ENHANCEMENT OF DURATION CURVE PREDICTIONS IN SOUTH GUAM USING SHORT TIME LOW FLOW MEASUREMENTS

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ABSTRACT

In order to properly manage a region's water resources, it is important for water managers to know the time variability of flow in the streams of that region. Not only what are the highest flows, such as what would be available from a flood frequency study, but also how the flows vary day to day, season to season, and year to year. Studies such as water supply studies, hydropower studies and those involving sediment transport depend on this kind of long term variability data in order to develop the best management practices for a region's water resources.

Guam is no different than other areas requiring water resources investigations. In order to properly carry out good water resources management, it is necessary to be able to define the variability of flow available in Guam's streams. This is normally done by direct analyses of streamflow data for the stream in question or by applying some sort of inferential technique from a gaged to an ungaged stream or from a gaged location on a stream to an ungaged location on that same stream. Of course, the most reliable means is to use actual stream flow data measured at the point of interest. The problem in Guam, as in most locations, is that stream flow information is not available for all possible sites where information is required. This study provides a better means of estimating the variability of flow at ungaged locations that are likely to become candidate sites for water resources investigations.

The flow duration curve provides us with a means of representing the variability of flow at a study site in a concise graphical fashion. Flow duration curves have proven to be useful in evaluation of surface water resources for water supply studies, hydropower design and planning studies, low flow studies such as in-stream flow requirements and other studies where it is desirable to define the variability of flows in streams.

A previous study titled "Prediction of Flow Duration Curves at Ungaged Sites in Guam" developed a means of predicting flow duration curves at ungaged stream sites in Guam. All of the major streams in Southern Guam were divided into stream reaches based on stream order and smaller stream segments based on similar average annual flow. Various statistical and analytical methods were applied to the existing streamflow data along with the physical characteristics of the reaches and segments in order to predict the streamflow variability in each stream reach.

The previous study revealed an issue in predicting accurately the low flow high exceedance percentage values at ungaged steam flow sites. This project developed a means of improving these low flow high percentage exceedance values using short time low flow measurements. The short time flow measurements were coupled with various statistical and analytical methods in order to improve the prediction of the low flow high exceedance values at ungaged sites. The methodology was tested on five ungaged flow sites in South Guam. Stream reaches along with the average reach flows and exceedance percentage flow values were identified on a set of GIS maps. These maps have been made available as part of the detailed Geographic Information System (GIS) map inventory of Guam available at the University of Guam, Water and Environmental Research Institute of the Western Pacific (WERI).

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INTRODUCTION

In order to properly manage a region's water resources, it is important for water managers to know the time variability of flow in the streams of that region. Not only what are the highest flows, such as what would be available from a flood frequency study, but also how the flows vary day to day, season to season, and year to year. Studies such as water supply studies, hydropower studies and those involving sediment transport depend on this kind of long term variability data in order to develop the best management practices for a region's water resources.

Guam is no different than other areas requiring water resources investigations. In order to properly carry out good water resources management, it is necessary to be able to define the variability of flow available in Guam's streams. This is normally done by direct analyses of streamflow data for the stream in question or by applying some sort of inferential technique from a gaged to an ungaged stream or from a gaged location on a stream to an ungaged location on that same stream. Of course, the most reliable means is to use actual stream flow data measured at the point of interest. The problem in Guam, as in most locations, is that stream flow information is not available for all possible sites where information is required. This study provided a better means of estimating the variability of flow at ungaged locations that are likely to become candidate sites for water resources investigations.

The flow duration curve provides us with a means of representing the variability of flow at a study site in a concise graphical fashion. Flow duration curves have proven to be useful in evaluation of surface water resources for water supply studies, hydropower design and planning studies, low flow studies such as in-stream flow requirements and other studies where it is desirable to define the variability of flows in streams.

A previous study titled "Prediction of Flow Duration Curves at Ungaged Sites in Guam" developed a means of predicting flow duration curves at ungaged stream sites in Guam (Heitz, L. F. and Sh. Khosrowpanah, 2014). All of the major streams in Southern Guam were divided into stream reaches based on stream order and smaller stream segments based on similar average annual flow. Various statistical and analytical methods were applied to existing streamflow data along with the physical characteristics of the reaches and segments in order to predict the streamflow variability in each stream reach.

The previous study revealed an issue in predicting accurately the low flow high exceedance percentage values at ungaged steam flow sites. This project developed a means of improving these low flow high percentage exceedance values using short time low flow measurements. The short time flow measurements were coupled with various statistical and analytical methods in order to improve the prediction of the low flow high exceedance values at ungaged sites. The methodology was tested on five ungaged flow sites in South Guam. Stream reaches along with the average reach flows and exceedance percentage flow values were identified on a set of GIS maps. These maps have been made available as part of the detailed Geographic Information System (GIS) map inventory of Guam available at the University of Guam, Water and Environmental Research Institute of the Western Pacific (WERI). (http://www.weriguam.org/)

STUDY AREA

As shown in Figure 1, the Island of Guam is located in the Western Pacific approximately 2,600 miles south east of Japan. Guam is a territory of the United States, and as of 2013 the population of the island was approximately 165,000. The land area of the island is approximately 212 square miles. Average annual rainfall on the island ranges from 80 to 120 inches per year. The topography of the South Guam study area is mountainous intersected with many streams. The more detailed map of Southern Guam in Figure 2 shows the many streams located on the south half of the island.

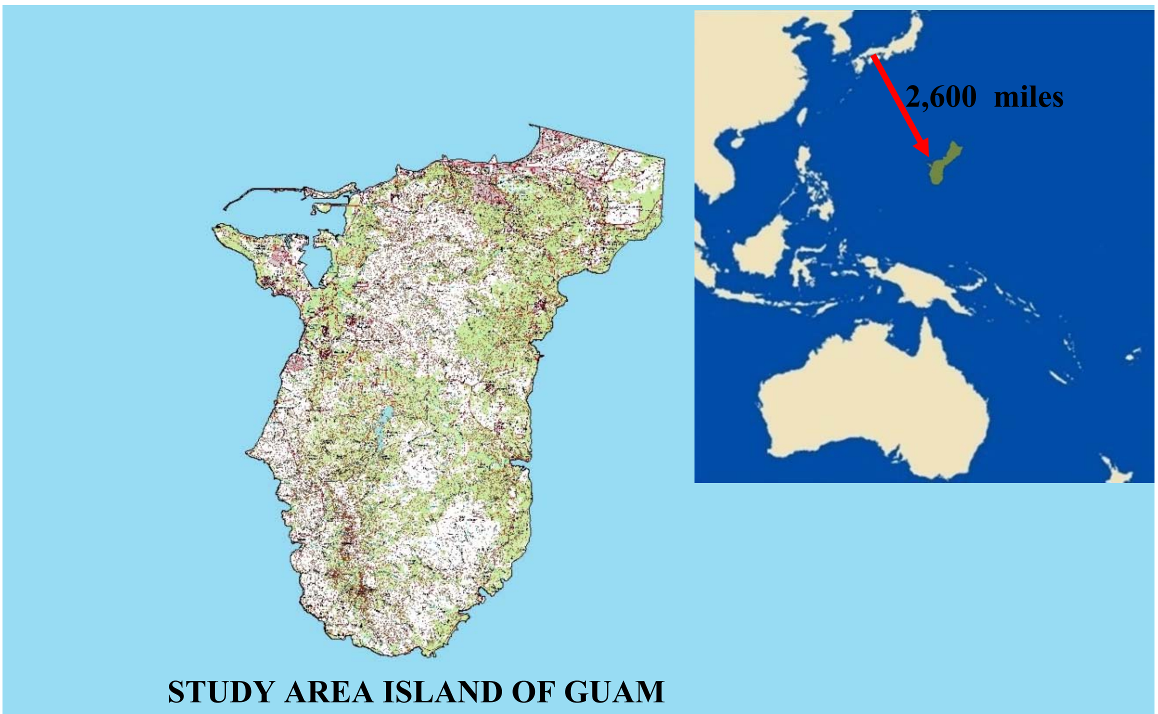


Figure 1. Guam study area and location map

Figure 2. South Guam showing streams

OBJECTIVES

The overall objective of this project was to enhance the prediction of low flow high exceedance value flows for ungaged streams sites in Southern Guam. These low flow values are essential for making studies of low flow requirements and availability of water for various surface water developments and to study the impacts of man's activities on stream flows

The study will use the historical record at presently active stream gage sites to predict duration curves at ungaged sites.

The specific objectives of the research were to:

1. Choose gaged stream sites and study periods to be used in the analysis.
2. Develop flow duration curves and parametric flow duration curves for the gaged stream sites. The parametric curves will be used for predicting duration curves for ungaged sites in South Guam.
3. Develop a means of predicting average flow and flow duration values at ungaged points on streams in South Guam.
4. Develop a set of GIS based maps showing the location and flow information for all stream reaches and segments.
5. Test the hypothesis that dry season low flow high exceedance values can be predicted at an ungaged site by averaging the exceedance values of the gaged flows for the same day.
6. Measure the streamflow at several ungaged sites during dry season and develop duration curves for the measured sites along with estimates of the dry season duration values using the average duration values at the gaged sites.

RELATED RESEARCH

Beginning in the late 70's the co-investigator of this project was involved with a large-scale project to predict the hydropower potential of the streams of the Pacific Northwest (Gladwell et al, 1979). Several different approaches were explored and the co-investigator for this project along with others developed the parametric duration curve technique that was applied in this project.

In 1984 the co-investigator for this project completed a study that used low flow short time flow measurement techniques to enhance low flow duration curve prediction in streams of Northern Idaho (Heitz, L. F. and J. R. Filler, 1984). Many of the techniques applied in this project were developed in this 1984 study.

The investigators on this project have recently completed similar duration curve prediction projects. These included studies for the islands of Pohnpei (Heitz, L. F. and Sh. Khosrowpanah, 2010), Kosrae (Heitz, L. F. and Sh. Khosrowpanah, 2012), and Guam (Heitz, L. F. and Sh. Khosrowpanah, 2014). The results of these three projects have provided valuable information to those carrying out water resources studies on those islands. The Guam study formed the basis for this project.

METHODS AND PROCEDURES

This project was divided into five phases. Each of these phases is described below.

PHASE I
Choose gaged stream sites and study periods to be used in the analysis

The first step in the study was to determine what stream flow data would be used and what period of analysis would be used for the data analysis that would be applied to the streamflow data. Figure 3 shows the location of all of the USGS stream gage sites that have ever been active in Guam. This study required that gage flow data be available at the time that stream flow measurements at ungaged sites are performed. Because of this, only presently active stream flow gages were used in the analysis. Figure 4 shows all of the presently active stream gages on Guam. Table 1 provides a description of each of the active stream gage sites. Figure 5 shows the availability of data at each of the active stream gage sites. The period of record, 9/14/2003 to 3/14/2016 was chosen as the common analysis period for the study. There was data available for all the gage sites during this 12.5-year period. The Imong stream flow gage data was dropped from consideration do to the fact that it had missing data during the study periods. The remaining five gages all had complete records for the study period

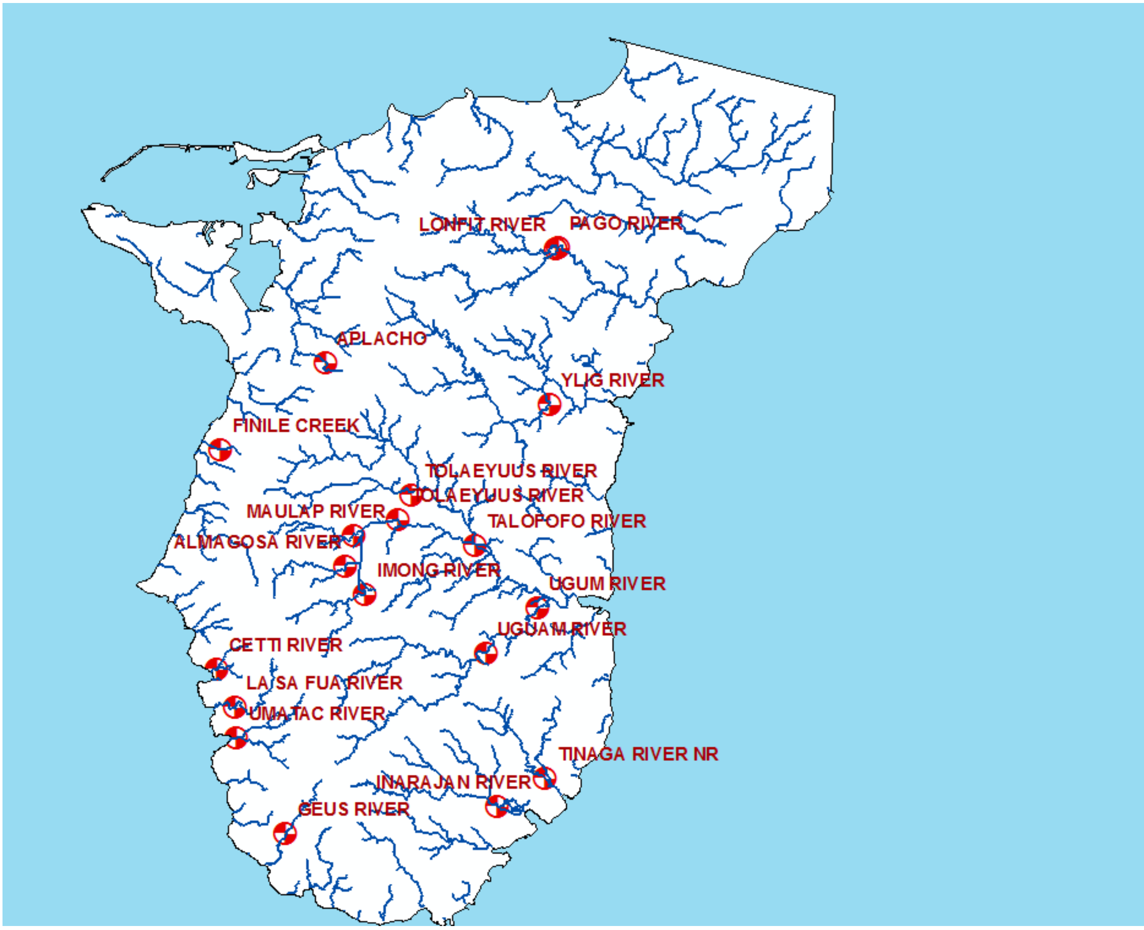


Figure 3. Location of all USGS stream gage sites past and present

Figure 4. Location of presently active USGS stream gage sites

GAGE NUMBER	NAME	DRAINAGE AREA
16809600	La Sa Fua River near Umatac, Guam	4.42
16847000	Imong River near Agat, Guam	9.71
16848100	Almagosa River near Agat, Guam	6.4
16848500	Maulap River near Agat, Guam	5.09
16854500	Ugum River above Talofofo Falls, nr Talofofo, Guam	24.34
1686500	Pago River near Ordot, Guam	25.7

Table 1. Description of active USGS gages on Guam

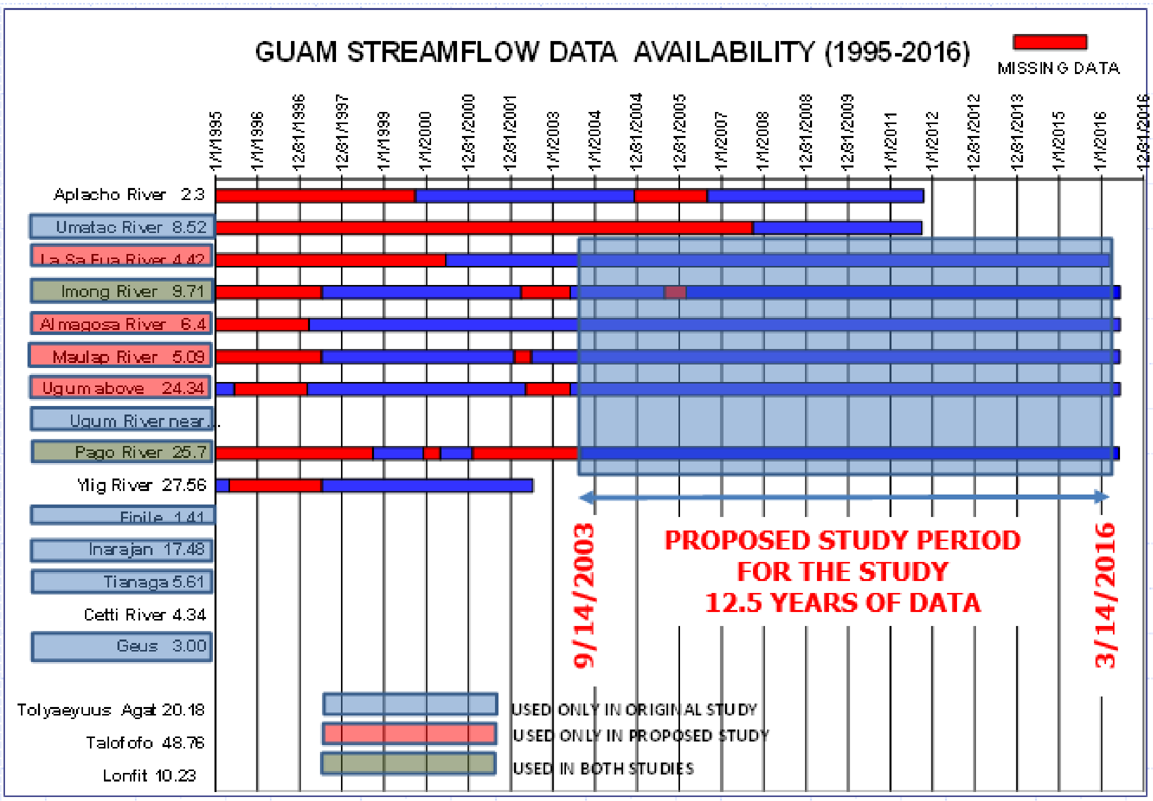


Figure 5. Availability of streamflow data from USGS gages on Guam

PHASE II
Develop flow duration curves for each gage site

The flow duration curve provides us with a means of representing the variability of flow at a study site in a concise graphical fashion. Figure 6 illustrates a daily flow duration curve for the Almagosa River at the USGS stream gaging station. The x axis of the graph is labeled percent of time flow is equaled or exceeded. The y axis is label flow in cfs. By reading horizontally across the graph from a particular flow value say 10 cfs and next moving vertically down from the intersection of flow value with the curve we can ascertain the exceedance percentage (16%) for that particular flow. This means that over the period of record that was used in the development of the flow duration curve a flow of 10 cfs was equaled or exceeded 10% of the time.

The average daily flow data required to develop flow duration curves for the South Guam active stream gages was downloaded from the United States Geological Survey (USGS) Pacific Islands Water Science Center web site http://hi.water.usgs.gov/. The daily flow data was separated by gage site and imported into a spreadsheet application. The flow data was ranked from low to high and the percentage of total values that equaled or exceeded each flow value was computed. An example of a daily flow duration calculations for the Almagosa River is shown in Table 2. A graph is made by plotting the exceedance percentage versus the value of flow for each of the ranked values. This graph is the daily flow duration curve. Figure 6 shows a typical flow duration curve for the Almagosa River in Guam. Note that the duration curve is normally plotted on a semi-log axis system. This is done because of the large variability between the high and low flows in the streams and to help straighten the flow duration curve for easier interpolation between values. This procedure was repeated for each of the gage sites in Guam. In addition to the duration values, the average annual flow was determined for each gage site. Figure 7 shows daily flow duration curves for the Maulap, Lasafua, Ugum, and Pago Rivers, in Guam. Data from all of these curves were used in the analyses which will be described later.

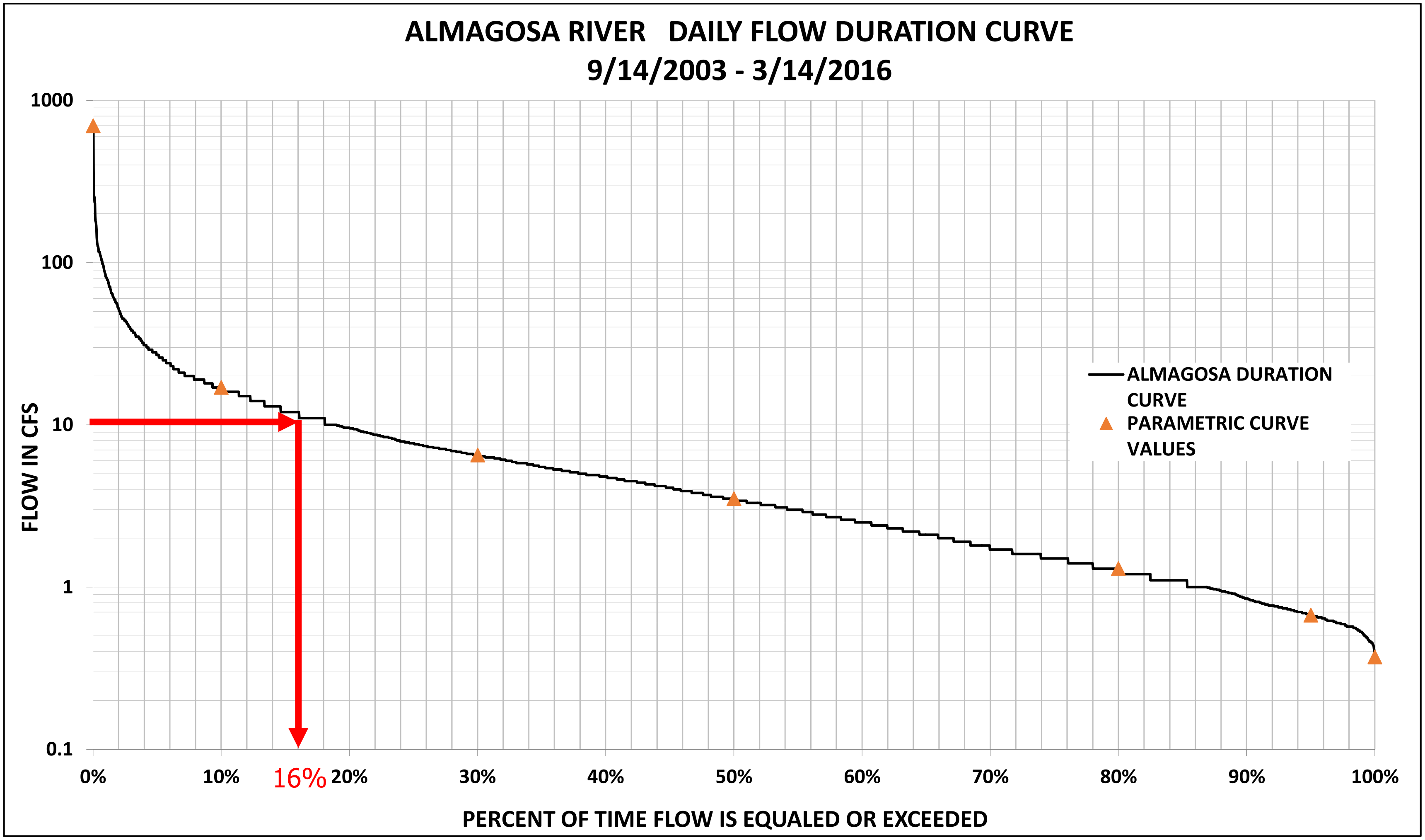


Figure 6. Flow duration curve for Almagosa River, Guam (2003-2016)

RANK	FLOW LOW TO HIGH (CFS)	EXCEEDANCE LOW TO HIGH (%)
1	0.37	100.0000%
2	0.39	99.9781%
3	0.41	99.9562%
4	0.42	99.9343%
5	0.43	99.9124%
6	0.44	99.8905%
7	0.44	99.8686%
8	0.44	99.8467%
9	0.45	99.8248%
10	0.45	99.8029%
11	0.45	99.7810%
12	0.45	99.7591%
13	0.46	99.7372%
14	0.46	99.7153%
15	0.46	99.6934%
16	0.46	99.6715%
17	0.46	99.6496%
18	0.46	99.6277%
19	0.46	99.6058%
20	0.46	99.5839%

Table 2. Flow duration calculation example for Almagosa River, Guam, (2003-2016)

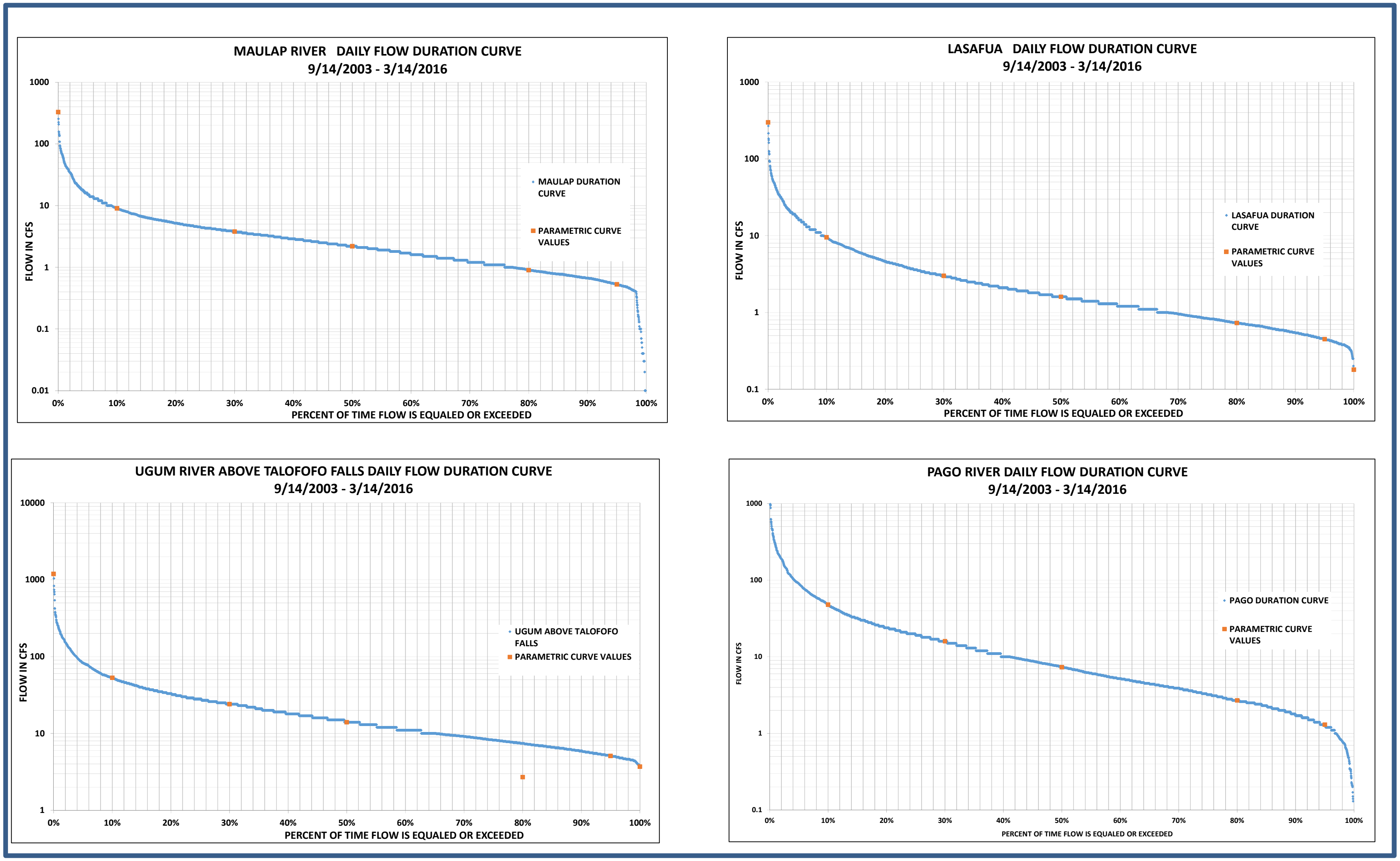


Figure 7. Flow duration curve for Maulap, Lasafua, Ugum, and Pago Rivers, Guam (2003-2016)

PHASE III
Predict duration curves at ungaged sites

Phase III involved the application of a technique to predict duration curves at ungaged sites on Guam. This step is important because many sites where flow information is desired are not located at or near stream gage locations. Some sites may be located upstream or downstream from gaged locations and some may be located on streams where no previous stream flow records are available.

The method that was applied involved the development of parametric curves of flow versus average annual flow for chosen specific exceedance percentages. This method was originally developed by the co-investigator in a study of hydropower potential in the Pacific Northwest. (Gladwell, et al, 1979). The method was applied to all of the streams in Idaho to assist in determining the hydropower potential for that state.

The first step in applying the method was to take the flow values for the key exceedance percentages of Q(95%), Q(80%), Q(50%), Q(30%)), Q(10%) , and Q(0%) from each of the gaged site duration curves developed in Phase II. These particular exceedance values were chosen because these percentages provide a good distribution of exceedance flow values from low flows to high flows. Next the average annual flow was computed for each site. The values of $Q_{(\text{exceedance }\%)}$ vs Average Annual Flow were plotted for each exceedance value at each site and a best fit curve was matched to the data sets. A separate curve was developed for each key exceedance value (0% through 95%). The resulting parametric curves are shown in Figure 8.

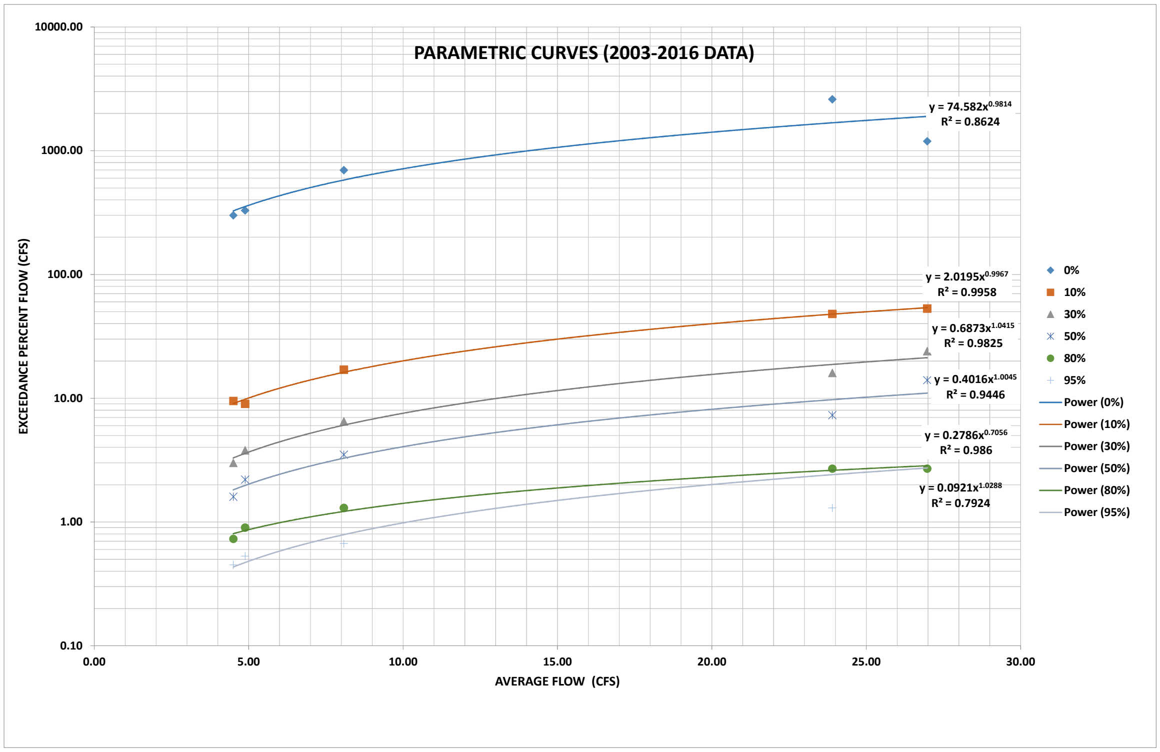


Figure 8. Parametric flow duration curves for South Guam streams

The best fit equations are shown at the end of the curves for each exceedance percentage. Although there were a limited number of data points, the high R^2 values indicate a very good fit to the data by the prediction equations for most of the curves. Even the poorest fit, Q(95) equation, resulted in an explanation of 79% of the variability between average flow and the Q(95) values. These equations were used later to predict actual flows at ungaged sites or stream reaches. The regression equations took the form:

$$Q(percent) = Constant \times (Q(average\ annual))^{Power}$$

Table 3 shows the regression equations constants and R squared value for each of the regression equation developed. Figure 9 shows an example of using the parametric duration curves to predict the flow duration curve values for an ungaged site with an average annual flow of 25 cfs.

An earlier study (Heitz and Khosrowpanah, 2014) used a slightly different data set of stream flow data for the development parametric duration curves. That study was able to use all historical data (active and discontinued gages). Figure 10 shows the parametric curves for that study. Table 4 shows the regression equations constants and R squared values for each of the regression equation developed for the 2014 study along with those developed for this study. Note that the high exceedance percentage (95%) values had considerably lower R Squared values than those for the other exceedance values. This illustrates the need for a means to refine those high exceedance value estimates. In this study we were required to use only data from stream sites that are presently active on Guam. The reason being that we required data from active stream gages to supplement the real-time flow measurements that were made. These analyses will be described later in this report.

PERCENT	CONSTANT	POWER	R^2
0	74.582	0.9814	0.8624
10	2.0195	0.9967	0.9958
30	0.6873	1.0415	0.9825
50	0.4016	1.0045	0.9446
80	0.2786	0.7056	0.986
95	0.0921	1.0288	0.7924

Table 3. Regression equation parameters and R Squared values for each of the regression equations (2003-2016 data)

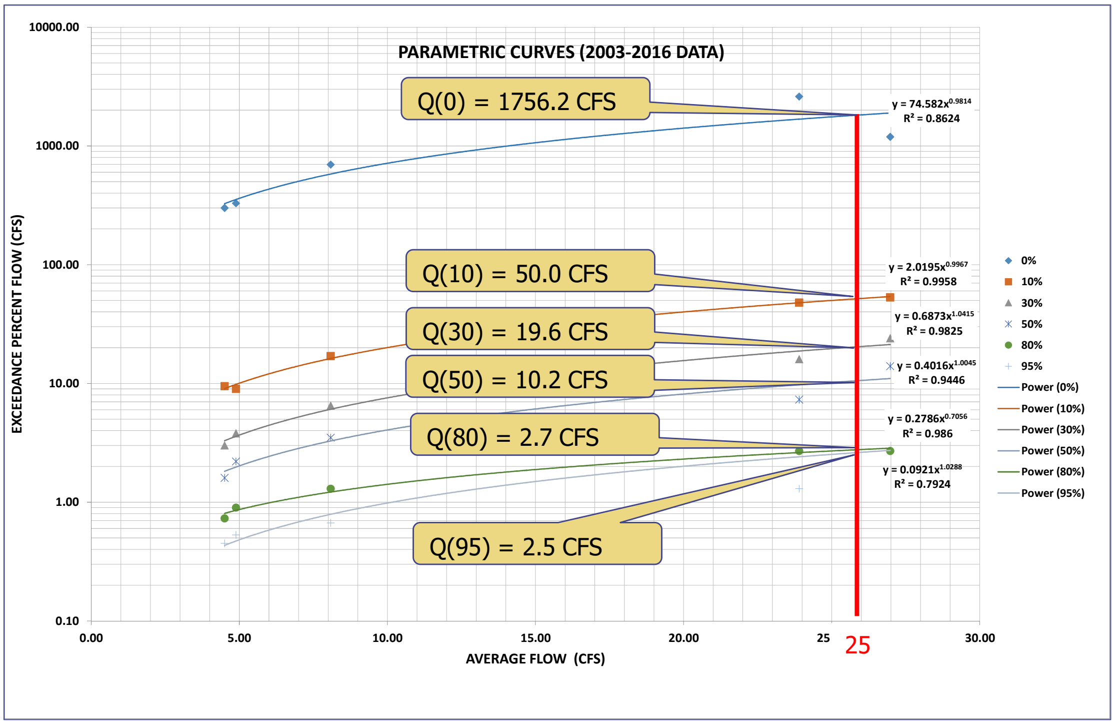


Figure 9. Use of parametric flow duration curves to predict flow duration values at an ungaged site with an average flow of 25 cfs (2016 Study)

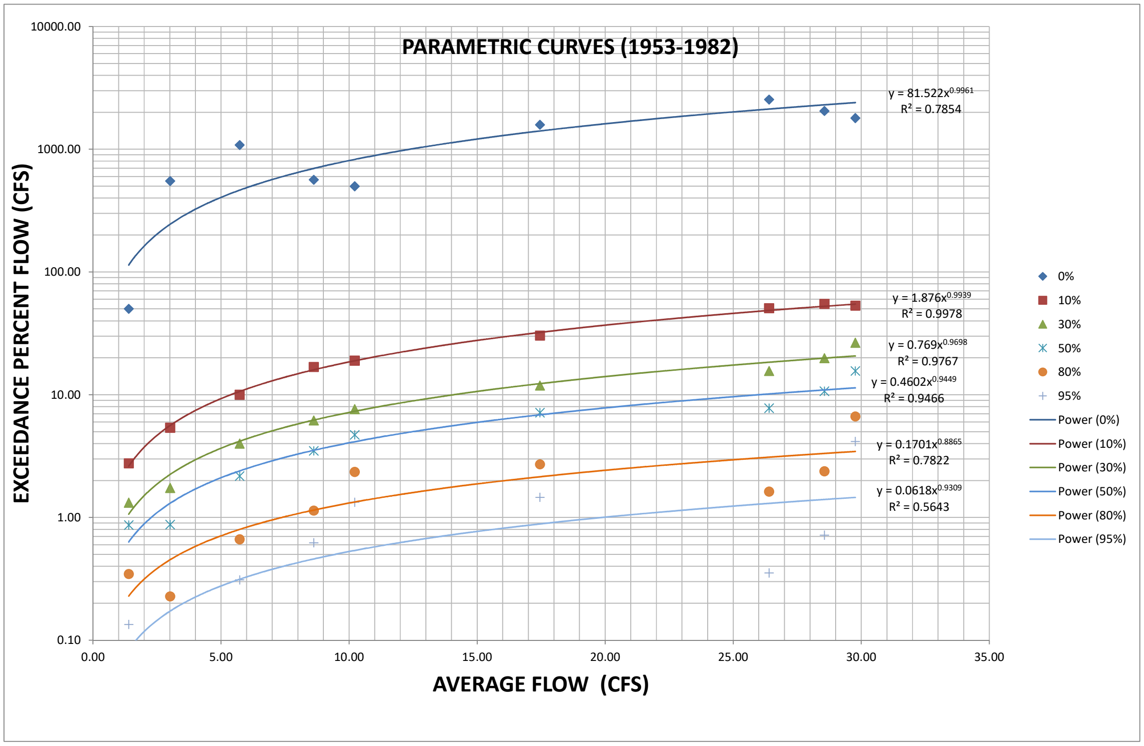


Figure 10. Parametric flow duration curves from 2014 study

2014 STUDY

PERCENT	CONSTANT	POWER	R^2
0	81.5220	0.9961	0.7854
10	1.8760	0.9939	0.9978
30	0.7690	0.9698	0.9767
50	0.4602	0.9449	0.9466
80	0.1701	0.8865	0.7822
95	0.0618	0.9309	0.5643

2016 STUDY

PERCENT	CONSTANT	POWER	R^2
0	74.582	0.9814	0.8624
10	2.0195	0.9967	0.9958
30	0.6873	1.0415	0.9825
50	0.4016	1.0045	0.9446
80	0.2786	0.7056	0.986
95	0.0921	1.0288	0.7924

Table 4. Regression equation parameters and R Squared values for each of the regression equations for the 2014 and present studies

PHASE IV
Predict average flow at ungaged points on streams

The starting point for this phase of the project was a set of GIS maps that were developed for the previous 2014 study (Heitz and Khosrowpanah, 2014). This project developed a means of estimating average flows at ungaged points on Guam's streams. The GIS techniques used are thoroughly described in the 2014 publication.

This phase began with the precipitation input GIS map that were developed in 2014. An example of a portion of that map is shown in Figure 11. First a runoff factor is computed for each study gage station. This factor is the ratio of the average annual flow at the station to the average annual precipitation input from the precipitation input GIS map. Table 5 show a listing of the computed runoff factors for all of the study gages. If we plot the precipitation input versus the average annual flow for each of the stream flow gage station we get the graph that is shown in Figure 12. If we fit a linear curve to the data we get the equation shown in Figure 12. The regression equation shown in Figure 12 was applied to the precipitation input grid using the grid Raster Calculator Tool of the Spatial Analyst Toolbar. The resulting grid, a portion of which is shown Figure 13, is an average annual flow grid map for all streams in south Guam.

Reach flow maps were developed by applying the methods described in the 2014 study to the precipitation input grid maps discussed above. Flow duration values were calculated using the parametric duration curve data developed in Phase III. Figure 14 shows a portion of the small stream segment polyline maps for South Guam. This map includes the average annual flow for each segment along with the exceedance percentage flows for the flow duration curve for each stream segment. Figure 15 shows South Guam stream segments with the reach median average annual flows shown in cfs.

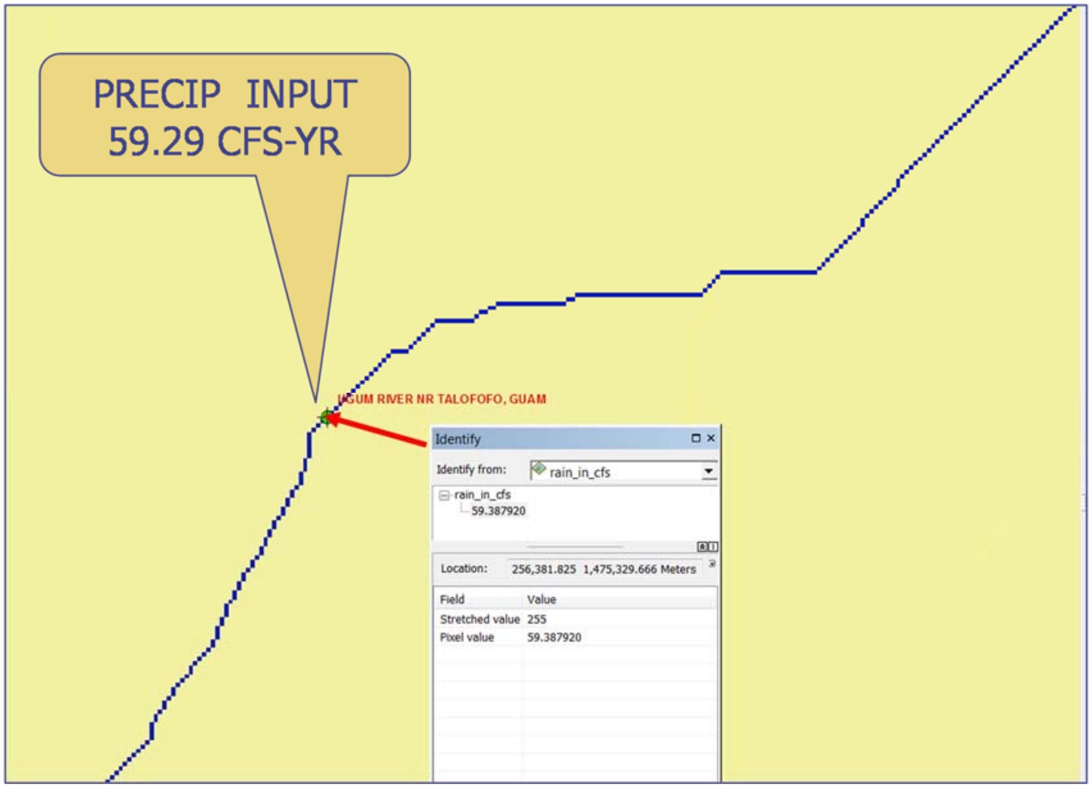


Figure 11. Precipitation input grid (from 2014 study) on the Ugum River near the Talofofo stream gage site

GAGE	AVERAGE FLOW (CFS)	PRECIP INPUT (CFS)
LASAFUA	4.50	8.613
ALMAGOSA	8.08	11.3943
MAULAP	4.88	10.7671
UGUM	26.97	50.4873
PAGO	23.90	40.9077

Table 5. Average runoff and precipitation input (average rainfall accumulation) for Guam's stream gage stations used in the analysis

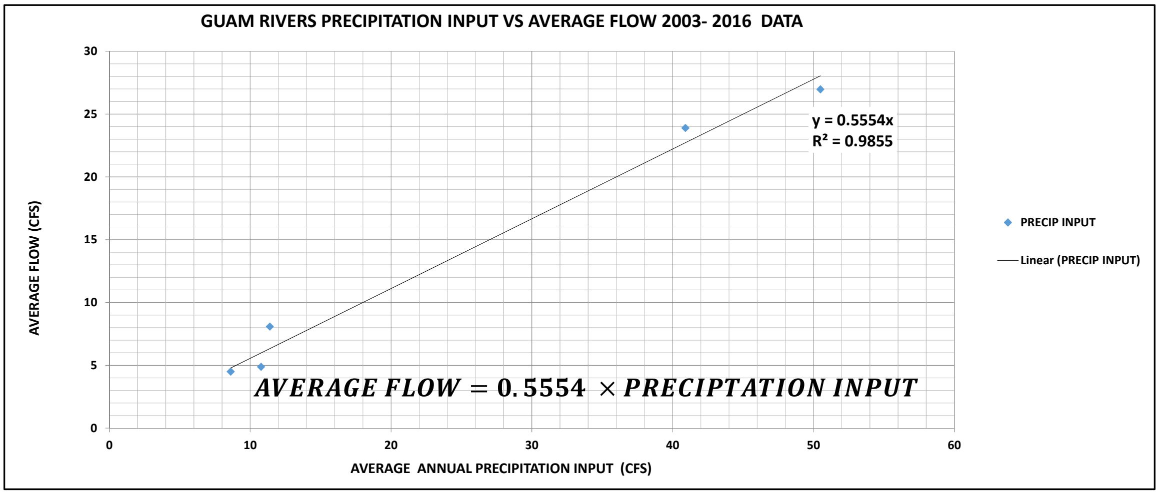


Figure 12. Average flow vs precipitation input for Guam's rivers (2016 data)

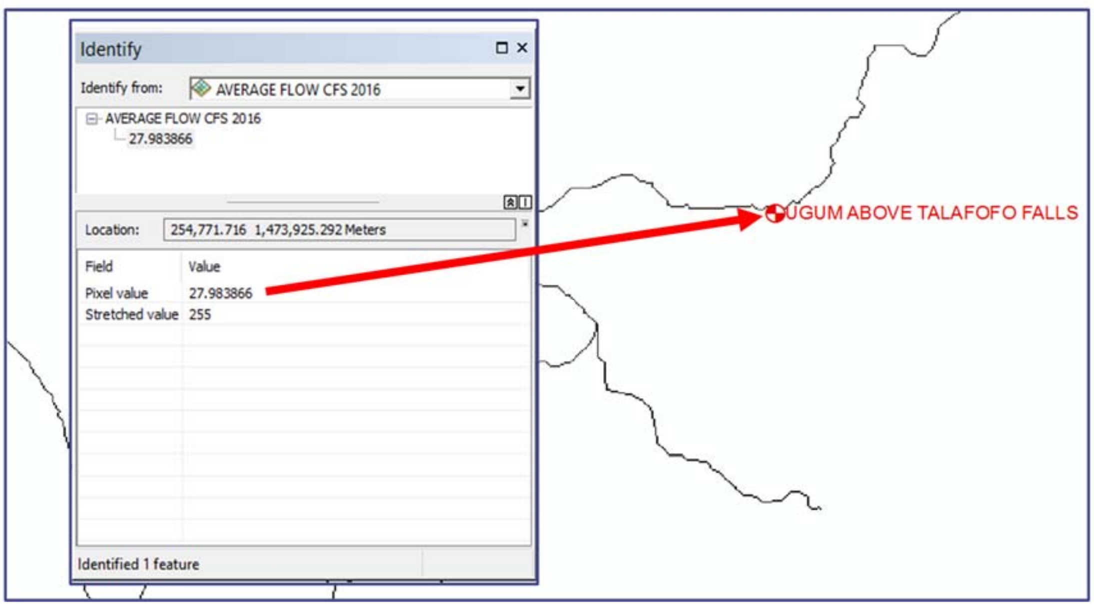


Figure 13. Average flow grid near the Ugum river stream gage site

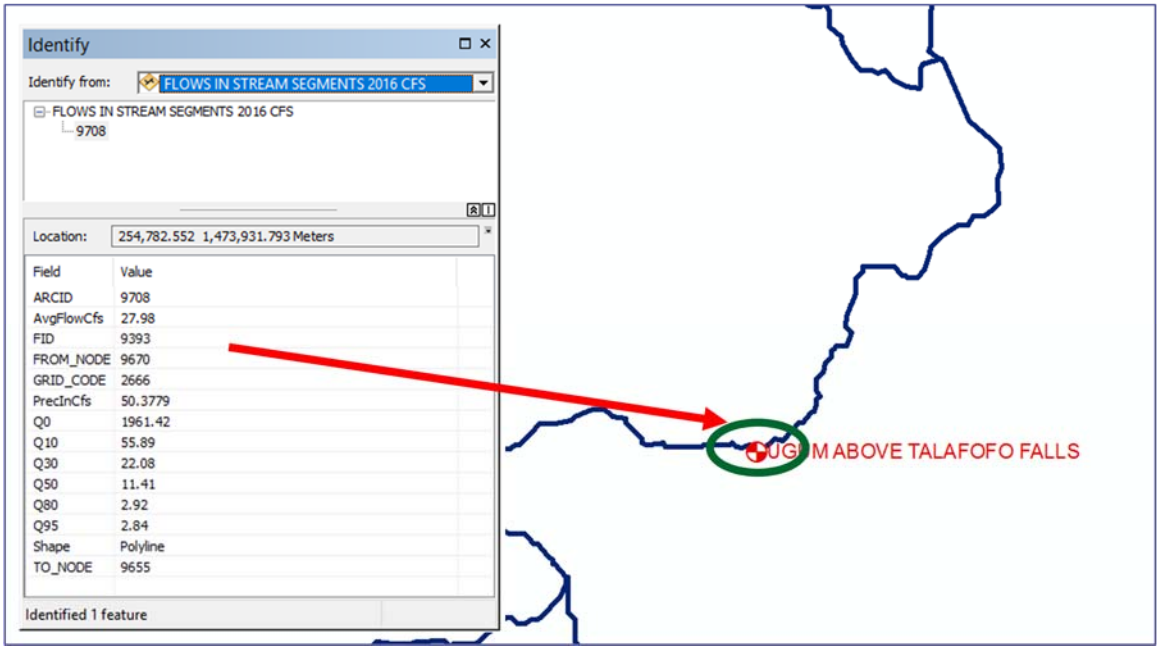


Figure 14. Small stream segment polyline map showing average annual flows and exceedance percent flows

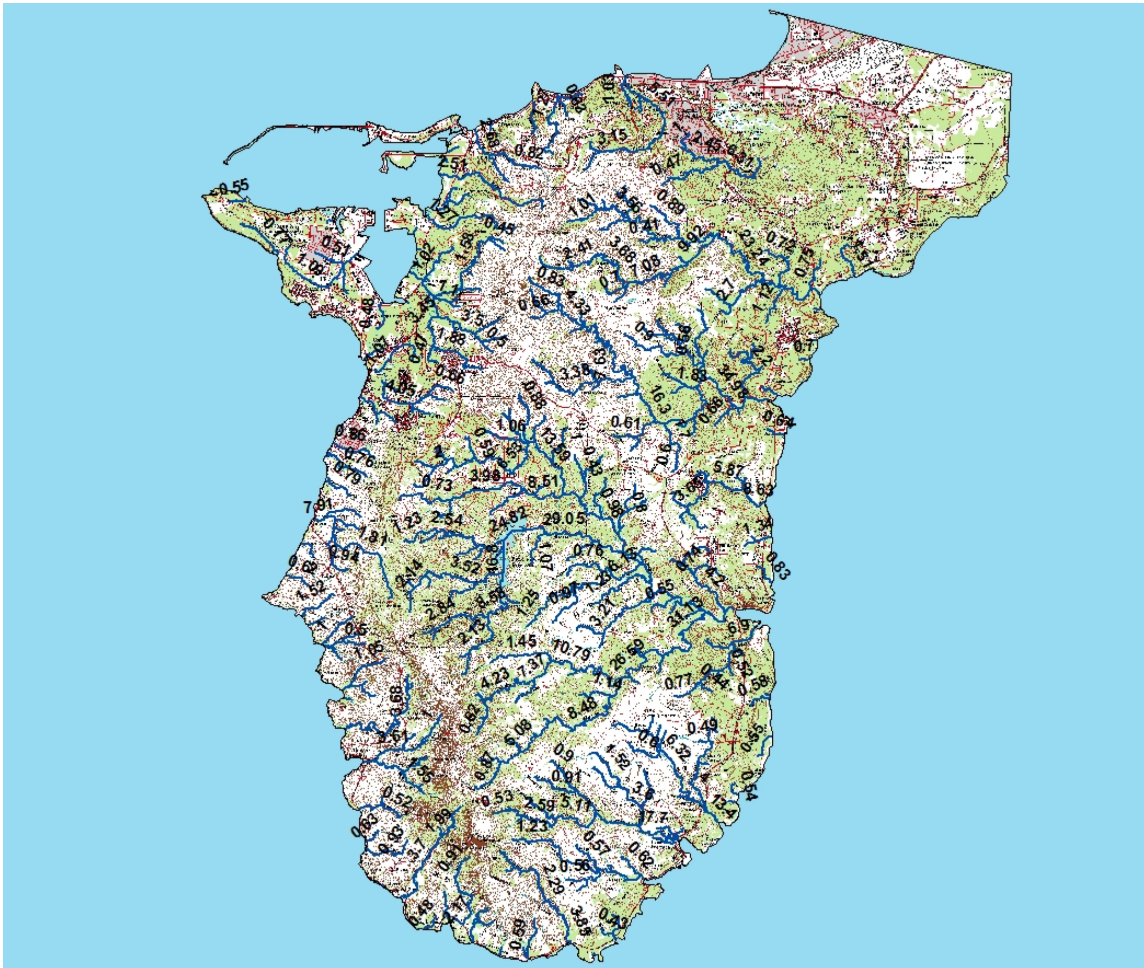


Figure 15. South Guam streams showing the median reach average annual flows in cfs

PHASE V

Predict dry season low flow high duration percent values

In this Phase of the work we explored the hypothesis that dry season low flow high exceedance value can be predicted at an ungaged site by averaging the exceedance values at the gaged flows for the same day. A previous study titled "Prediction of Flow Duration Curves at Ungaged Sites in Guam" (Heitz and Khosrowpanah, 2014) developed a means of predicting flow duration curves at ungaged stream sites in Guam. All of the major streams in Southern Guam were divided into stream reaches based on stream order and smaller stream segments based on similar average annual flow. Various statistical and analytical methods were applied to the existing streamflow data along with the physical characteristics of the reaches and segments in order to predict the streamflow variability in each stream reach. The techniques used are describe in Phase III and Phase IV above.

The previous study revealed an issue in predicting accurately the low flow high exceedance percentages values at ungaged steam flow sites. This phase of the project developed a means of improving these low flow high percentage exceedance values using short time low flow measurements. The short time flow measurements were coupled with various statistical and analytical methods in order to improve the prediction of the low flow high exceedance values at ungaged sites.

The co-investigator for this project completed a study that also used low flow short time flow measurement techniques to enhance low flow duration curve predictions in streams of Northern Idaho. (Heitz, L. F. and J. R. Filler, 1984). Many of the techniques applied in this project were developed in this 1984 study.

The steps in the technique for making improvements to low flow high percentage duration value predictions at a stream site on Guam are:

1. Measure flow at an ungaged stream site of interest several times during the low flow period (dry season).
2. Determine the flows at the active gaged streamflow sites in South Guam for the same days the ungaged site was measured.
3. Determine average of the exceedance percentage values for the flows at the gaged sites
4. Assign the average of the exceedance percentage values of the flows at the gaged sites to the flow at the ungaged site.

The key issue in applying this technique is step 4. above is **"Assign the average flow duration value of the gages to the flow at the ungaged site"**. The hypothesis that the flow duration exceedance value at an ungaged site can be estimated by averaging the flow duration exceedance values at nearby gage streams for the same day sounds reasonable, but we must first test this hypothesis to determine if acceptable results occur by applying the technique. We performed what we called a "Dummy Gage Analysis" to test our hypothesis. A description of this analysis follows.

DUMMY GAGE ANALYSIS

The steps in the dummy gage analysis were:

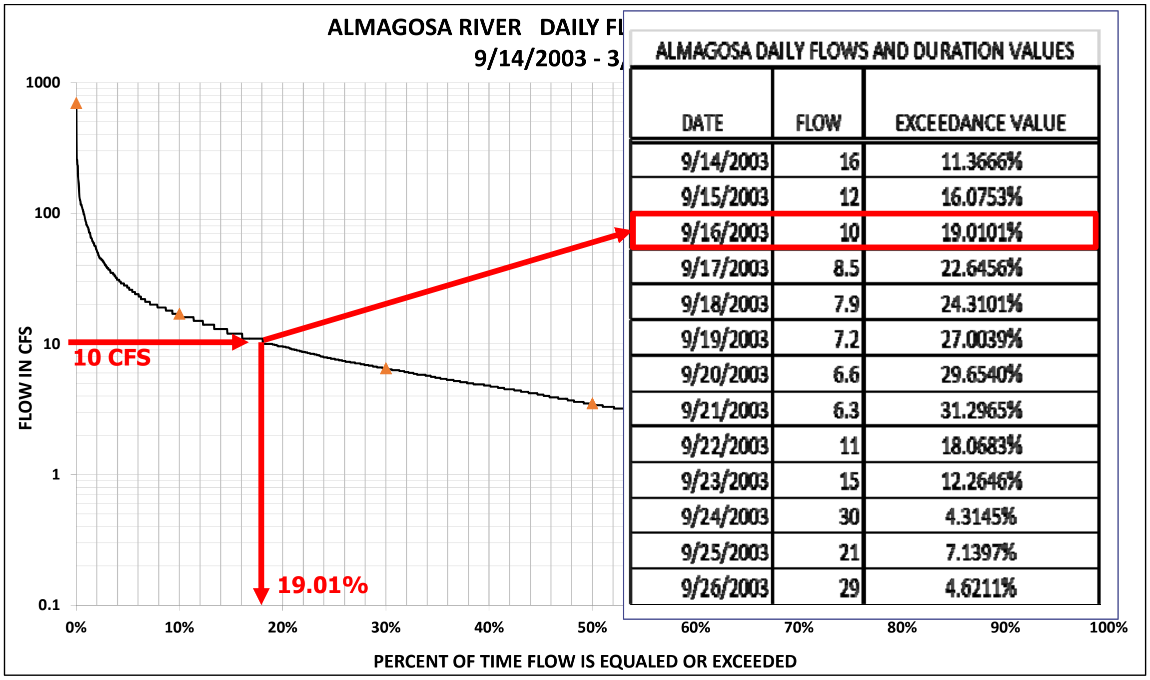
1. Determine the exceedance percent value for all the daily flows for all the study gages in South Guam for a common period of record.
2. Choose one of the known gages as the dummy or test gage.
3. Assign the average exceedance percent value of the other gages to the exceedance percent at the dummy site (for chosen dry season dates)
4. Repeat for all active gages
5. Test the accuracy of our predictions using standard statistical techniques.

Figure 16 provide an easy reference for the locations of the five gages that were used in the dummy gage analysis.

The first step in the dummy gage analysis was to determine average daily flow exceedance percent values for all the daily flows for all the gages shown in Figure 16. This was done for the common period of record (9/14 2003 to 3/14/2016) that was described in Phase II in developing flow duration curves for the gage sites. Figure 17 shows an example of choosing exceedance percentage values for the flows in the gage record for the Almagosa River stream gage. This procedure was repeated for all days in the analysis period for all five of the study gages. We then had a complete data set from which to pick flow and exceedance percent data for our dummy analysis. We next assigned the first gage as a dummy gage. For each day of our study period we created a new data set with the first column being the date, the second column being the exceedance percentage at the dummy gage, and the third column being the average exceedance percent for the other four gages. This step was repeat making each of the gages assume the role of dummy gage. Table 6 shows a portion of the data set for the Lasafua River.

Since we were looking for low flow data to use in our dummy analysis we wanted to look for days during the dry season (January-June) where rainfall did not affect the normal dry season low flows. The second criteria we used was to consider low flows as those that are exceeded more than 70% of the time. We used a special Excel multi-parameter viewer application to pick the study dates for the dummy analysis. A screen from one year (2015) from the viewer application is shown in Figure 18. It is quite easy to observe which areas of the exceedance flow plot are greater than 70%. It is also easy to see the effect of rainfall during the dry season. All dry seasons dates between 9/14 2003 to 3/14/2016 were included in the analysis period. Table 7 shows the dry season dates that were chosen from the analysis period that met the greater than 70% exceedance flow and were not effected by preceding rain fall. We picked off flow and exceedance percent and average of other gage exceedance percent values for each of the study dates. This procedure was repeated for each of the gages as the dummy gage. A portion of the resulting data set is shown in Table 8.

Figure 16. Location of presently active USGS stream gage sites that were used in the Dummy gage analysis



DATE	FLOW	EXCEEDANCE VALUE
9/14/2003	16	11.3666%
9/15/2003	12	16.0753%
9/16/2003	10	19.0101%
9/17/2003	8.5	22.6456%
9/18/2003	7.9	24.3101%
9/19/2003	7.2	27.0039%
9/20/2003	6.6	29.6540%
9/21/2003	6.3	31.2965%
9/22/2003	11	18.0683%
9/23/2003	15	12.2646%
9/24/2003	30	4.3145%
9/25/2003	21	7.1397%
9/26/2003	29	4.6211%

Figure 17. Choosing exceedance percent values for flows in Almagosa Flow record

LASAFUA AS DUMMY		
DATE	LASAFUA (%)	AVERAGE OF OTHERS (%)
9/14/2003	10.1183%	20.4774%
9/15/2003	20.2146%	26.5495%
9/16/2003	29.4788%	30.0756%
9/17/2003	33.9466%	29.7197%
9/18/2003	35.3263%	33.3333%
9/19/2003	33.9466%	33.7768%
9/20/2003	37.6697%	29.1448%
9/21/2003	11.4980%	24.4525%
9/22/2003	17.4770%	15.8892%
9/23/2003	4.8839%	7.6873%
9/24/2003	3.3290%	5.3274%
9/25/2003	8.1253%	8.8425%
9/26/2003	4.1612%	9.2587%

Table 6. Portions of the dummy gage data set for the Lasafua River

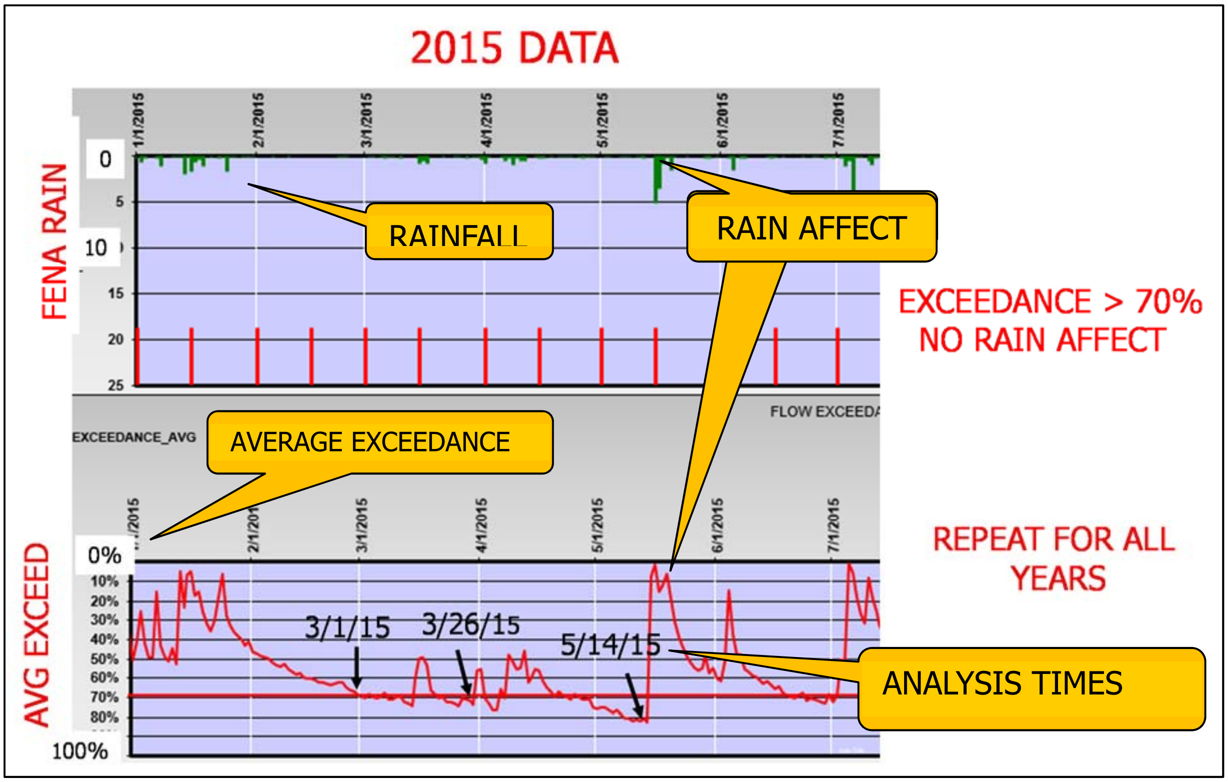


Figure 18. Excel multi-parameter viewer application used to pick the study dates for the dummy analysis

SAMPLING DATE 2004-2005	SAMPLING DATE 2006-2007	SAMPLING DATE 2008-2009	SAMPLING DATE 2010-2011	SAMPLING DATE 2012-2013	SAMPLING DATE 2013-2014
4/1/2004	3/1/2006	3/25/2008	2/15/2010	3/10/2012	3/29/2014
5/1/2004	3/15/2006	4/1/2008	2/28/2010	4/7/2012	4/14/2014
5/12/2004	4/1/2006	4/15/2008	3/15/2010	4/21/2012	4/23/2014
5/26/2004	4/15/2006	5/5/2008	4/1/2010	1/15/2013	5/18/2014
6/4/2004	5/1/2006	6/10/2008	4/16/2010	2/4/2013	6/4/2014
1/31/2005	5/13/2006	2/1/2009	5/2/2010	2/25/2013	6/16/2014
3/11/2005	6/11/2006	2/15/2009	5/22/2010	3/11/2013	3/1/2015
4/1/2005	6/20/2006	3/3/2009	6/1/2010	3/17/2013	3/26/2015
5/1/2005	7/1/2006	4/1/2009	6/15/2010	4/9/2013	5/14/2015
5/15/2005	1/23/2007	4/15/2009	4/22/2011	4/25/2013	6/29/2015
5/30/2005	2/21/2007	4/24/2009	4/30/2011	5/26/2013	
6/15/2005	4/1/2007	6/1/2009	5/9/2011	6/3/2013	
	4/15/2007	6/26/2009	6/12/2011	6/26/2013	
	5/6/2007		6/17/2011	7/19/2013	
	6/1/2007			8/11/2013	
	6/15/2007				
	7/1/2007				

Table 7. Sampling dates chosen meeting greater that 70% exceedance and no preceding rainfall criteria

EXCEEDANCE DATA FOR DRY SEASON NO RAIN TIMES										
DATE	LASAFUA	ALL OTHERS	ALMAGOSA	ALL OTHERS	MAULAP	ALL OTHERS	UGUM	ALL OTHERS	PAGO	ALL OTHERS
4/1/2004	74.00%	74.36%	87.36%	71.02%	69.58%	75.47%	75.54%	73.98%	64.98%	76.62%
5/1/2004	83.90%	85.91%	89.66%	84.47%	72.40%	88.78%	85.48%	85.51%	96.08%	82.86%
5/12/2004	94.72%	86.85%	92.14%	87.49%	69.58%	93.13%	89.60%	88.13%	96.08%	86.51%
5/26/2004	99.61%	84.87%	85.35%	88.44%	75.89%	90.80%	94.06%	86.26%	84.19%	88.73%
6/4/2004	99.61%	88.82%	88.85%	91.51%	80.20%	93.67%	97.07%	89.45%	89.16%	91.43%
1/31/2005	68.83%	73.95%	80.03%	71.16%	72.40%	73.06%	68.62%	74.01%	74.77%	72.47%
3/11/2005	81.45%	84.59%	96.98%	80.71%	72.40%	86.85%	84.78%	83.75%	84.19%	83.90%
4/1/2005	79.22%	84.18%	97.79%	79.54%	75.89%	85.01%	82.68%	83.32%	80.38%	83.89%
5/1/2005	96.58%	92.06%	95.49%	92.33%	79.72%	96.27%	98.86%	91.49%	94.15%	92.66%
5/15/2005	96.25%	92.55%	92.77%	93.42%	83.14%	95.83%	99.17%	91.82%	95.12%	92.83%
5/30/2005	98.42%	95.72%	93.93%	96.84%	90.19%	97.78%	99.93%	95.34%	98.82%	95.62%

Table 8. Portions of the dummy gage data set for the dry season no rainfall effect days that were selected

We used regression analysis to test the validity of our hypothesis that the exceedance percentage for a flow measured at an ungaged site could be predicted by averaging the exceedance percentages for the gaged sites. The basic equation that represents our hypothesis is:

$$\boldsymbol{Y = bX}$$

Where:

Y = exceedance percentage of the flow at our ungaged site (represented by the dummy gage)

X = average of the exceedance values for the other gage sites

The above equation is a simple linear equations with a zero intercept. We will test our hypothesis by doing a simple linear regression (with zero intercept) analysis of our dummy gage data set. We first did separate regression analysis for each of the gages assumed as the dummy gage. Figure 19 shows an example of the regression analysis using the Lasafua exceedance percent as the Y variable and the average of exceedance percent of all the other gages as the X variable. The R^2 value for this regression is 0.634. Meaning that 63.4% of the variation between y and x is explained by the regression. The slope coefficient given by the regression is 1.0152. If that value was exactly 1.0 it would support our hypothesis that exceedance percent of dummy gage is equal to average of other gages.

We repeated the regression analysis substituting each of the gages as a dummy gage. We also did a regression analysis that included all of the dummy gages in one data set. The results of this regression is shown in Figure 20. The results of all of the regression analyses are summarized in Table 9. The slope coefficient for the individual dummy gage regressions varied from 0.9846 to 1.0152 all supporting our hypothesis that the dummy exceedance are equal to the average of other gage exceedance. The R^2 values ranged from 0.4555 to 0.7377 indicating that 45 to 74 percent of the variability between x and y is explained by the regression. The slope coefficient for the combination of all dummy gages data was 0.9996. This strongly supports our one to one relationship between dummy gage values and those for the average of all gages. The R^2 values was 0.5948 indicating that 59% percent of the variability between our variables is explained by the regression. The 95% confidence bounds for the regressions using the full data set are shown in Figure 21.

We now have strong support for our hypothesis that there is a one to one correspondence between dummy gage values and the average of the other gages. We can also compute the range of predictions that would result from using this one to one correspondence. We will use this one to one correspondence relationship in our later studies. In those studies, we will assume that the flows measured at an ungaged site can be assigned the exceedance percentage of the average exceedance value for the flows of the active gage sites in South Guam.

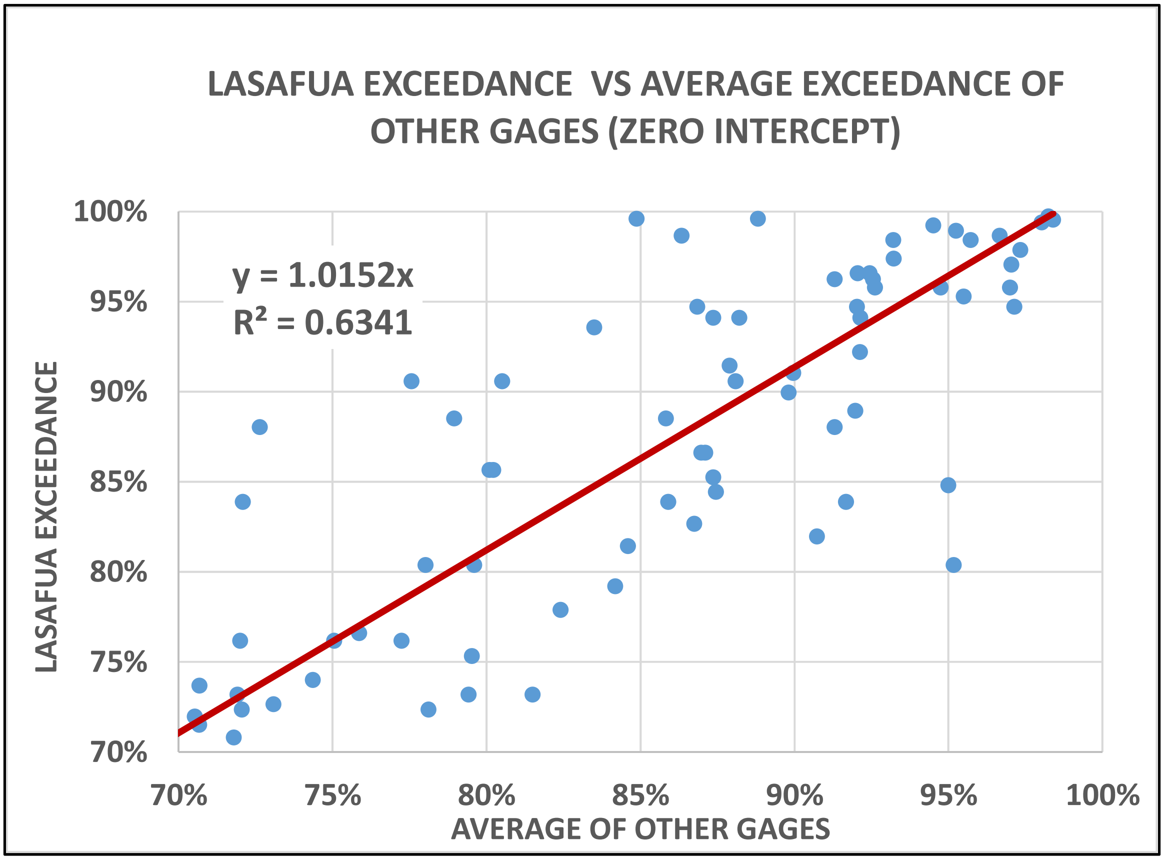


Figure 19. Zero intercept regression analysis for Lasafua exceedance percent vs average of the exceedance percent of all others

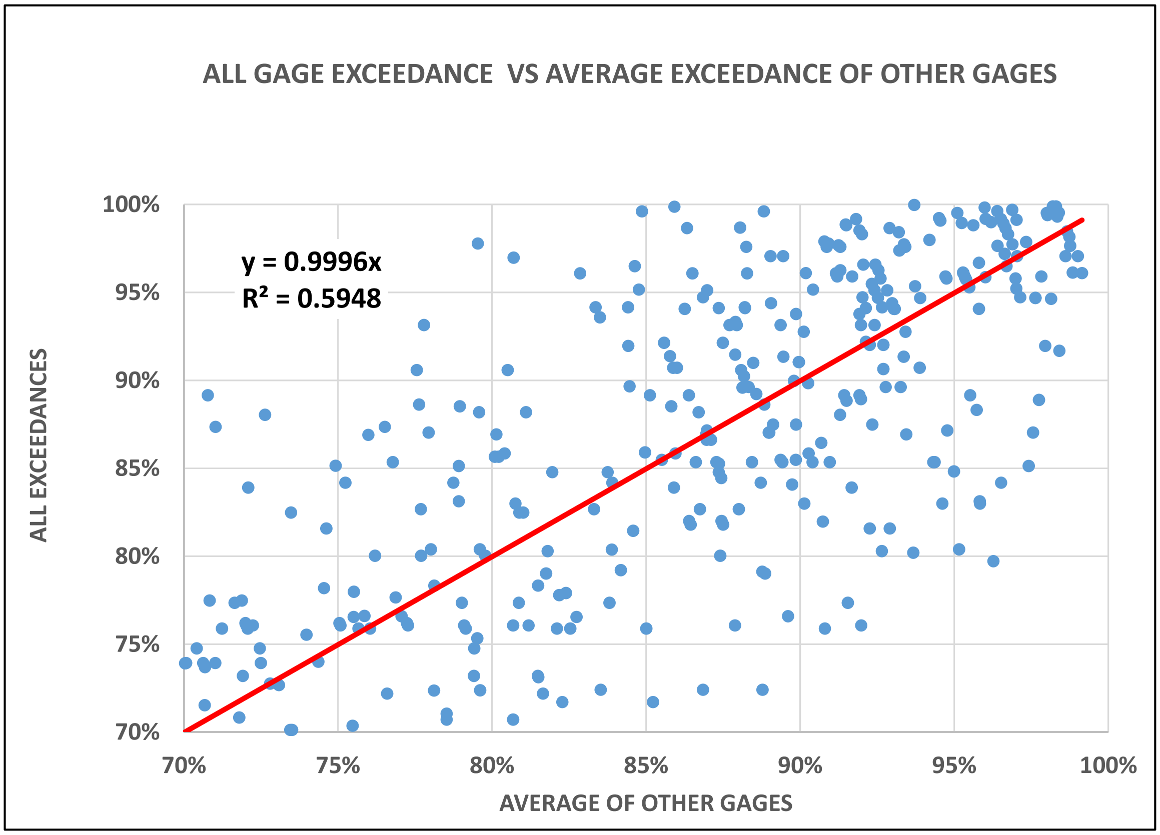


Figure 20. Zero intercept regression analysis for all dummy gages combined

DUMMY GAGE	SLOPE	R SQUARED
LASAFUA	1.0152	0.6341
MAULAP	0.9881	0.4555
PAGO	1.0092	0.5069
UGUM	0.9846	0.7377
COMBINED	0.9996	0.5948

Table 9. Regression parameters for dummy gage vs average of others gages exceedance percent for each dummy gage and the combination of all dummy gages

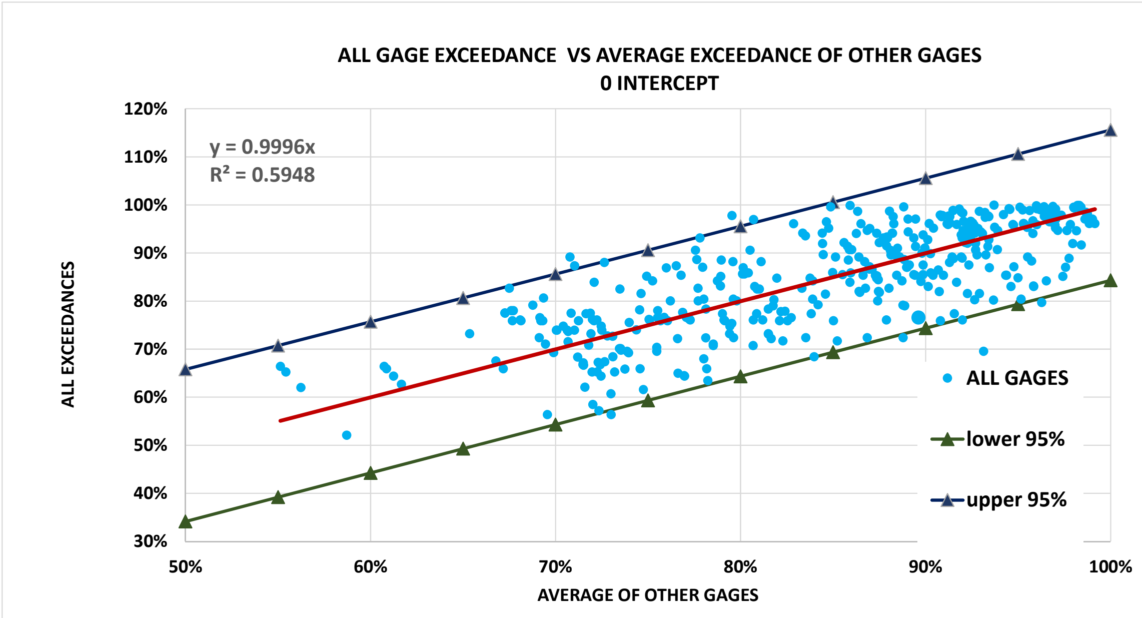


Figure 21. Confidence bounds for zero intercept regression analysis for all dummy gages combined

PHASE VI

Measure dry season flows at ungaged sites and predict enhanced duration curves

The purpose of this phase of the study is to develop enhanced duration curves for several stream sites using the techniques developed in the first four phases of the study. The steps that were carried out in this phase are:

1. Develop flow duration curves for the ungaged sites using the techniques and parameters developed in Phase II.
2. Measure flows at ungaged sites several times during the low flow period (dry season).
3. Determine flows at gaged streamflow sites in south Guam for the same times as flows are measured at the ungaged sites.
4. Determine average flow exceedance values for all of the gaged sites for each time the ungaged sites are measured.
5. Assign the average flow exceedance value of the gages to the flow duration at the ungaged site.

DEVELOPMENT OF FLOW DURATION CURVES AT UNGAGED SITES

First we chose the streamflow measuring sites to be included in this phase of the study. The basis for this selection was ease of access to site, good distribution of site location and site drainage area. Figure 22 shows the seven sites that were included in the study. Table 10 provides information on upstream drainage area, precipitation input and average flow for each site. This data was obtained from the GIS maps that were developed in phase IV of the study.

Flow duration curves were developed using the procedures and parameters developed in Phase II of the study. Figure 23 through 28 shows the duration curve developed for the ungaged stream measuring sites.

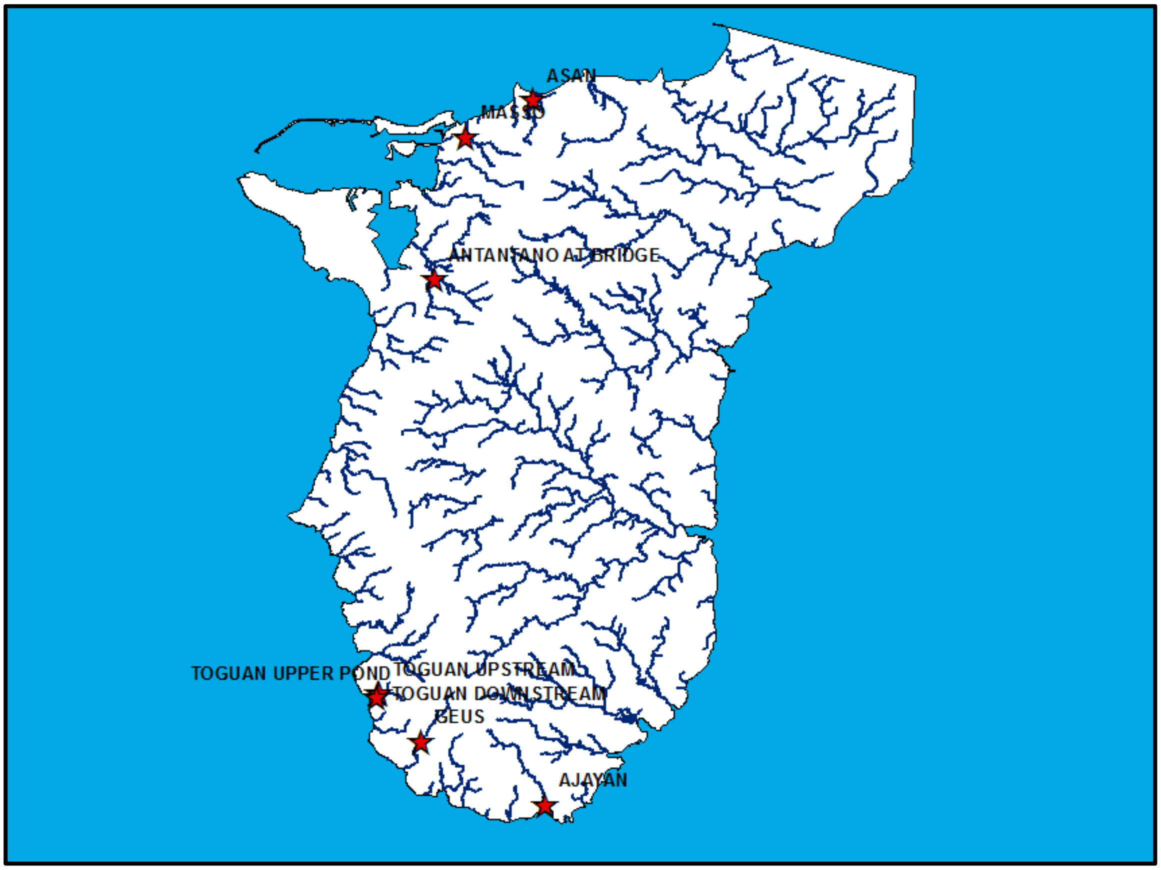


Figure 22. Location of ungaged streams flow measurement sites

STREAM NAME	DRAINAGE AREA	PRECIPITATION INPUT (CFS)	AVERAGE FLOW (CFS)
TOGUAN DOWNSTREAM	0.43	3.18	1.77
TOGUAN UPSTREAM	0.40	2.99	1.66
ASAN	0.60	4.33	2.40
MASSO	0.73	5.17	2.87
ANTANTANO AT BRIDGE	2.11	16.65	8.98
GEUS	0.93	7.12	3.95
AJAYAN	1.38	9.71	5.39

Table 10 Description of ungaged stream flow measurement sites

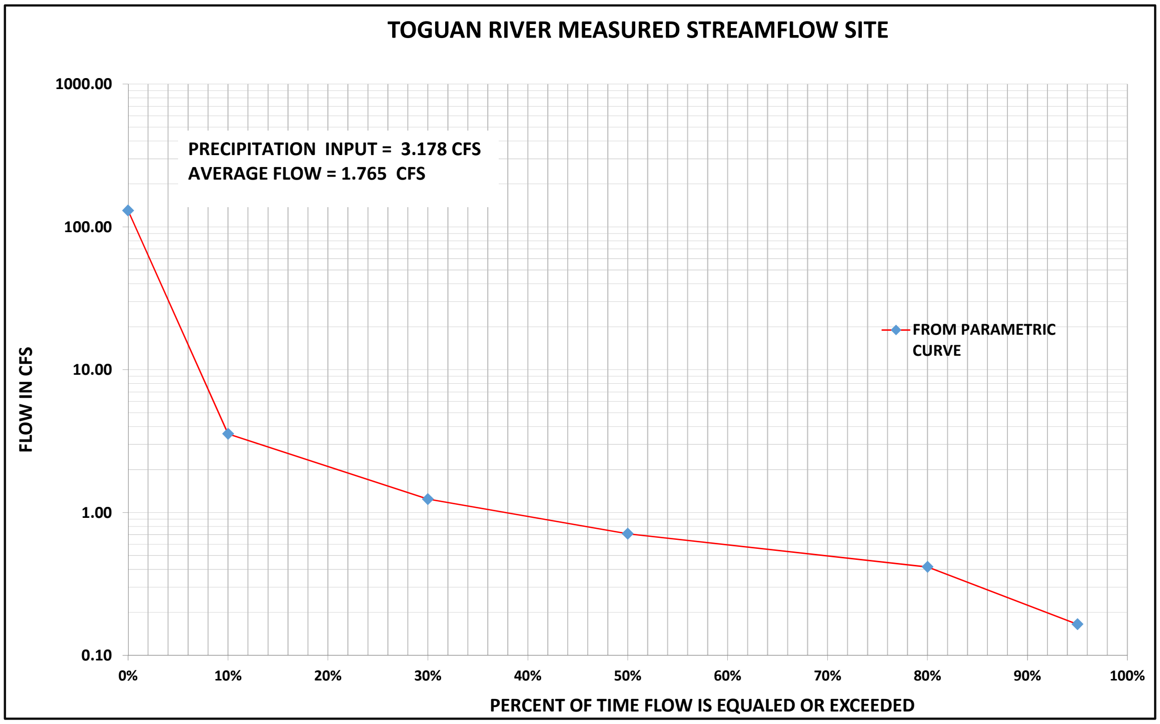


Figure 23 Flow duration curve for Toguan River measured stream site

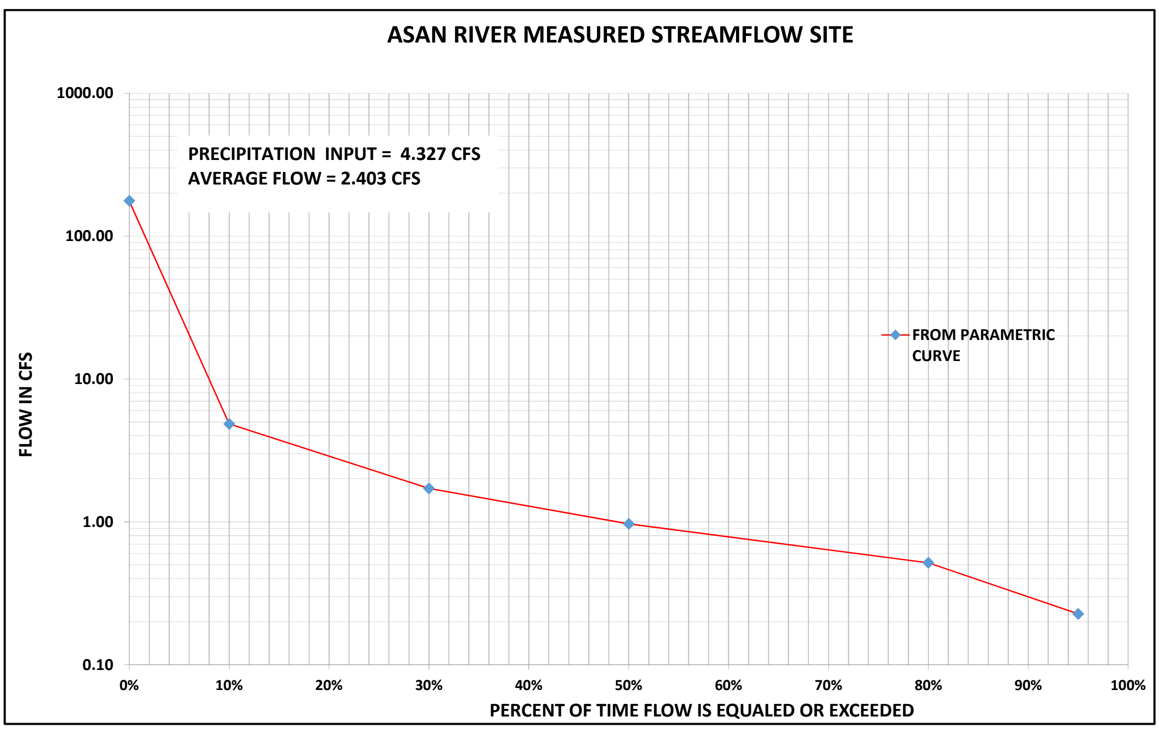


Figure 24. Flow duration curve for Asan River measured stream site

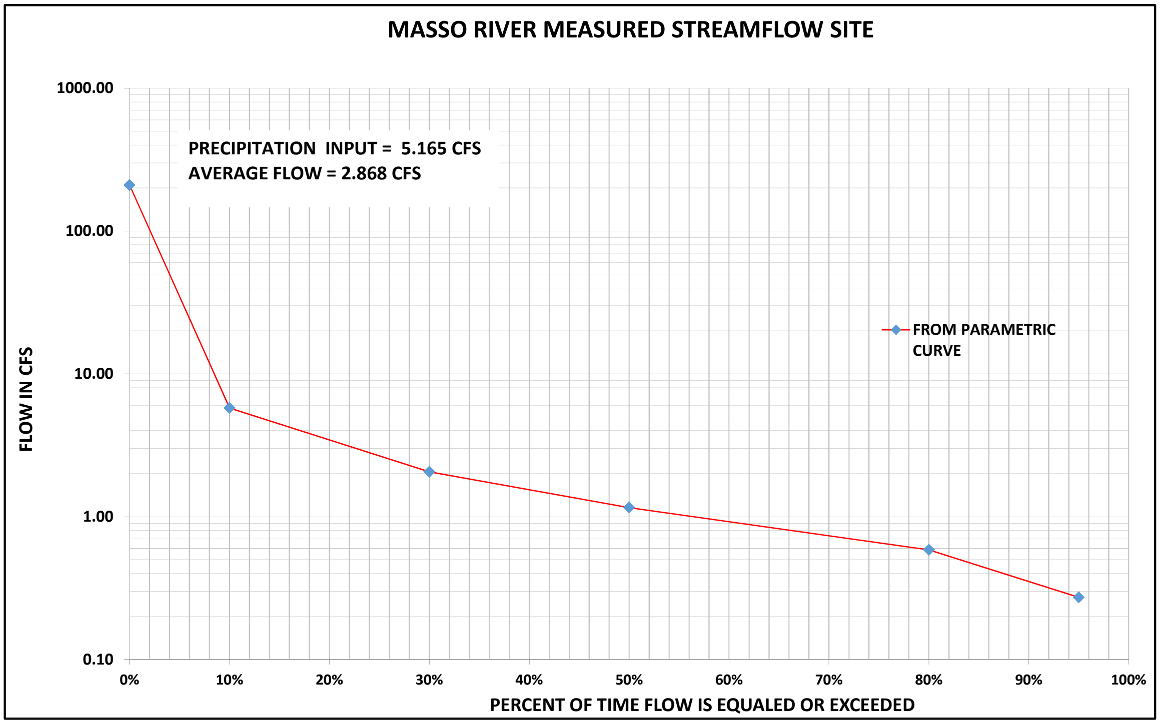


Figure 25 Flow duration curve for Masso River measured stream site

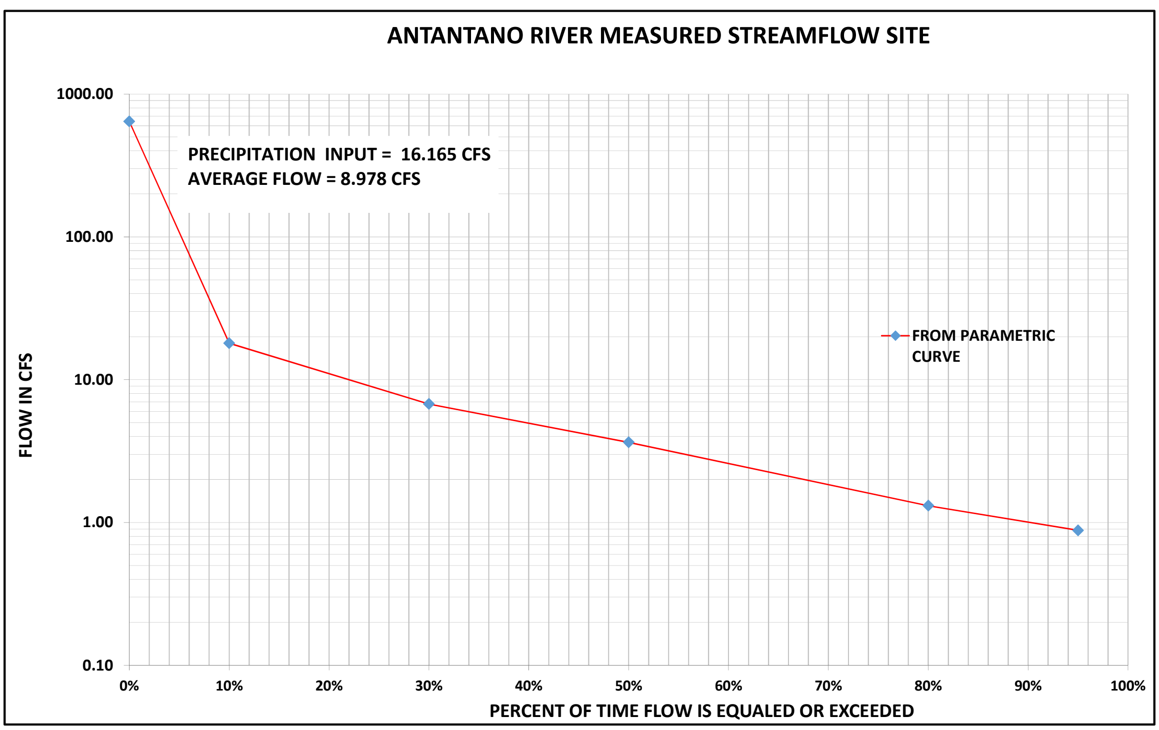


Figure 26. Flow duration curve for Atantano River measured stream site

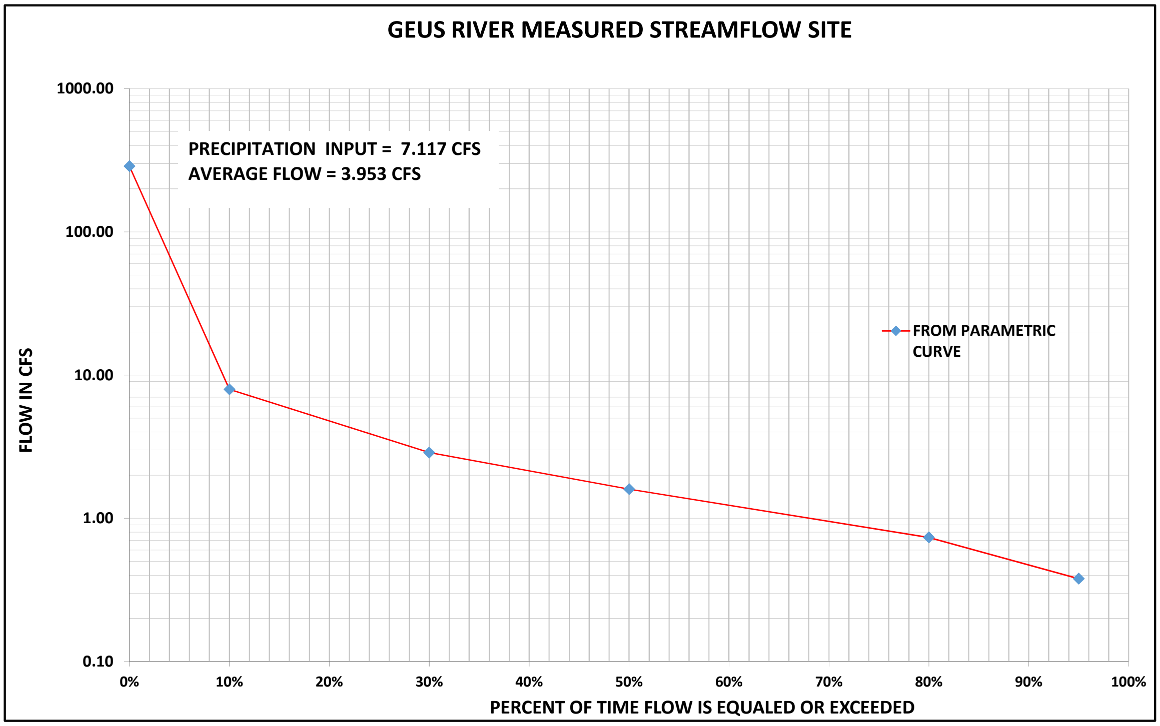


Figure 27 Flow duration curve for Geus River measured stream site

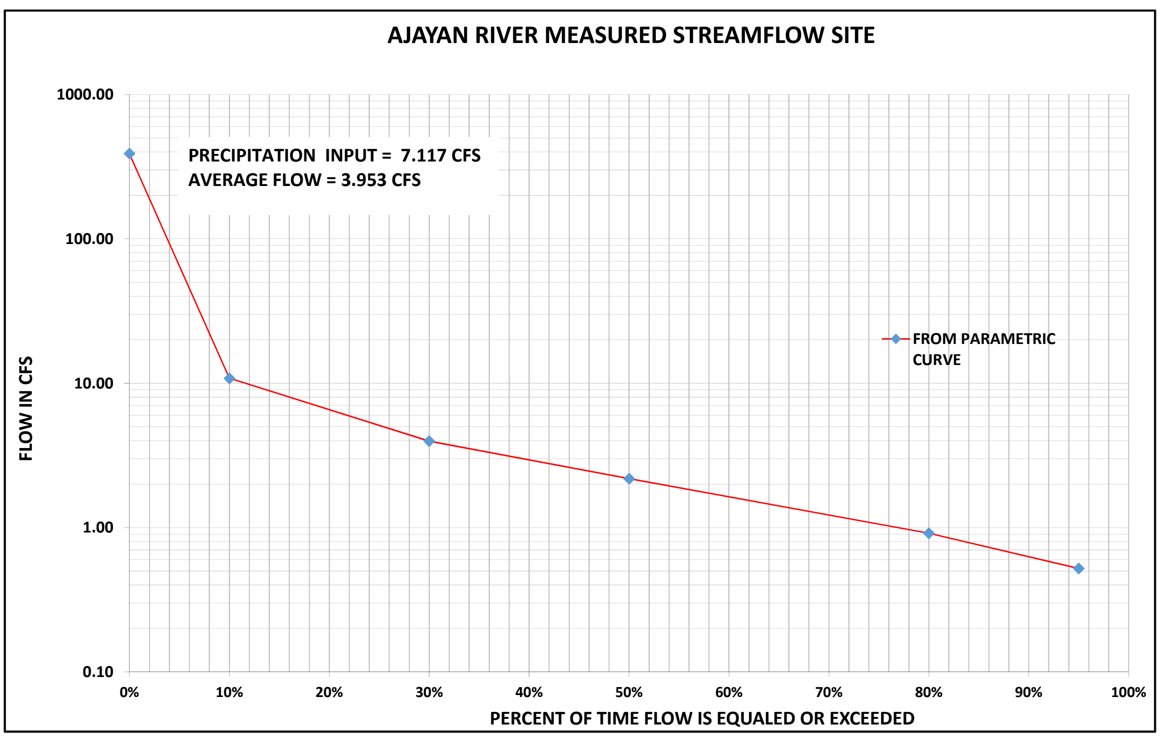


Figure 28. Flow duration curve for Ajayan River measured stream site

MEASURE FLOW AT UNGAGED SITES
To be completed Dry Season 2017

APPLYING DUMMY GAGE TECHNIQUE TO ENHANCE DURATION CURVES
To be completed Dry Season 2017

SUMMARY AND CONCLUSIONS

The information provided in this report and its accompanying GIS data bases can be most helpful to those performing studies such as the evaluation of surface water resources for water supply studies, hydropower design and planning studies, low flow studies such as in-stream flow requirements and other studies where it is desirable to define the variability of the flows in streams.

The low flow measurement methodology developed enables water resources managers to better predict the low flow high exceedance percentage flows at ungaged sites. The methodology involves making low flow measurements at the site of interest. The flow duration exceedance percentage for the measured flow is determined by averaging the exceedance percentages for flows at the gaged sites for the same day as the ungaged site flow measurement was made. The methodology not only provides a means of predicting low flow exceedance percentage at ungaged sites, but also provides a means of estimating the bounding limits of the predictions.

The improved methodology for predicting low flow exceedances will be useful to those making low flow or instream flow requirement studies when future water resources developments are being considered in Guam.

ACKNOWLEDGMENT

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