Characterization of High Pulse Flows at Ungaged Locations for the Purpose of Applying Environmental Flow Standards

Alison Wood

December 1, 2011

GIS in Water Resources – Dr. David Maidment

The University of Texas at Austin

Table of Contents

Table of Figures

Table of Tables

Introduction – Environmental Flows and the TCEQ

Human users of water have come to recognize that we must keep our water resources healthy so that they – and we, dependent on them – may thrive for many years to come. For streams and rivers to remain healthy, they must maintain certain levels of flow. These minimum flow levels vary with season and year, and are collectively called “environmental flows.” It is not only important that certain minimum levels are met; the variability over time is also crucial to keeping a river healthy. To describe the variability of flows, environmental flow regimes can be developed that categorize flows in some number of different ways. One common categorization uses four classes: subsistence flow, base flow, high flow pulses, and overbank flows [1]. The research described here focuses on high flow pulses.

High flow pulses are defined as “relatively short-duration, high flows within the stream channel that occur during or immediately following a storm event” [2]. According to research done by Professor Robyn Watts at Charles Sturt University in Australia, “water ‘pulses’ trigger a release of organic matter into the river and within hours you get a bacterial response which plays a vital role in the river’s food web. This in turn triggers organisms that feed on the bacteria and that flows [on to] other groups in the web” [3]. Clearly it is not only constant minimum flows that are necessary to maintain healthy ecosystems in rivers: high flow pulses are also critical.

Environmental flow regimes, including high flow pulses, are of interest to the Texas Commission on Environmental Quality (TCEQ), as it is tasked with “[protecting] our state's human and natural resources consistent with sustainable economic development,” which necessarily includes a “goal…[of] clean water” [4]. Since the adoption of Texas Senate Bill 3 in 2007, the TCEQ has followed “an aggressive schedule for determining environmental flow standards adequate to support a sound ecological environment in the State’s river basins and bay systems” [1]. An important part of establishing those standards is defining high flow pulses at various locations in each basin.

The Problem – Defining Environmental Flows at Ungaged Locations

It is not enough for TCEQ to establish standards – it must enforce those standards if Texas’s waters are to be maintained in good health. There is some difficulty in enforcement, however, because the standards are defined only at a relatively small number of specified gage locations, while water withdrawals for human use take place in many locations across each basin. If a withdrawal (a.k.a. diversion) takes place on a tributary stream and the nearest gage location named in the standards is downstream on the main stem of the basin's major river, a single high pulse flow event will have different characteristics at the diversion point and at the gage.

Flow events can be characterized using five primary components: the magnitude of the pulse, the frequency (how often a similar pulse occurs in the same location), the duration of the pulse event, the timing of the event (i.e. when it occurs), and the rate of change of flow at the beginning and end of the event [1]. While a single storm is likely to produce pulses at both upstream and downstream locations, it is easy to see that these five characteristics will change as the water flows from one location to the other. For example, it takes time for the water to flow downstream: this means that the large flow of water will pass the upstream point before it reaches the downstream point, which makes the timing of the pulse different at the two points. The large flow of water that passes the upstream point may also be joined by large flows from other tributaries joining the main stem, so that there will be a much larger flow at the downstream point than at the upstream point: the magnitude is different at the two points. Similarly, frequency, duration, and rate of change of flow differ between points within a basin.

Because of these spatial variations, the characteristics that define a high flow pulse at a gage location do not adequately define a high flow pulse at another, ungaged location. But diversions can take place at any location within a basin, not just at or near gages. TCEQ needs to be able to enforce environmental flow standards at all locations, and so a method must be developed for characterizing high pulse flows at all possible diversion locations. In this age of advanced computing, a common way of addressing problems such as this – in which questions must be answered at locations or in situations without available measured data – is to use a model or multiple models of phenomena such as rainfall and flows of water over land and in streams.

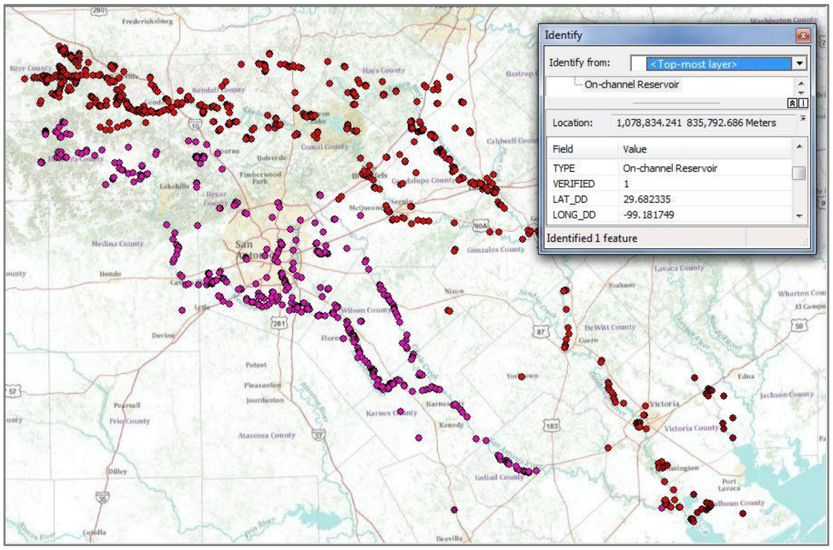
The research described here looks at using output from a flow model to establish a process for characterizing high pulse flows at ungaged locations such that they are commensurate with the high pulses characterized at specific gages in standards documents. The Guadalupe and San Antonio basins are used in creating an example of this characterization process.

Review of Literature and Available Data

Characterizing high pulse flows at ungaged locations such that they agree with high pulse flows defined in TCEQ standards documents requires the synthesis of data from multiple sources. These data include the environmental flow standards that have already been written for basins in the state of Texas, the locations of water diversion points currently recognized by the TCEQ as examples of where high pulse flows may need to be characterized, the locations of gages named in those standards and other gages that might be used for monitoring flows, and flow data at both gaged and ungaged locations.

Unfortunately, environmental flow standards have, as of the writing of this paper, only been written for the Sabine-Neches basin and the Trinity-San Jacinto basin including Galveston Bay. The study area, however, was set as the Guadalupe and San Antonio basins, largely because those basins have been studied extensively by the Center for Research in Water Resources (CRWR) at the University of Texas at Austin (UT Austin), which has overseen this research. Because of the research group's familiarity with this region, it was chosen for the initial analysis and process development. However, because no environmental flow standards have yet been set for the Guadalupe and San Antonio basins, a portion of the process could not be established: it was not possible to deduce (or receive from the TCEQ) the parameters used in creating the given standards in order to use the same parameters in characterizing flows at other locations. Instead, parameter values were chosen based on standards found in the literature: high flow events are defined as flows above the 75th percentile in the period of record, as well as flows between the 25th and 75th percentile with an initial rate of change of 50% or more and an ending rate of change of 5% or less. High flows that are equal to or greater than flows with a 1.5 year return period are classified as overbank flows (i.e. floods); all other high flows are classified as high pulse events [1]. Future work will be needed to incorporate the parameters used in creating the written standards so that the flow regimes defined at ungaged locations will agree with those defined in the standards.

A shapefile (used in map applications) with the locations of recognized water diversion points was provided by TCEQ for use in this work (Figure 1). The locations of United States Geological Survey (USGS) gages were also easily acquired from the USGS website (Figure 2). The USGS shapefile chosen includes gages "snapped to" flowlines in the National Hydrography Dataset (NHD). This means that the USGS has, where necessary, adjusted the location information attached to each gage so that, in a mapping application such as ArcGIS, the gages will appear directly on the streams on which they make measurements; this avoids misalignments of gages and streams on the resulting map.



Identify from: <Top-most layer>

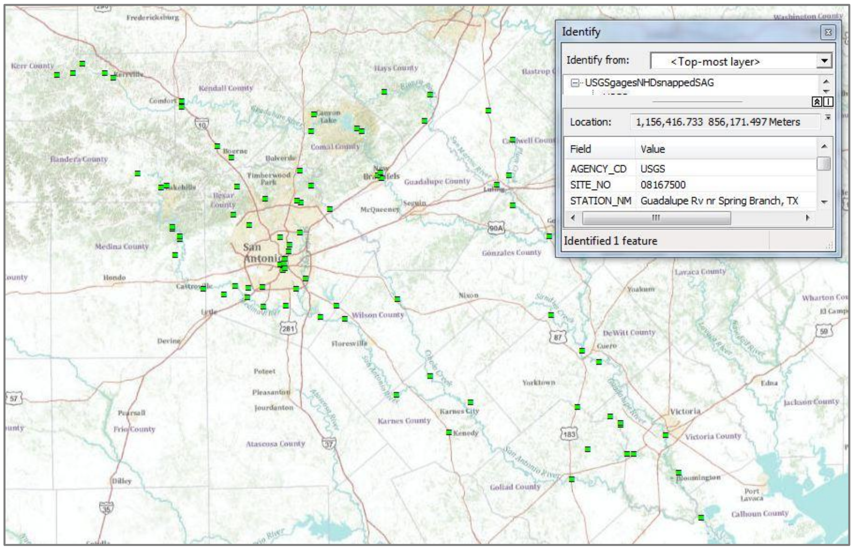
On-channel Reservoir

Location: 1,078,834.241 835,792.686 Meters

Field	Value
TYPE	On-channel Reservoir
VERIFIED	1
LAT_DD	29.682335
LONG_DD	-99.181749

Identified 1 feature

Figure 1. TCEQ Water Rights Points with Feature Identify Example



Identify from: <Top-most layer>

USGSgagesNHDsnappedSAG

Location: 1,156,416.733 856,171.497 Meters

Field	Value
AGENCY_CD	USGS
SITE_NO	08167500
STATION_NM	Guadalupe Rv nr Spring Branch, TX

Identified 1 feature

Figure 2. USGS Gage Locations with Feature Identify Example

Finally, flow data are obviously required and easily obtainable from USGS for gaged locations, but how can they be obtained for ungaged locations? Fortunately, UT Austin researcher Cédric David has created a model called RAPID (Routing Application for Parallel computatIon of Discharge): “given surface and groundwater inflow to rivers, this model can compute flow and volume of water everywhere in river networks made out of many thousands of reaches” [5]. The model is based on the Muskingum method for routing; the river network comes from the enhanced NHD (NHDPlus), and “the water inflow from outside of the river network” comes from the Community Noah Land Surface Model with Multi-Physics Options [6]. While the model can be widely applied, David’s initial work “[calculated] river flow in all 5175 river reaches of the Guadalupe and San Antonio River Basins for four years (01 January 2004

– 31 December 2007)” with output given in 3-hour time steps [6]. (The study area for David’s work was another reason the Guadalupe and San Antonio basins were chosen for this initial research.)

The output from RAPID provides flows in reaches throughout the basin of interest, so characterization of flow is not restricted to the locations of flow gages. The output files are in NetCDF format, which can be used directly in the ArcGIS suite of mapping softwares; David has written a tutorial describing how to ingest the model output in ArcMap (an ArcGIS program) and use it to create either maps of all reaches at specific time steps (Figure 3) or hydrographs of specific reaches at all time steps (Figure 4) [7].

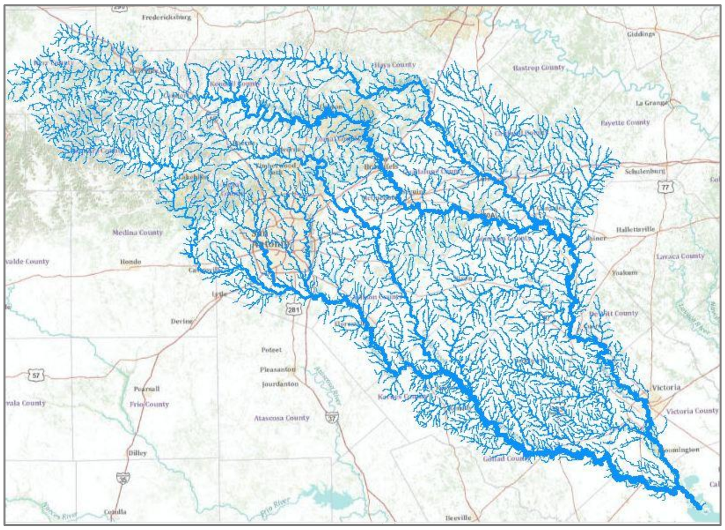


Figure 3. RAPID Output: Map of All Reaches at a Single Time Step

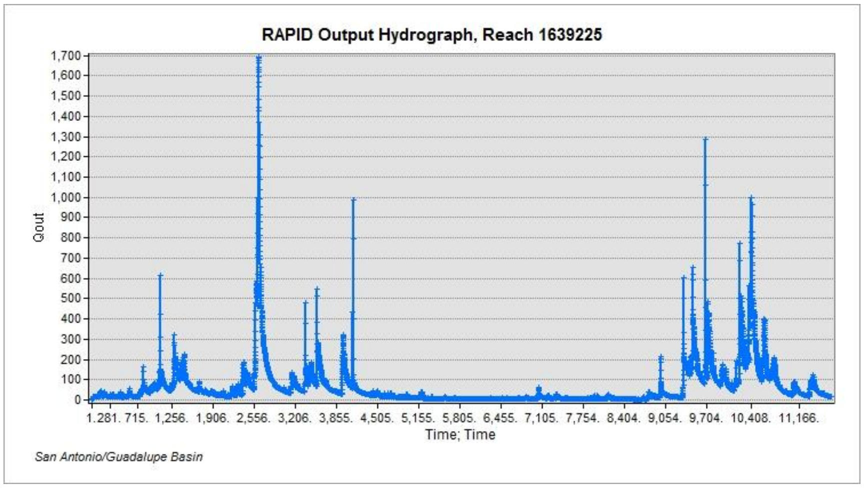


Figure 4. RAPID Output: Hydrograph of a Single Reach at All Time Steps

The USGS flow data needed for this research were acquired directly from the USGS website, using a REST call. A REST call consists of a single URL constructed to describe the parameters of the data desired; the URL essentially communicates with a USGS server and returns the desired data in a WaterML file (a version of XML). One such URL used to acquire data is http://waterservices.usgs.gov/nwis/dv?huc=12100201,12100202,12100203,12100204,12100301,12100302,12100303,12100304&startDT=2004-01-01&endDT=2004-12-31&parameterCd=00060. An explanation of the components of this URL is given in Table 1. This call returns maximum, minimum, and mean flow values (as available); for this research, mean flows were used because they appeared to be the most consistently available across all gages. For example, of the two gages chosen as examples in this report, one has gaps of several days at a time in its maximum flow data and the other has no maximum flow data at all.

Table 1. Explanation of Components of REST Call URL

Component of REST Call URL	Meaning
waterservices.usgs.gov/nwis	The information should come from the USGS National Water Information System (NWIS).
dv	Daily values are desired, rather than instantaneous values or values from any other NWIS dataset.
huc=12100201,12100202,12100203,12100204,12100301,12100302,12100303,12100304	the hydrologic unit codes (HUCs) of the hydrologic regions for which information is wanted, in this case the sections of the Guadalupe and San Antonio basins
startDT=2004-01-01	the start date for the desired information
endDT=2004-12-31	the end date for the desired information
parameterCd=00060	the parameter desired: flow, or “discharge,” in cubic feet per second (cfs)

The synthesis of all of these data sources happens primarily in ArcMap, a program which allows mapping of multiple datasets as layers that can be superimposed on one another to facilitate analysis. “‘The GIS framework is ideally suited’ for work that entails effective synthesis of data from many sources… because multiple datasets can be combined and viewed simultaneously in a GIS application” [8]. The datasets used in this research all have inherent geo-spatial components, and are thus naturally appropriate for this type of synthesis using GIS. In laying out the process of characterizing pulse flows at ungaged locations, a single map displaying data from all available sources (Figure 5) was used to identify river reaches of interest and nearby flow gages. Mapping capabilities will also be crucial in eventually applying the widely-characterized pulse flows to writing and enforcing environmental flow standards for ungaged locations. As an example of how a web-accessible map can be used in the future application of these standards, the desktop map was also published as a map service so that it can be viewed online, via a web browser (Figure 6).

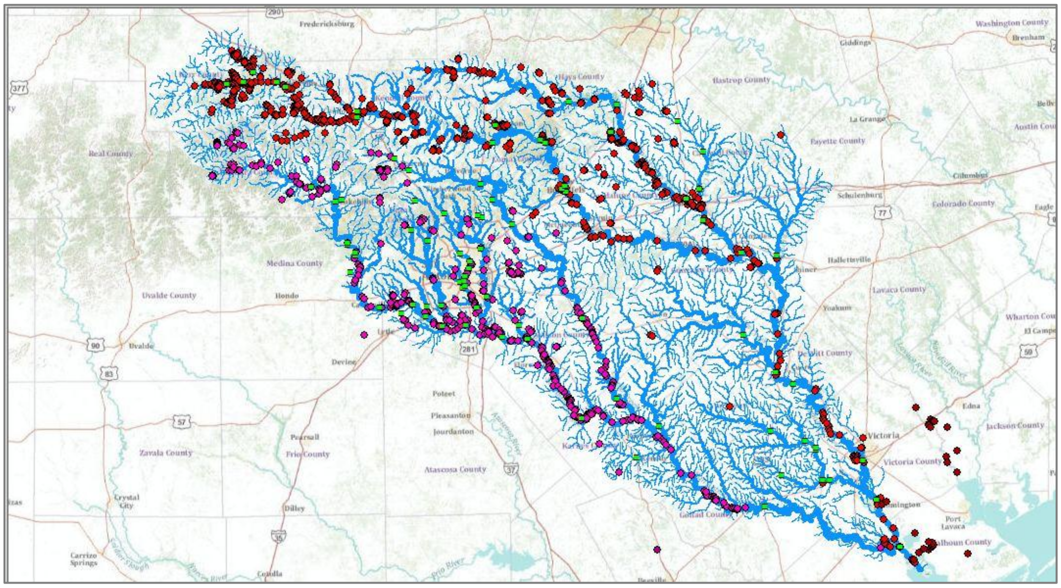
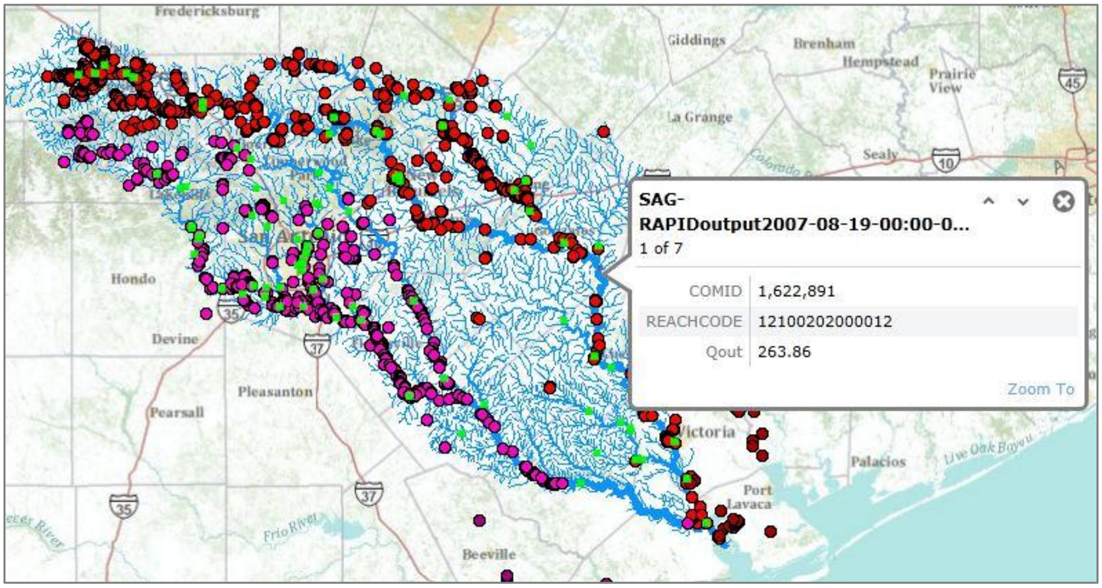


Figure 5. Desktop Map: TCEQ Rights Points, USGS Gages, RAPID Output on NHDPlus Flowlines



SAG-RAPIDoutput2007-08-19-00:00-0...
1 of 7

COMID 1,622,891
REACHCODE 12100202000012
Qout 263.86

Figure 6. Web-Accessible Map in ArcGIS Online with Popup Showing Flow (Qout)

The Tools Used in the Process

Once the necessary data had been acquired and understood through relevant literature, they had to be compiled into a map for initial analysis, and then further analysis was carried out based on what was discovered through consideration of the map. All relevant data were used to create a map in the desktop application ArcMap, and then this local map was published to a web server to serve as an example of a web-accessible flow map (important for future work on this problem). Based on the map, a reach of interest (with a TCEQ rights point located on it) and nearby flow gages were chosen to serve as examples of the process of characterizing pulse flows at ungaged locations and to provide data for comparison between pulse flows at gaged and ungaged locations. Finally, pulse flows were characterized at the chosen locations and the process documented.

Standard tools in ArcMap were used to create the map, primarily “add data.” RAPID output was mapped according to the tutorial written by David: the Make NetCDF Table View tools was used to add the model data to the ArcMap project, and the Select by Dimension tool was used to select time step 10,609 (00:00-03:00 AM on 19 August, 2007) as an example time step. The information in the table was added to the map by joining the table to a feature layer of flowlines acquired from NHDPlus. The completed and nicely symbolized map was published to a CRWR ArcGIS server using the server publishing tools available in ArcMap. After it had been published as a map service, the map could be viewed using ArcGIS Online.

For the flow characterization process, two tools were used: the Indicators of Hydrologic Alteration-Modified Base Flow Index with Threshold (IHA-MBFIT) tool, and the Hydrology-Based Environmental Flow Regime (HEFR) tool, both Excel spreadsheet tools available from the TCEQ [8]. Flow data, acquired either in an XML file from USGS or in a NetCDF file from the RAPID model (described in more detail in the previous and following sections, respectively), were converted into Excel spreadsheet format and prepared for processing, then processed through first the IHA-MBFIT tool followed by the HEFR tool (using the IHA results, not the MBFIT results). As mentioned previously, the parameters used in these tools were taken from available literature. The output from the HEFR tool is an environmental flow regime matrix: these matrices present the flow characterizations aimed at in this research. More detailed explanation of the characterization process will be given in the next section, as that process is the primary result of this work.

Results

The Process of Characterizing High Pulse Flows at Ungaged Locations

The first step in the process of characterizing high pulse flows at ungaged locations is to discover the parameters used in characterizing flows for the written standards (e.g. what percentile flow is considered a high flow). The easiest way to acquire these is to get them directly from the TCEQ or the reports given to the TCEQ by the study groups that recommended the standards (Basin and Bay Expert Science Teams and Basin and Bay Area Stakeholder Committees). If the parameters are not directly available, then they must be derived from the written standards and the flow data for the gages at which the standards are written. Flow data can be acquired from the USGS using a REST call as previously described; the call would specify the gage(s) of interest and a long period of record (preferably at least 20 years), and would be constructed according to guidelines given in http://waterservices.usgs.gov/rest/DV-Service.html [9]. These flow data would then be processed through the IHA-MBFIT tool and then the HEFR tool, as described below, and the output compared with the written standards. This processing would be repeated with different parameters until the output matched the written standards. These parameters would then be used in the following steps. One challenge is that different parameters may need to be used when processing the flow data at different gages in order to match the output to the written standards; these different parameters would then have to be judiciously applied to various groups of reaches based on proximity to the relevant gages. Further study on this issue will be needed.

Before these parameters can be used to characterize flows at ungaged locations, the flow data for the reach(es) of interest must be acquired and prepared for processing. Model output for a single reach is easily extracted from a NetCDF output file using ArcMap, following the steps outlined in David's *Displaying RAPID outputs in ArcGIS* tutorial, beginning on page 8 at "Example hydrograph for the San Antonio and Guadalupe Basins in Texas" [7]. At the point in the example at which David chooses COMID 1639225 for use in the Select by Dimension tool, the COMID of the reach of interest should be substituted. This COMID can be found by clicking on the reach of interest with the Identify tool in an ArcMap map of the reaches in the study area. After the table has been updated using the Select by Dimension tool, the table should be exported using ArcMap's data export feature. The resulting DBF file can be opened with Excel and saved as a spreadsheet containing time and flow data.

The time/flow spreadsheet exported from ArcMap will show sequentially numbered time steps in one column and 3-hourly flow values in the second column. The sequential time steps must be converted to calendar dates, with time step 1 corresponding to 01 January 2004, 12:00 AM, time step 2 corresponding to 01 January 2004, 03:00 AM, and so on. The 8 values for each day must then be converted first from cubic meters per second to cubic feet per second (cfs), and then to daily flows, using Excel formula capabilities. New columns for ‘Date’ and ‘Flow’ can be created next to the ‘Time’ and Qout’ columns. The first cell in the ‘Date’ column can be set equal to the first cell in the ‘Time’ column, but formatted to give the date without the time. The first cell in the ‘Flow’ column can be set equal to “SUM(cells for day 1)/8” to give the mean flow for that day. These calculations can be carried down the columns to the end of the dataset, but it is important to calculate the flow only once per day and leave blank cells in the other 7 rows per day. The IHA-MBFIT tool will not tolerate multiple entries for a single day. It will also not tolerate empty rows, so the ‘Date’ and ‘Flow’ columns must be copied and the values pasted (right click and “Paste Special”) into a new worksheet; the date column must be reformatted as “date” and the columns must be sorted on the date (oldest to newest) to eliminate the empty rows. The new worksheet must be named “daily efcs” for a later step in this process – this daily efcs sheet displays date and flow data in a form usable by the IHA-MBFIT and HEFR tools.

Gage flow data need preparation as well. They can be acquired from the USGS web service and the resulting XML file saved and imported into Excel. There will be a wealth of information in this file, much of which is not needed for this work. To proceed, the chosen gage must be found by gage number or site name, and the flow data – date and mean (used here), maximum, or minimum flow value, as desired – should be copied and pasted into a new spreadsheet, including the entire time period of interest (in this case 2004-2007). The final steps in preparing gage data for processing are to move the date column into column A, with the flow column in column B, and to again name the worksheet daily efcs.

Once the flow data have been prepared, they can be processed with the IHA-MBFIT and HEFR tools using the parameters acquired in step 1. The tools can be downloaded from http://www.tceq.texas.gov/permitting/water_rights/eflows/resources.html and documentation can be found in Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology, available from the same web page, and Indicators of Hydrologic Alteration Version 7.1 User’s Manual, available from http://conserveonline.org/.

To process data with the IHA-MBFIT tool, simply download the tool, open the spreadsheet and paste the dates and flows copied from the daily efcs worksheet in the spreadsheet with the model output flow data into cells A43 and B43 (and below) in the “IHA and MBFIT” worksheet. Input the parameters from step 1 in the highlighted cells in column F. Click the “Update Calculations” button at the top of the spreadsheet, and wait for the calculations to complete. The tool goes through many calculations and creates a number of results, most of which are not directly needed in this process. The output needed for the next step – processing with the HEFR tool – is explicitly marked as such.

When the IHA-MBFIT calculations are complete, the results in columns H and I (marked "IHA output for HEFR") can be copied and pasted into the daily efcs worksheet in the spreadsheet with the model output flow, next to the 'Date' and 'Flow' columns so that there are 4 populated columns in the daily efcs worksheet (columns A-D). This worksheet now displays the dates for the entire time period being analyzed, the flow on each date, and some classification of flow information for each date, all formatted properly as input for the HEFR tool.

To process the data with the HEFR tool, the add-in must be downloaded from the TCEQ website and added to Excel through the File/Options/Add-Ins menu. Once the add-in has been successfully added, simply navigate to the "Add-Ins" tab on the ribbon (in Office 2010), click the arrow next to "HEFR" to display a drop-down menu, and click "Run HEFR." A wizard will open: change inputs from the defaults if necessary, click the "Check Inputs" button, and if no errors are detected, click "OK" and then click the "Run HEFR" button. (Don't be concerned about a message saying "IHA 'analysis.in' path missing, Metadata sheet will be incomplete." IHA used to be available as a standalone tool – outside of Excel – and it created output files that could be used by HEFR. The metadata sheet that is now incomplete is not necessary for this analysis.)

The HEFR tool creates a number of new worksheets in the spreadsheet. The sheet of interest in this analysis is FlwMtxSeasonal, which displays a seasonal environmental flow matrix based on the flow data processed. TCEQ defines environmental flows on a seasonal basis, so this matrix is relevant whereas the FlwMtxMnthly sheet (a monthly flow matrix) is less so. In particular, the "High Flow Pulses" section of the matrix is exactly the output that is the goal of this process. The High Flow Pulses part of the matrix characterizes high pulse flows in terms of frequency, duration, peak flow, and volume, for wet, dry, and average conditions (i.e. how much precipitation has fallen that year relative to other years on record); this characterization is what's used in environmental flow standards documents, and knowing it for ungaged locations will allow the TCEQ to apply flow standards in those places.

The output from this process can be verified by repeating this process with model output flow data for a reach on which a USGS gage is located and with measured flow data from the gage at that location; the output based on the model data can be compared with the output based on the measured gage data. If the high pulse flow definitions based on the two different datasets agree (within some margin of error) then pulse flow definitions based on model data in other reaches can be used confidently in making and applying environmental flow standards.

Process Summary

1. Acquire or derive parameters used to create written standards.
2. Acquire and prepare flow data for reach(es) of interest, including converting to appropriate units and combining 3-hourly model output into daily average flows.
3. Using the parameters from step 1, process reach flow data with the IHA-MBFIT and HEFR tools to produce an environmental flow regime matrix for each reach of interest. The high flow pulse components are the components of interest.
4. Verify this process by completing steps 2 and 3 for a reach on which a gage not named in the standards is located, once using model output data and once using gage flow data. Compare the high pulse components of the resultant flow regime matrices to ensure that they match within some margin of error; this will demonstrate that the model output gives the same high pulse flow characteristics as the gage flow measurements.

Examples of Process Outcomes

As examples of the process, results are presented here from examination of one ungaged tributary reach, one nearby gaged reach on the tributary, and one nearby gaged reach on the main stem (with 75th percentile high pulse flows shown below and complete environmental flow matrices shown in Appendix A). Both model output and gage data were analysed at the gaged locations and compared for verification of this method. The locations of the reaches and gages can be seen in Figure 7, and a key to interpreting the flow matrices is in Table 2. The results from the ungaged reach, COMID 1623195, can be seen in Table 3. Results based on data from the gage at Sandies Creek near Westhoff, TX (the gaged tributary location) can be seen in Table 4, with results based on model output for that location in Table 5. Gage results for the gaged main stem location, Guadalupe River at Cuero, TX, can be seen in Table 6, with results based on model output at that location in Table 7.

The peak flows (Q values) in Table 3– for the ungaged reach – are vastly different from the peak flows in any of the other tables, showing that the high pulse is indeed characterized very differently at the upstream tributary location than at a downstream location either on the tributary or on the main stem of the river. This validates the need for the work being done here: it is not accurate to simply apply the same pulse flow standards at all points throughout a basin. These results are an example of what could be used by the TCEQ to define and enforce high pulse flow standards at ungaged locations.

Tables 4 and 5 and Tables 6 and 7 show the gage and model flows for the gaged tributary location and gaged main stem location, respectively, so the two tables in each pair should show similar values. Unfortunately, this is not the case. The winter and spring peak flow values for the Sandies Creek location (Tables 4 and 5) agree closely, but none of the other peak flow values match. It is possible that the model doesn’t take into account all necessary factors, such as human withdrawals that might decrease flows, which would cause discrepancies between the predicted flows and the measured flows. Not including withdrawals would not, however, account for model results that are lower than corresponding gage results, such as in Tables 6 and 7. The precise cause of the mismatches must be identified before this work is carried forward; if the model flows do not result in accurate flow characterizations, they cannot be used for the writing or enforcing of legal standards.

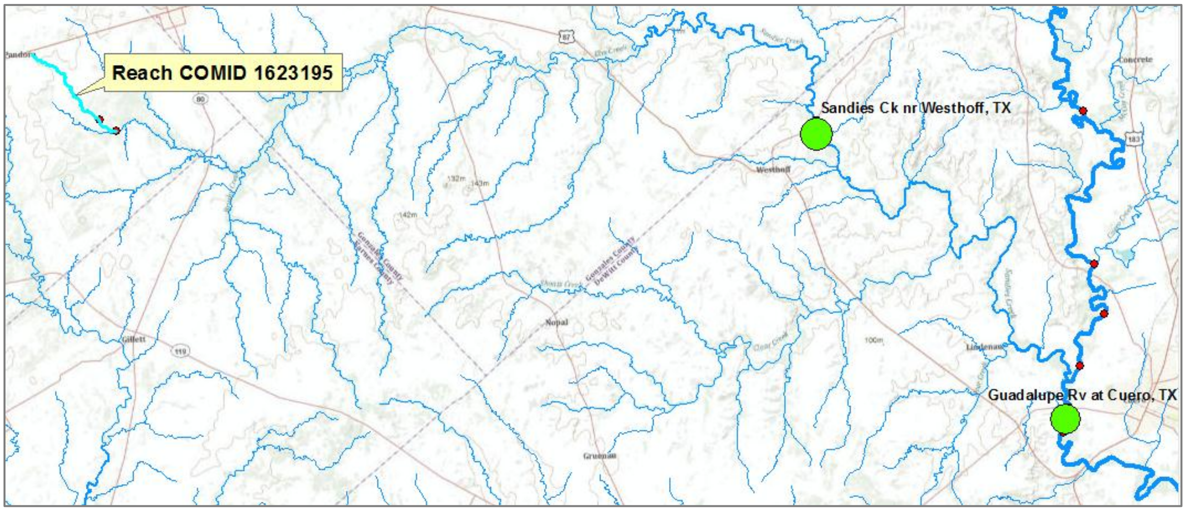


Figure 7. Reach 1623195, Gage 8175000 (Sandies Creek near Westhoff), Gage 8175800 (Guadalupe River at Cuero)

Table 2. Key for Interpreting Environmental Flow Matrices

High Flow Pulse Characteristics	**F = Frequency (per season)**
	D = Duration (days)
	Q = Peak Flow (cfs)
	V = Volume (ac-ft)

Table 3. Reach COMID 1623195 (75th % High Flow Pulses)

High Flow Pulses (75th percentile)	F: 1	F: 0.75	F: 1.5	F: 2.3
	D: 2.8	D: 3.5	D: 3.8	D: 3
	Q: 3.3	Q: 2.8	Q: 4.5	Q: 3.7
	V: 13	V: 15	V: 21	V: 16
	Winter	**Spring**	**Summer**	**Fall**

Table 4. Gage 8175000 - Sandies Creek near Westhoff, TX (75th % High Flow Pulses)

	Winter	Spring	Summer	Fall
High Flow Pulses (75th percentile)	F: 1	F: 1	F: 1	F: 1.8
	D: 20	D: 11	D: 12	D: 10
	Q: 282	Q: 490	Q: 103	Q: 136
	V: 2749	V: 2627	V: 810	V: 891

Table 5. Reach COMID 1623207 - Sandies Creek Near Westhoff, TX (75th % High Flow Pulses)

	Winter	Spring	Summer	Fall
High Flow Pulses (75th percentile	F: 1.5	F: 2	F: 1.8	F: 1.8
	D: 3	D: 8	D: 4	D: 4
	Q: 292	Q: 479	Q: 540	Q: 484
	V: 1458	V: 5625	V: 3081	V: 1476

Table 6. Gage 8175800 - Guadalupe River at Cuero, TX (75th % High Flow Pulses)

	Winter	Spring	Summer	Fall
High Flow Pulses (75th percentile	F: 0.75	F: 1	F: 1	F: 0.75
	D: 18	D: 9	D: 19	D: 5.5
	Q: 5640	Q: 6200	Q: 7030	Q: 3758
	V: 81661	V: 73934	V: 185693	V: 27818

Table 7. Reach COMID 1637437 - Guadalupe River at Cuero, TX (75th % High Flow Pulses)

	Winter	Spring	Summer	Fall
High Flow Pulses (75th percentile)	F: 1.5	F: 1.8	F: 1	F: 1.8
	D: 6	D: 5.5	D: 4	D: 5.3
	Q: 1359	Q: 2738	Q: 1996	Q: 1937
	V: 12625	V: 23721	V: 8768	V: 9927

Conclusions and Future Work

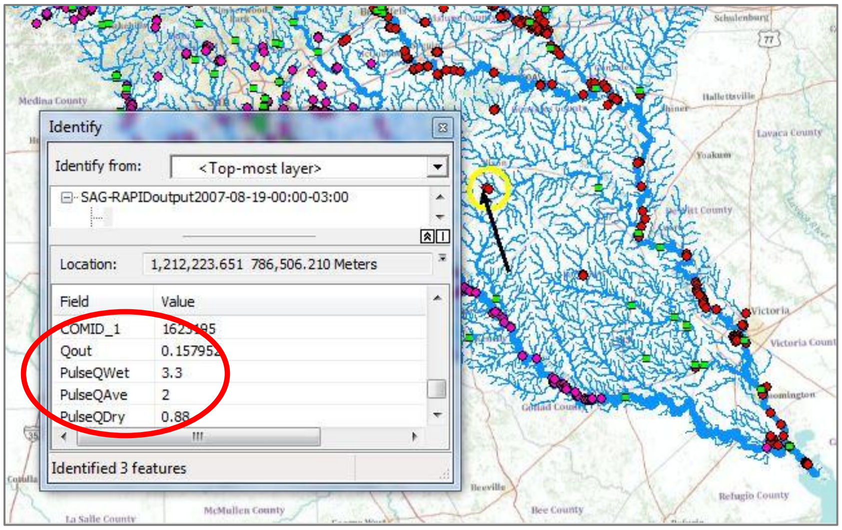
Based on the good agreement between the gage and model data results seen in the winter and spring peak flow values for the Sandies Creek location, this process appears to hold promise. There are, however, challenges that must be addressed before this work can be carried through and the results put to practical use. Most importantly, the discrepancies between the gage and model results for all of the other high flow pulse characteristic values must be investigated and the underlying problem solved. The results cannot be used unless the model data produce similar results to the gage data and can thus be considered reliable.

Once the reliability of the model has been assured, the process of acquiring or deriving the parameters used in the written environmental flow standards documents must be attempted and refined as necessary. The issue of possibly applying different parameters in different locations in a single basin may also need to be addressed. Again, the results of the process described herein cannot be used unless they agree closely with the prescriptions approved by the TCEQ.

Once the primary challenges have been addressed, the process of characterizing high pulse flows at ungaged locations – including at far upstream points on tributaries – can be carried out for any given reach as information about that reach is needed. However, with over 5,000 reaches in the Guadalupe and San Antonio basins alone, repeating the process by hand for all reaches potentially of interest throughout the state of Texas will not be feasible. Therefore the process must be automated as much as possible.

Even if the process is completely automated and high pulse flows are characterized for all river reaches in Texas, enforcement of environmental flow standards will be impossible without some way to monitor flows in rivers so as to identify times when withdrawals must stop at given locations. Because high pulse flow events necessarily pass upstream points – and have usually concluded at those upstream points – before they pass downstream flow gages, gage measurements will not be sufficient for the necessary flow monitoring. Real time flow maps, based on model data output continuously (or at very short intervals) with up-to-the-moment precipitation information, will be needed. The web map created as a part of this research serves as an example of what these real time flow maps might look like: they can be made publicly accessible or kept private for use only by specific people, and HTML popups can be used to easily display information such as the flow in the chosen reach.

These real time flow maps can also include high pulse flow characteristics as feature attributes, which would allow a user to view the various pulse flow thresholds alongside the current flow simply by clicking on a reach on the map. The pulse flow thresholds are the values given in the environmental flow matrices created through the process described here; the feature attributes in the map could include only the peak flow values (the “triggers” that define when pulse events begin), or they could also include the other values displayed in the environmental flow matrix (duration, frequency, and volume). As an example, the peak flow values for wet, dry, and average seasons have been added to the attribute table for a single reach, and Figure 8 shows them displayed with the map. The process of updating feature attribute tables to include these values should also be automated as much as possible. This would be a worthwhile undertaking, because the result would be a single web-accessible tool that a TCEQ staff member could use to identify the current conditions at any location and compare those conditions with the standards for high pulse flow events, all with a single click.



SAG-RAPIDoutput2007-08-19-00:00-03:00

Location: 1,212,223.651 786,506.210 Meters

Field	Value
COMID_1	1623195
Qout	0.157952
PulseQWet	3.3
PulseQAve	2
PulseQDry	0.88

Identified 3 features

Figure 8. Reach COMID 1623195 with ID Showing Flow and Pulse Peak Flows

In time, with the refinement of this process and the development of real time flow maps with pulse characteristic attributes, the TCEQ will be able to easily, effectively, and accurately enforce environmental flow standards at any and all points on rivers and streams throughout Texas, and thus help protect those waterbodies so that they – and we humans dependent on them – may thrive for many years to come.

Works Cited

[1] R. Brandes, F. Heitmuller, R. Huston, P. Jensen, M. Kelly, F. Manhart, P. Montagna, G. Ward and J. Wiersema, "Use of Hydrologic Data in the Development of Instream Flow Recommendations for the Environmental Flows Allocation Process and the Hydrology-Based Environmental Flow Regime (HEFR) Methodology," 2009.

[2] Texas Commission on Environmental Quality, "Chapter 298 – Environmental Flow Standards for Surface Water," 2011.

[3] W. Ward, "Pulse flows to liven up rivers," [Online]. Available: http://news.csu.edu.au/director/features.cfm?itemID=BA0B55400C264A8DC90A267318803F3B. [Accessed November 2011].

[4] Texas Commission on Environmental Quality, "About the TCEQ," 2011.

[5] C. David, "RAPID," [Online]. Available: http://www.geo.utexas.edu/scientist/david/rapid.htm. [Accessed October 2011].

[6] C. David, "Towards river flow computation at the continental scale," Austin, 2009.

[7] C. David, "Displaying RAPID outputs in ArcGIS," Austin, 2011.

[8] A. Wood, "Automated Data Acquisition for Integration of Multiple Datasets Using GIS Applications," 2011.

[9] Texas Commission on Environmental Quality, "Environmental Flows Resources," 31 August 2011. [Online]. Available: http://www.tceq.texas.gov/permitting/water_rights/eflows/resources.html. [Accessed November 2011].

[The Nature Conservancy, T. Rybicki, Totten Software Design and Smythe Scientific Software, 10] "Indicators of Hydrologic Alteration: Version 7.1 User's Manual," 2009.

11] United States Geological Survey, "USGS Daily Values Site Web Service," 22 July 2011. [Online]. Available: http://waterservices.usgs.gov/rest/DV-Service.html. [Accessed November 2011].

Appendix A – Example Environmental Flow Matrices

Table A-1. Reach COMID 1623195

Overbank Flows	**Return Period (R) : 4 (years)**		**Duration (D) : 79 (days)**	
	Volume (V) : 1036 (ac-ft)		**Peak Flow (Q) : 21 (cfs)**	
High Flow Pulses	F: 1	F: 0.75	F: 1.5	F: 2.3
	D: 2.8	D: 3.5	D: 3.8	D: 3
	Q: 3.3	Q: 2.8	Q: 4.5	Q: 3.7
	V: 13	V: 15	V: 21	V: 16
	F: 5.3	F: 3.8	F: 4.8	F: 6.5
	D: 2	D: 2	D: 2	D: 2
	Q: 2	Q: 1.7	Q: 3.6	Q: 2.5
	V: 5.5	V: 6	V: 12	V: 8.3
	F: 6	F: 6	F: 6.3	F: 7
	D: 1.3	D: 1	D: 1.3	D: 1
	Q: 0.88	Q: 1	Q: 0.86	Q: 1
	V: 2.8	V: 2	V: 2.6	V: 3.2
Base Flows (cfs)	1.3(36.5%)	1.1(63.0%)	2(47.6%)	1.3(29.9%)
	0.84(61.3%)	0.37(77.7%)	1.2(59.8%)	0.73(53.3%)
	0.38(82.2%)	0.29(88.9%)	0.81(71.5%)	0.49(73.4%)
Subsistence Flows (cfs)	N/A	N/A	0.22(91.6%)	0.21(95.9%)
	Dec Jan Feb	**Mar Apr May**	**Jun Jul Aug**	**Sep Oct Nov**
	Winter	**Spring**	**Summer**	**Fall**

Flow Levels	**High (75th %ile)**
	Medium (50th %ile)
	Low (25th %ile)
	Subsistence

High Flow Pulse Characteristics	**F = Frequency (per season)**
	D = Duration (days)
	Q = Peak Flow (cfs)
	V = Volume (ac-ft)

Table A-2. Gage 8175000 - Sandies Creek near Westhoff, TX

Overbank Flows	**Return Period (R) : 2 (years)**		**Duration (D) : 37 (days)**	
	Volume (V) : 38801 (ac-ft)		**Peak Flow (Q) : 5390 (cfs)**	
High Flow Pulses	F: 1	F: 1	F: 1	F: 1.8
	D: 20	D: 11	D: 12	D: 10
	Q: 282	Q: 490	Q: 103	Q: 136
	V: 2749	V: 2627	V: 810	V: 891
	F: 2.8	F: 1	F: 1.8	F: 1.8
	D: 8	D: 8	D: 6	D: 5.5
	Q: 43	Q: 13	Q: 14	Q: 19
	V: 308	V: 114	V: 113	V: 151
	F: 3	F: 2.8	F: 3.5	F: 3
	D: 3.3	D: 3	D: 3	D: 3.8
	Q: 5.3	Q: 4.3	Q: 3.2	Q: 4.4
	V: 31	V: 23	V: 18	V: 26
Base Flows (cfs)	12(49.4%)	9.6(58.4%)	4.2(51.6%)	6.6(41.5%)
	4.6(68.9%)	3.8(76.4%)	2.2(66.6%)	2.3(64.3%)
	2.6(87.8%)	2.4(89.7%)	1.6(76.6%)	1.7(78.3%)
Subsistence Flows (cfs)	N/A	0.73(100.0%)	0.28(93.5%)	0.45(96.7%)
	Dec Jan Feb	**Mar Apr May**	**Jun Jul Aug**	**Sep Oct Nov**
	Winter	**Spring**	**Summer**	**Fall**

Flow Levels	
	High (75th %ile)
	Medium (50th %ile)
	Low (25th %ile)
	Subsistence

High Flow Pulse Characteristics

F = Frequency (per season)
D = Duration (days)
Q = Peak Flow (cfs)
V = Volume (ac-ft)

Table A-3. Reach COMID 1623207 - Sandies Creek Near Westhoff, TX

Overbank Flows	Return Period (R) : 2 (years)		Duration (D) : 61 (days)	
	Volume (V) : 145626 (ac-ft)		Peak Flow (Q) : 4331 (cfs)	
High Flow Pulses	F: 1.5	F: 2	F: 1.8	F: 1.8
	D: 3	D: 8	D: 4	D: 4
	Q: 292	Q: 479	Q: 540	Q: 484
	V: 1458	V: 5625	V: 3081	V: 1476
	F: 3.5	F: 5	F: 3.8	F: 3.8
	D: 2.5	D: 3	D: 2	D: 2
	Q: 204	Q: 168	Q: 305	Q: 195
	V: 886	V: 704	V: 1312	V: 759
	F: 5.5	F: 5.8	F: 4.5	F: 5.3
	D: 2	D: 1	D: 2	D: 1
	Q: 83	Q: 101	Q: 133	Q: 99
	V: 266	V: 212	V: 426	V: 335
Base Flows (cfs)	162(34.0%)	136(62.5%)	222(50.3%)	199(32.7%)
	69(57.1%)	43(78.0%)	114(67.7%)	107(50.5%)
	41(76.6%)	30(89.1%)	25(84.8%)	58(67.0%)
Subsistence Flows (cfs)	17(96.7%)	N/A	N/A	19(90.9%)
	Dec Jan Feb	Mar Apr May	Jun Jul Aug	Sep Oct Nov
	Winter	Spring	Summer	Fall

Flow Levels	**High (75th %ile)**
	Medium (50th %ile)
	Low (25th %ile)
	Subsistence

High Flow Pulse Characteristics

F = Frequency (per season)
D = Duration (days)
Q = Peak Flow (cfs)
V = Volume (ac-ft)

TableA-4. Gage 8175800 - Guadalupe River at Cuero, TX

Overbank Flows	Return Period (R) : 4 (years)		Duration (D) : 37 (days)	
	Volume (V) : 409607 (ac-ft)		Peak Flow (Q) : 22000 (cfs)	
High Flow Pulses	F: 0.75	F: 1	F: 1	F: 0.75
	D: 18	D: 9	D: 19	D: 5.5
	Q: 5640	Q: 6200	Q: 7030	Q: 3758
	V: 81661	V: 73934	V: 185693	V: 27818
	F: 1	F: 2.8	F: 1.8	F: 2.8
	D: 9	D: 5	D: 5	D: 3.5
	Q: 2460	Q: 3350	Q: 3520	Q: 2150
	V: 19954	V: 17455	V: 25468	V: 12667
	F: 2.8	F: 4.3	F: 2.8	F: 2.8
	D: 3	D: 3	D: 5	D: 2
	Q: 1400	Q: 1425	Q: 2910	Q: 1120
	V: 10651	V: 10326	V: 16899	V: 3706
Base Flows (cfs)	1123(44.2%)	1823(47.8%)	1520(50.3%)	1438(38.2%)
	744(67.5%)	1195(67.7%)	1120(62.8%)	884(56.3%)
	698(83.6%)	679(84.8%)	940(74.5%)	656(73.4%)
Subsistence Flows (cfs)	371(99.7%)	N/A	319(92.9%)	332(94.8%)
	Dec Jan Feb	Mar Apr May	Jun Jul Aug	Sep Oct Nov
	Winter	**Spring**	**Summer**	**Fall**

Flow Levels	**High (75th %ile)**
	Medium (50th %ile)
	Low (25th %ile)
	Subsistence

High Flow Pulse Characteristics

F = Frequency (per season)

D = Duration (days)

Q = Peak Flow (cfs)

V = Volume (ac-ft)

Table A-5. Reach COMID 1637437 - Guadalupe River at Cuero, TX

Overbank Flows	Return Period (R) : 4 (years)		Duration (D) : 66 (days)	
	Volume (V) : 920861 (ac-ft)		Peak Flow (Q) : 17472 (cfs)	
High Flow Pulses	F: 1.5	F: 1.8	F: 1	F: 1.8
	D: 6	D: 5.5	D: 4	D: 5.3
	Q: 1359	Q: 2738	Q: 1996	Q: 1937
	V: 12625	V: 23721	V: 8768	V: 9927
	F: 3.5	F: 5.3	F: 2.8	F: 3.5
	D: 4	D: 4	D: 3	D: 4
	Q: 879	Q: 828	Q: 962	Q: 801
	V: 5889	V: 5208	V: 4106	V: 3981
	F: 4.8	F: 6.8	F: 5.8	F: 5.5
	D: 2	D: 1.5	D: 2.3	D: 2
	Q: 358	Q: 371	Q: 519	Q: 353
	V: 1257	V: 939	V: 2611	V: 1238
Base Flows (cfs)	691(34.0%)	1117(58.2%)	1154(49.5%)	777(37.9%)
	282(59.9%)	277(75.5%)	567(67.9%)	356(56.0%)
	150(77.4%)	116(88.0%)	140(85.3%)	235(70.9%)
Subsistence Flows (cfs)	67(96.7%)	0(100.0%)	99(99.5%)	86(92.3%)
	Dec Jan Feb	Mar Apr May	Jun Jul Aug	Sep Oct Nov
	Winter	Spring	Summer	Fall

Flow Levels
High (75th %ile)
Medium (50th %ile)
Low (25th %ile)
Subsistence

High Flow Pulse Characteristics

F = Frequency (per season)
D = Duration (days)
Q = Peak Flow (cfs)
V = Volume (ac-ft)