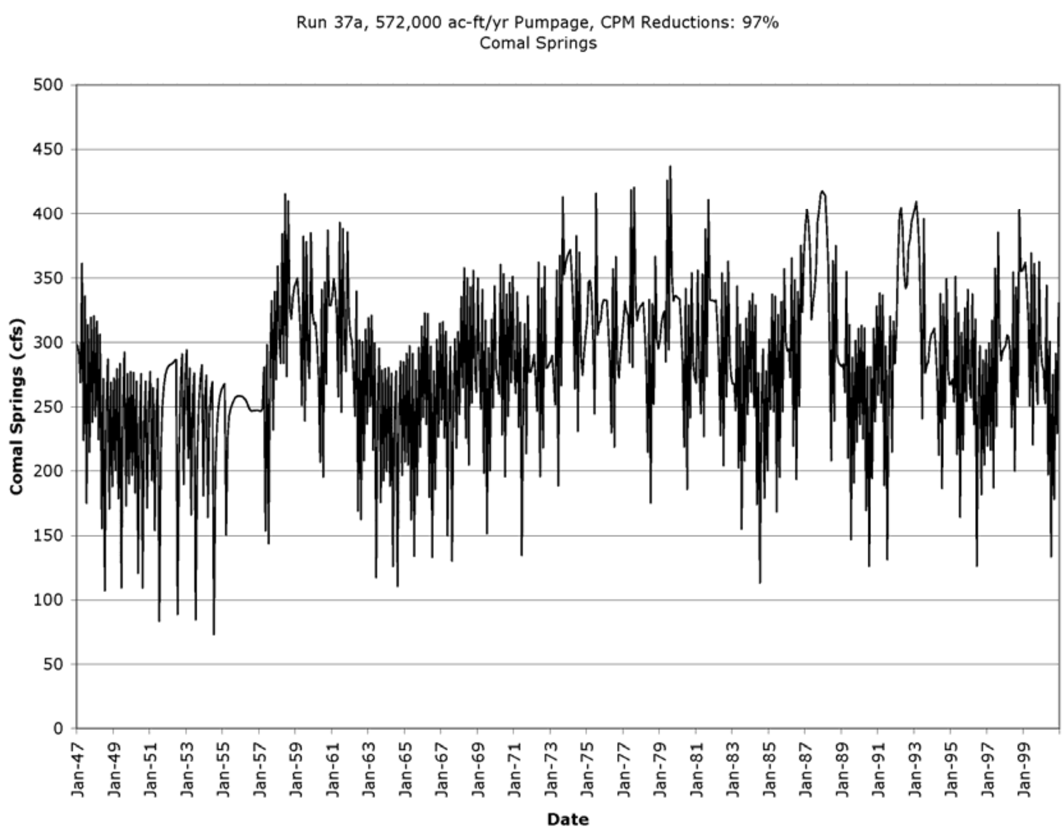
Run 37a, 572,000 ac-ft/yr Pumpage, CPM Reductions: 100%
Comal Springs



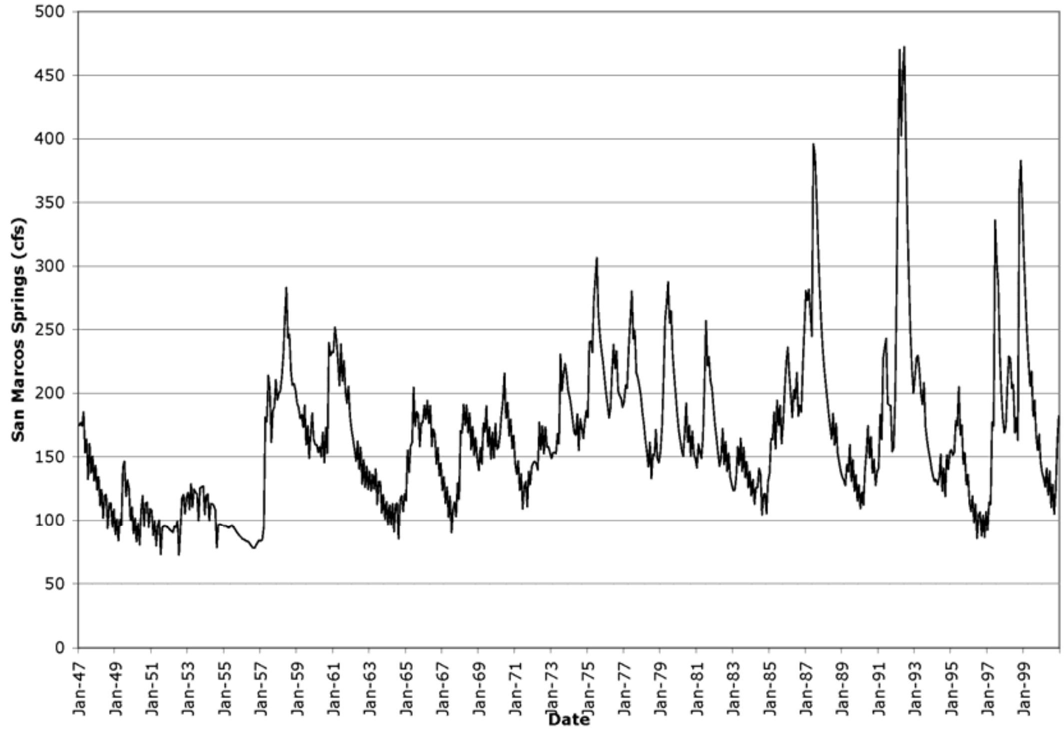

Run 37a, 572,000 ac-ft/yr Pumpage, CPM Reductions: 98%
San Marcos Springs
San Marcos Spring Flow (cfs)
Date


Run 37a, 572,000 ac-ft/yr Pumpage, CPM Reductions: 98%
Comal Springs
Comal Springs (cfs)
Date

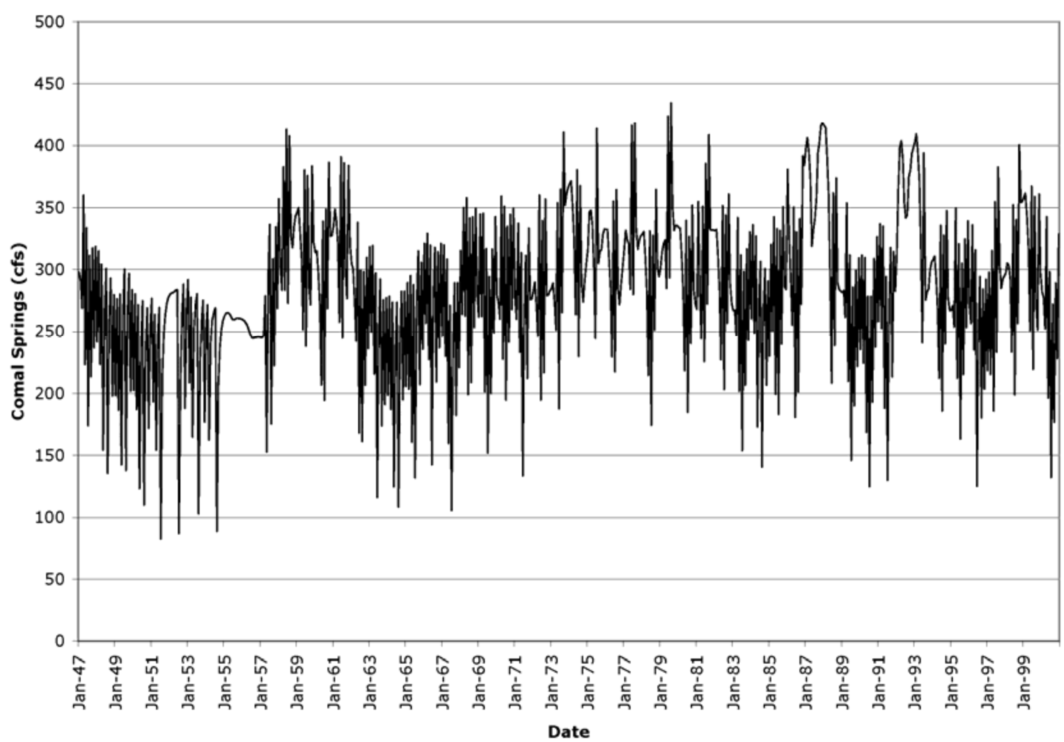

Run 37a, 572,000 ac-ft/yr Pumpage, CPM Reductions: 97%
San Marcos Springs
San Marcos Springs (cfs)
Date

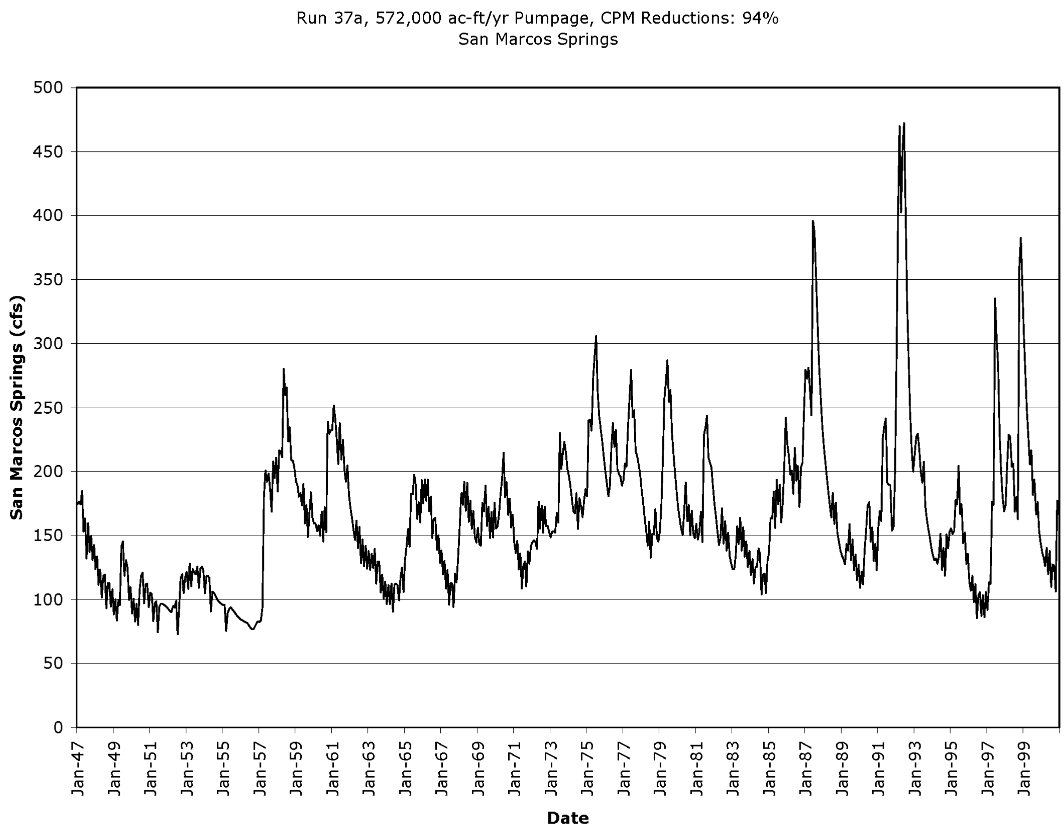

Run 37a, 572,000 ac-ft/yr Pumpage, CPM Reductions: 97%
Comal Springs
Comal Springs (cfs)
Date

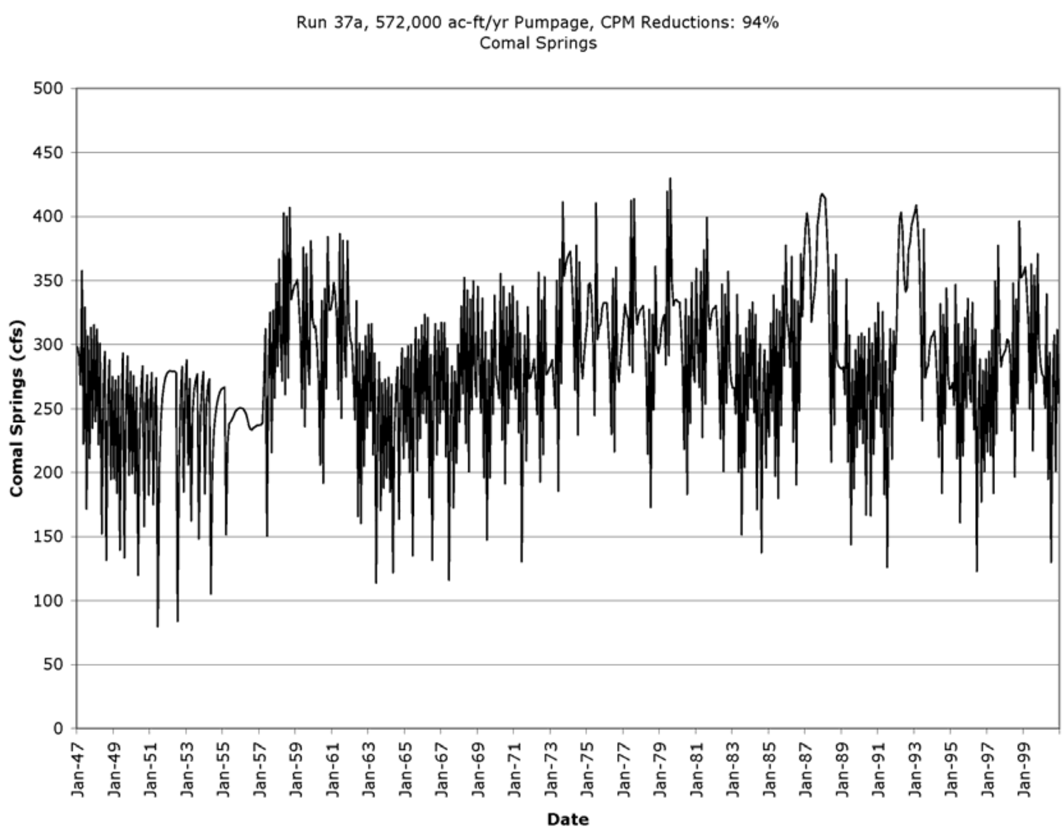
Run 37a, 572,000 ac-ft/yr Pumpage, CPM Reductions: 96%
San Marcos Springs

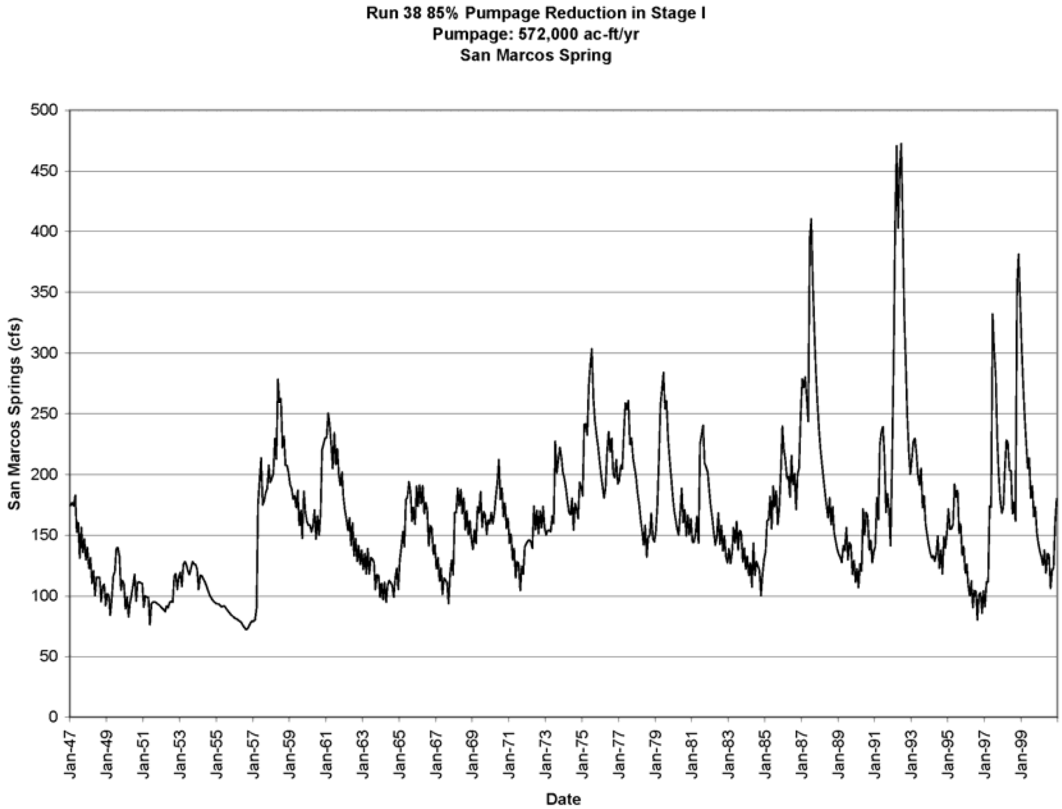


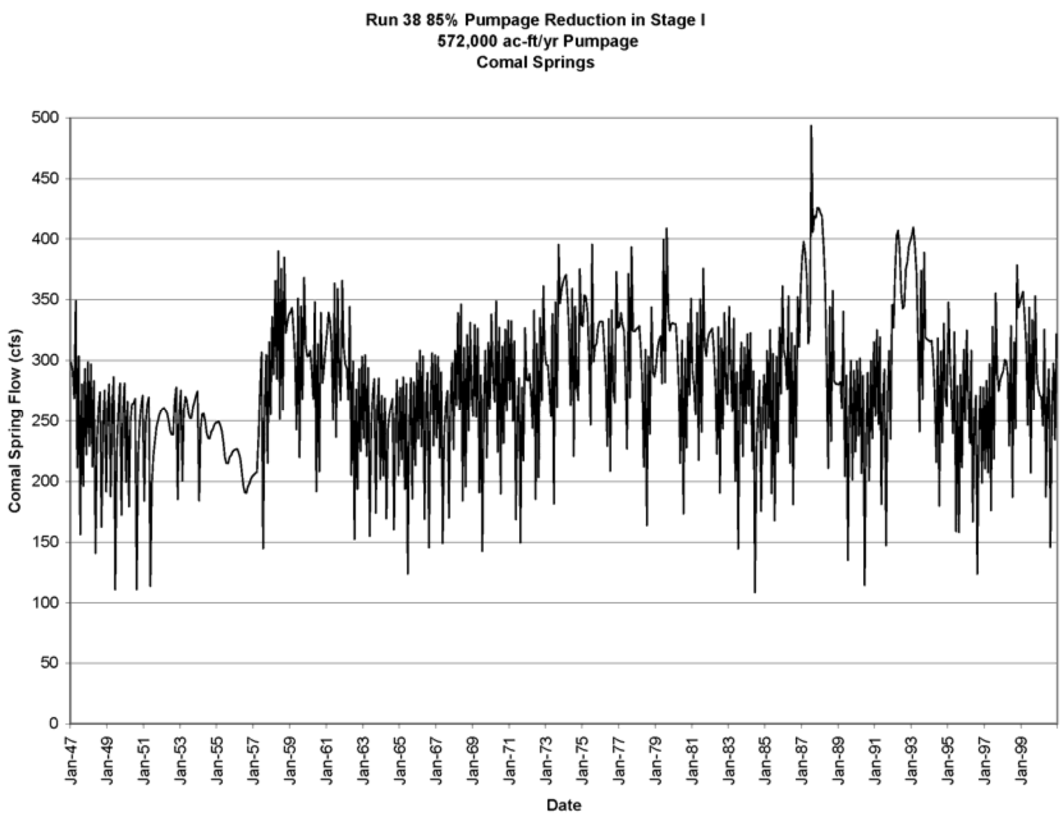
Run 37a, 572,000 ac-ft/yr Pumpage, CPM Reductions: 96%
Comal Springs




Run 37a, 572,000 ac-ft/yr Pumpage, CPM Reductions: 94%
San Marcos Springs
San Marcos Springs (cfs)
0
50
100
150
200
250
300
350
400
450
500
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99
Date


Run 37a, 572,000 ac-ft/yr Pumpage, CPM Reductions: 94%
Comal Springs
Comal Springs (cfs)
0
50
100
150
200
250
300
350
400
450
500
Jan-47
Jan-49
Jan-51
Jan-53
Jan-55
Jan-57
Jan-59
Jan-61
Jan-63
Jan-65
Jan-67
Jan-69
Jan-71
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99
Date


Run 38 85% Pumpage Reduction in Stage I
Pumpage: 572,000 ac-ft/yr
San Marcos Spring
San Marcos Springs (cfs)
Date


Run 38 85% Pumpage Reduction in Stage I
572,000 ac-ft/yr Pumpage
Comal Springs
Comal Spring Flow (cfs)
Date

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Appendix H.
Edwards Aquifer model run reports and output files

See attached compact disk or folder of files.

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