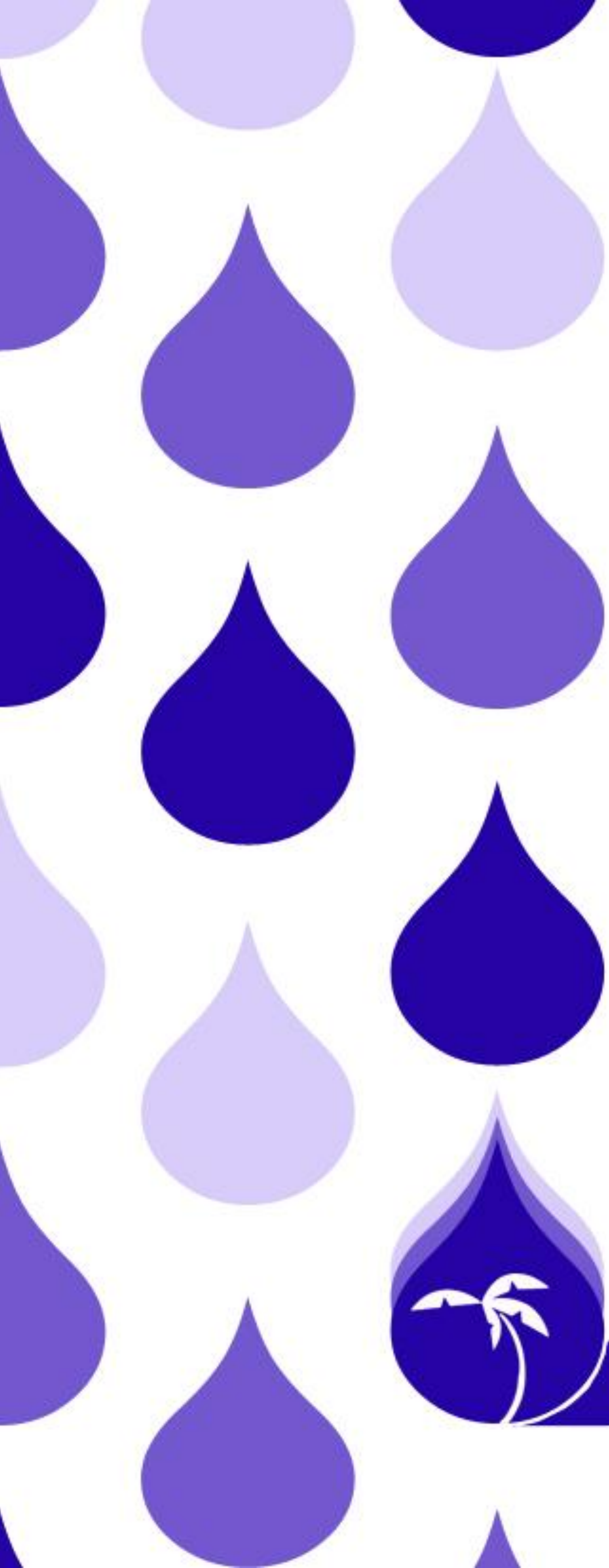

# PREDICTION OF FLOW DURATION CURVES AT UNGAGED SITES IN GUAM

By

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WERI
WATER AND ENVIRONMENTAL RESEARCH INSTITUTE
OF THE WESTERN PACIFIC
UNIVERSITY OF GUAM

Tecnical Report No. 154
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The activities on which this report is based were financed in part by the Department of the Interior, U.S. Geological Survey, through the University of Guam Water and Environmental Research Institute of the Western Pacific.

# 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 techniques 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. What is needed is 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.

The results of this project was the development of a means of predicting flow duration curves at ungaged 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. These reaches and segments were identified on maps developed from 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). 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 and segment.

An Excel application was also developed to perform a preliminary hydropower production and economic analysis for any new proposed site. Those wishing to explore the feasibility of hydropower at a particular site will be able to enter the average flow and available head (hydraulic drop) information into the simple spreadsheet application which is provided as part of the study. This application allows the user to explore various turbine sizing and economic considerations to determine the preliminary feasibility of developing a hydropower facility at a particular site. The GIS maps, and Excel application developed are available from the WERI web site: http://www.weriguam.org

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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.

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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.

The result of this project was the development of a means of predicting flow duration curves at ungaged 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. These reaches and segments were identified on maps developed from the detailed Geographic Information System (GIS) map inventory of Guam available at University of Guam, Water and Environmental Research Institute of the Western Pacific (WERI). Various statistical and analytical methods, as described in the methods section below, 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 and segment.

An Excel application was also developed to perform a preliminary hydropower production and economic analysis for any new proposed site. Those wishing to explore the feasibility of hydropower at a particular site will be able to enter the average flow and available head (hydraulic drop) information into the simple spreadsheet application which is provided as part of the study. This application allows the user to explore various turbine sizing and economic considerations to determine the preliminary feasibility of developing a hydropower facility at a particular site. The GIS maps, and Excel application developed are available from the WERI web site: 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. The more detailed map of Southern Guam in Figure 2 shows the many streams on the island. 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. As of 2013 the population of the island is approximately 165,000.

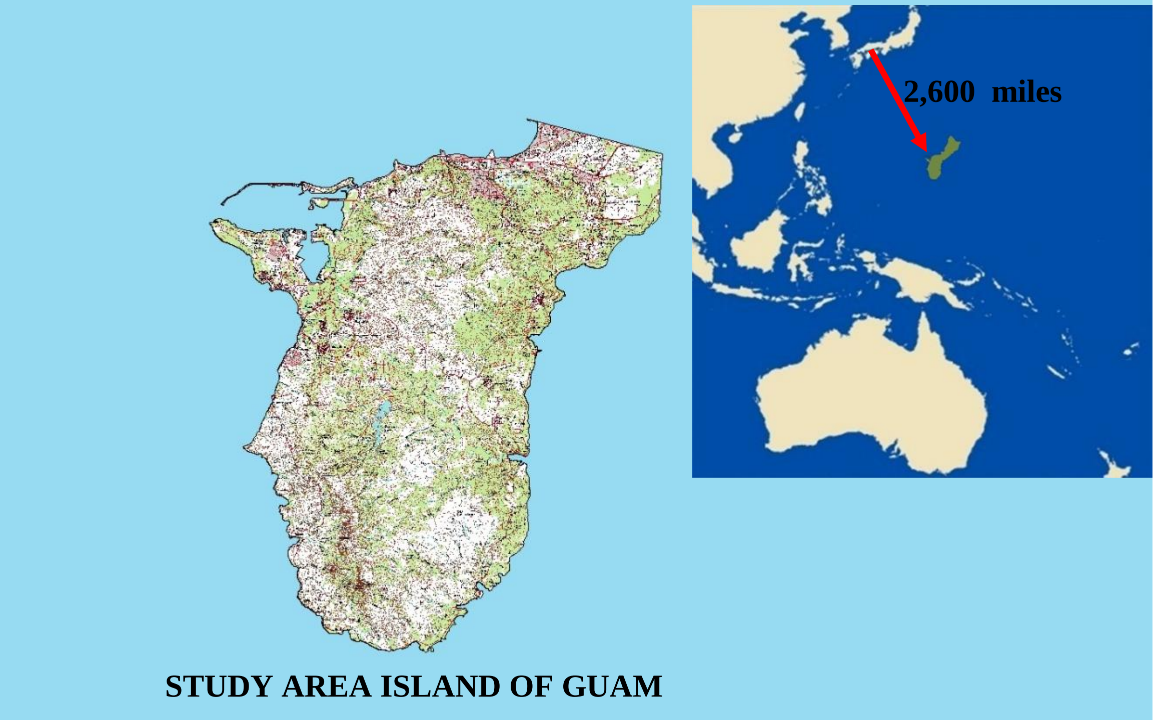


Figure 1. Guam Study Area and location map

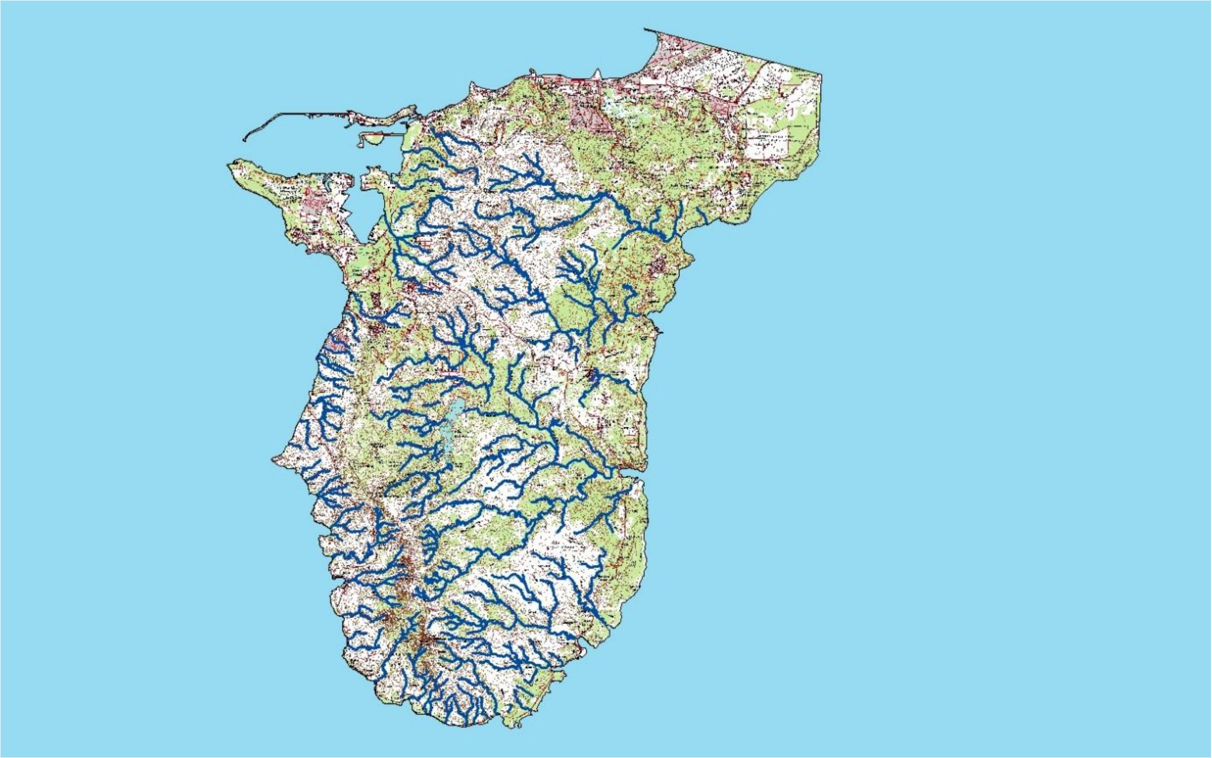


Figure 2. South Guam showing streams

## OBJECTIVES

The overall objective of this project was to develop average annual flow and flow durations curves for the streams in Southern Guam. These flow duration curves 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 specific objectives of the research were to:

1. Develop flow duration curves for all of the previously gaged stream sites in Guam.
2. Develop techniques, based on average annual stream flow, for transferring the flow duration curve information available at the gaged locations to ungaged sites in Guam.
3. Develop estimates of average annual flow for Guam's streams.
4. Divide Guam's streams into segments based on similar flow characteristics and assign average annual flows and flow duration characteristics to the segments.
5. Divide Guam's streams into stream reaches based on stream order and assign average flows to each of the reaches.
6. Develop a set of GIS based maps showing the location and flow information for all stream reaches and segments.
7. Provide an Excel application that will compute flow duration curves for the reaches and any proposed sites and also perform analyses to determine preliminary power potential and economics for specific hydropower site locations.

## RELATED RESEARCH

Beginning in the late 70's the co-investigator of this project was involved with a large scale project to predict the hydro 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.

The investigators on this project have recently completed similar projects for the islands of Pohnpei (Heitz, L.F. and Sh Khosrowpanah, 2010) and Kosrae (Heitz, L.F. and Sh. Khosrowpanah, 2012). The results of these two projects have provided valuable information to those carrying out water resources studies on those islands.

# METHODS AND PROCEDURES

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

## PHASE I

## Development of Flow Duration Curves for Each Gage Site

The first step was to gather all the available daily streamflow data for Guam's streams into computer spreadsheet format.  The required daily flow data was downloaded from the United States Geological Survey (USGS) Pacific Islands Water Science Center web site http://hi.water.usgs.gov/.   Figure 3 shows the location of the USGS stream gage sites that were available for use in the study.  Figure 4 provides information on the period of record for each of the gages.  The period of record for each gage site was examined. Some gages were rejected because of short records.  A common analysis period (1953 through 1982) was chosen for the remaining gages.  Figure 5 shows the common analysis period used for the duration curve computations.  The nine gages that were chosen for the study are shown highlighted in blue.

A spreadsheet program developed specifically for use on this project assigned each of the daily flows into flow range categories specified by the user.  The number of daily flow values greater than or equal to the upper limit of each category was then calculated. This value was divided by the total number of flows to find the percent of daily flows greater than or equal to the highest flow in that category.  This term is called the exceedance percentage.  An example of a flow duration calculation is shown in Table 1.  A graph is made by plotting the exceedance percentage versus the value for the upper limit flow in each category. This graph is the flow duration curve.  Figure 6 shows a typical flow duration curve for the Umatac 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 runoff was determined for each gage site.  Figure 7 shows a set of duration curves for the remaining gage sites that were used in the analysis.

Figure 3. Location of USGS stream gage sites

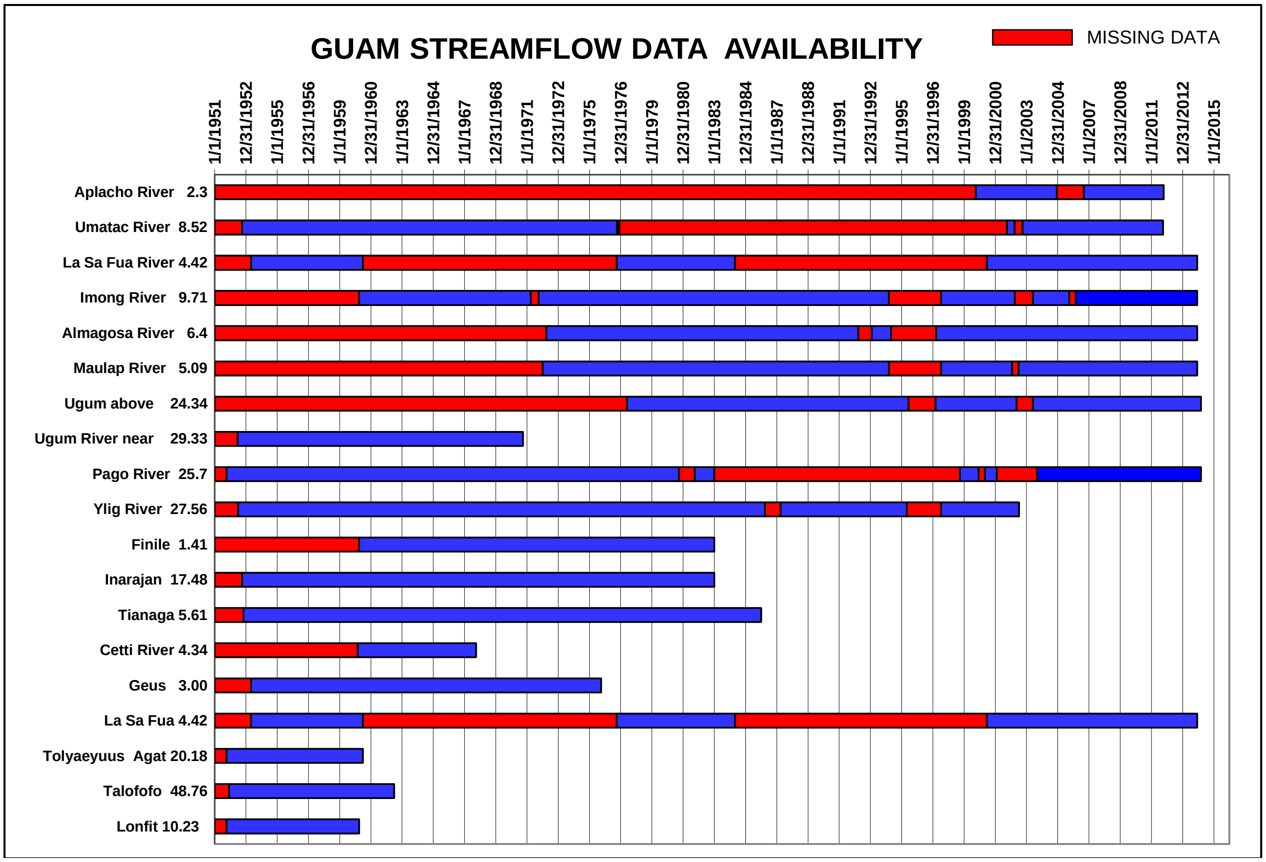


Figure 4. Availability of streamflow data from USGS gages on Guam

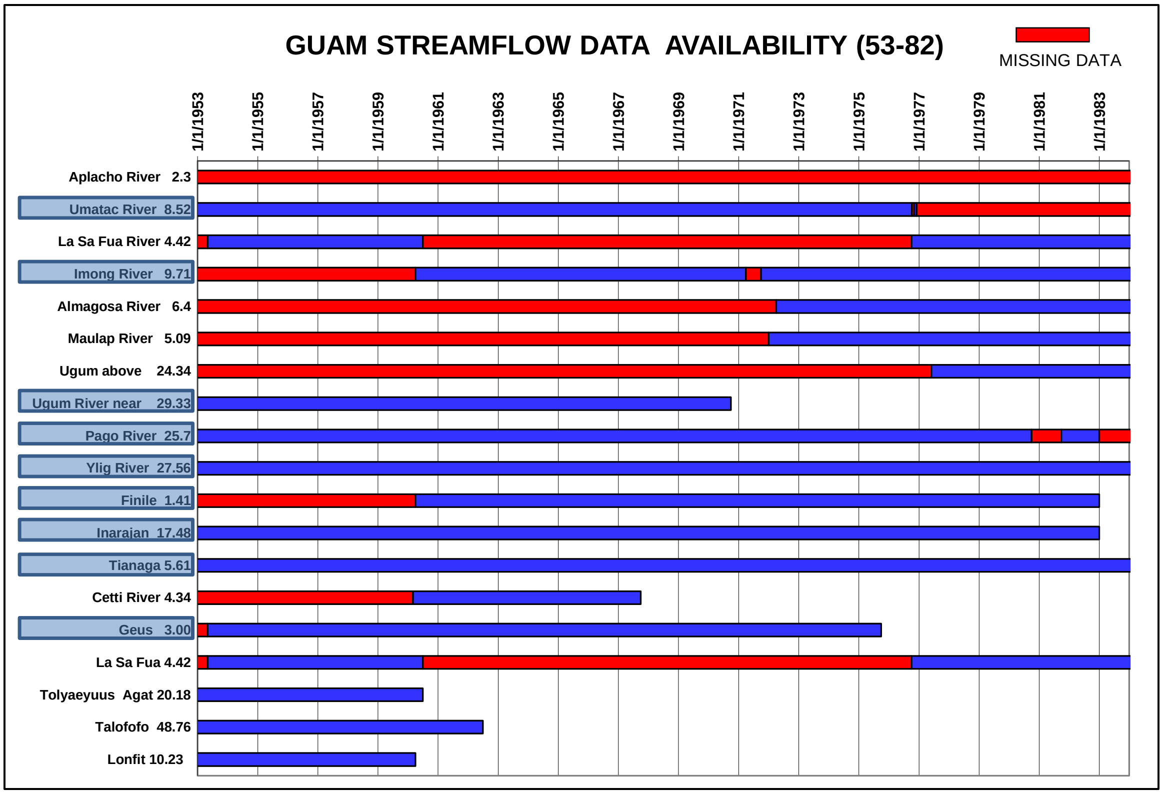


Figure 5. Gages chosen (highlighted in blue) and analysis period used in the flow duration analysis

**UMATAC FLOW DURATION TABLE 1953-1982**

| LOW | HIGH | IN BIN | NUMBER GREATER | % GREATER |
|---|---|---|---|---|
| 0 | 0.09 | 0 | 8711 | 100.0000% |
| 0.09 | 0.6 | 378 | 8333 | 95.6607% |
| 0.6 | 0.8 | 486 | 7847 | 90.0815% |
| 0.8 | 0.99 | 522 | 7325 | 84.0891% |
| 0.99 | 1.2 | 493 | 6832 | 78.4296% |
| 1.2 | 1.5 | 463 | 6369 | 73.1145% |
| 1.5 | 1.9 | 414 | 5955 | 68.3618% |
| 1.9 | 2.3 | 434 | 5521 | 63.3796% |
| 2.3 | 2.7 | 428 | 5093 | 58.4663% |
| 2.7 | 3.15 | 436 | 4657 | 53.4611% |
| 3.15 | 3.7 | 480 | 4177 | 47.9509% |
| 3.7 | 4.3 | 536 | 3641 | 41.7977% |
| 4.3 | 5 | 451 | 3190 | 36.6204% |
| 5 | 6 | 517 | 2673 | 30.6853% |
| 6 | 7.5 | 461 | 2212 | 25.3932% |
| 7.5 | 9.5 | 509 | 1703 | 19.5500% |
| 9.5 | 12 | 490 | 1213 | 13.9249% |
| 12 | 19 | 465 | 748 | 8.5868% |
| 19 | 45 | 468 | 280 | 3.2143% |
| 45 | 400 | 276 | 4 | 0.0459% |
| 400 | 500 | 3 | 1 | 0.0115% |
| 500 | 564 | 1 | 0 | 0.0000% |
| | | | | |
| | **TOTAL** | 8711 | | |

Table 1.  Flow duration table for Umatac River, Guam, (1953-1982)

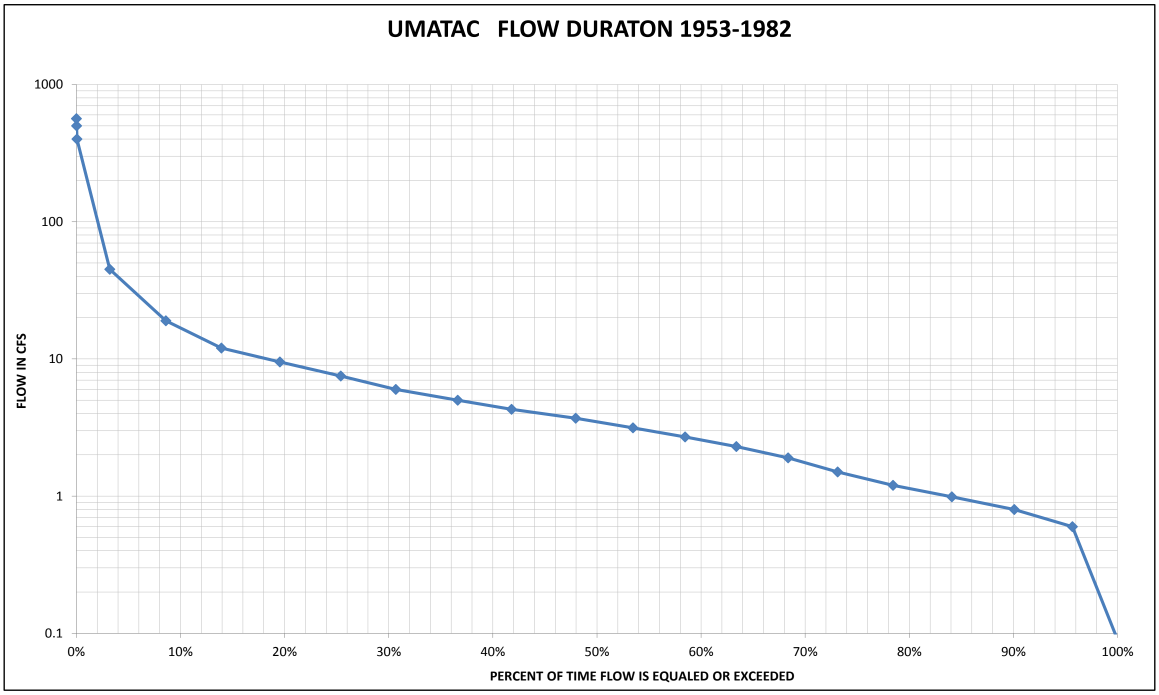


Figure 6. Flow duration curve for Umatac River, Guam (1953-1982)

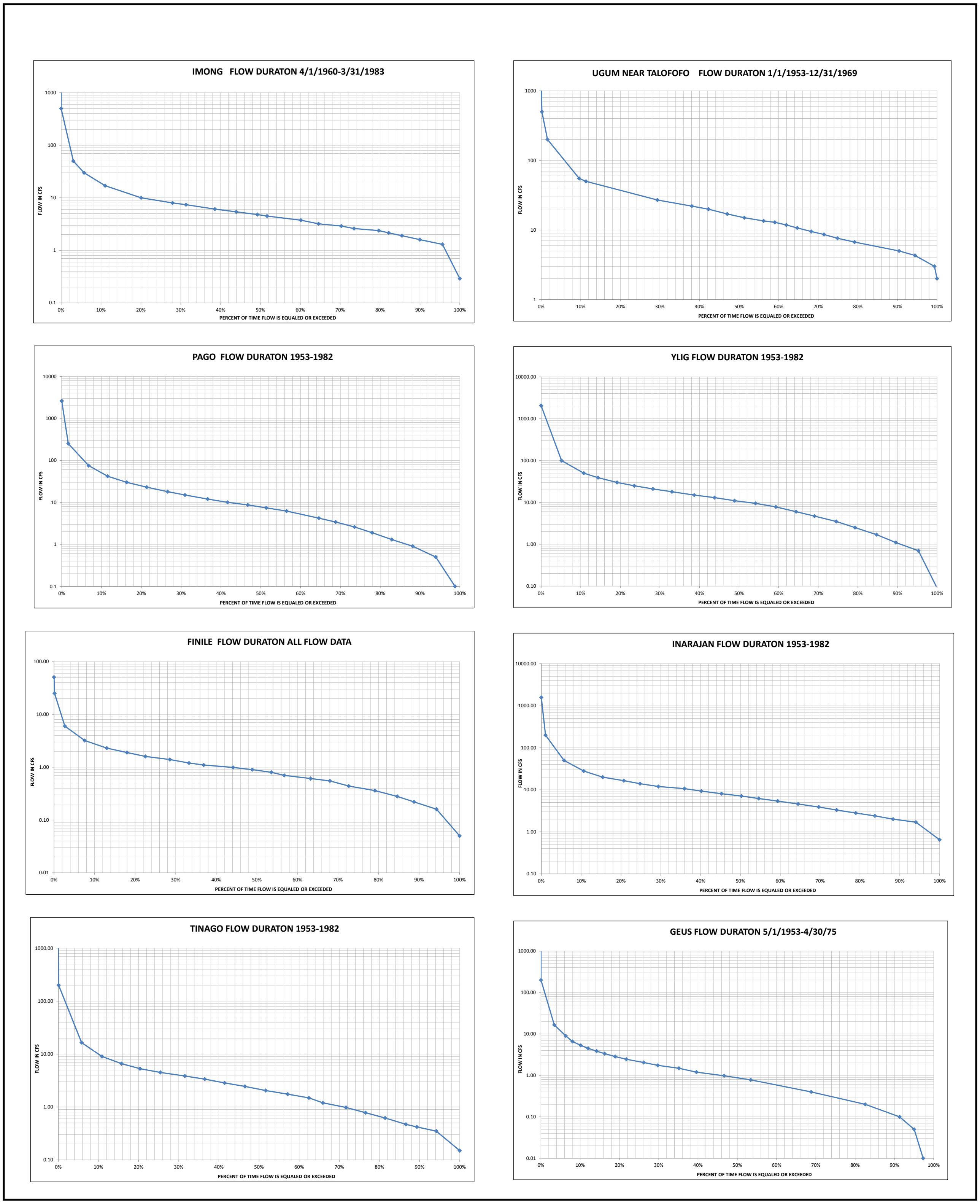


Figure 7. Duration curves for Imong, Ugum, Pago, Ylig, Finile, Inarajan, Tinago, and Geus Rivers

# PHASE II
## Prediction of Duration Curves at Ungaged Sites

Phase II 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 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 duration curves developed in Phase I. 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.

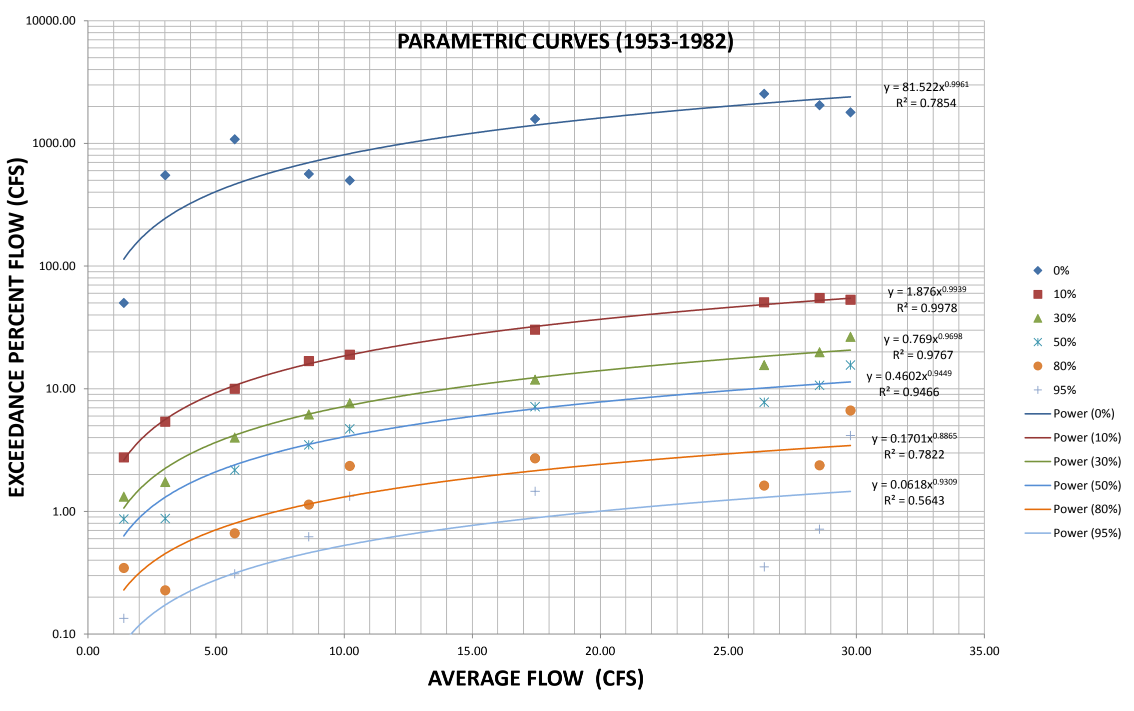


Figure 8. Parametric flow duration curves

The best fit equations are shown at the end of the curves for each exceedance percentage. Although there were 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 56% 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 2 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.

| 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 |

Table 2. Regression equation parameters and R Squared Values for each of the regression equations

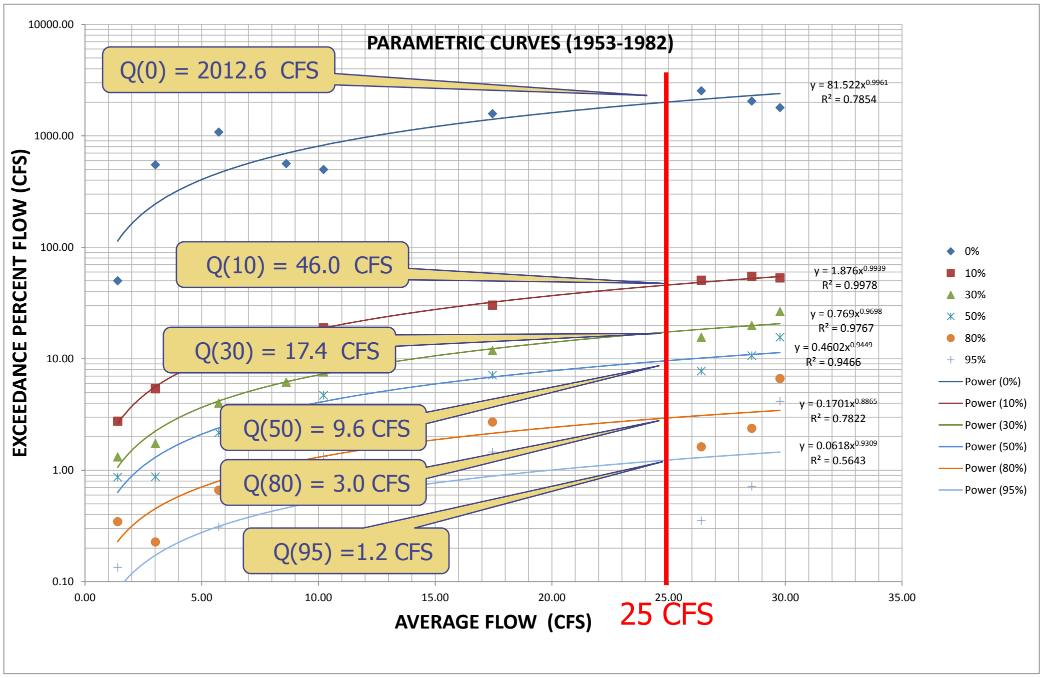


Figure 9. Use of parametric flow duration curves to predict flow duration values at an ungaged site with an average flow of 25 cfs

# PHASE III
## Development of a Means to Predict Average Flow at Ungaged Points on Streams

In Phase III we developed a means to predict average flows at ungaged points on Guam's streams. The technique called for the development of grid based maps of elevations and average annual rainfall and then applying various GIS watershed functions available in the computer program ArcMap. The end products were grid and line based maps of the average annual flow in the streams. Following is a detailed explanation of this process. The average flow values predicted were used as input to the parametric duration curves developed in Phase II in order to predict the duration curves at ungaged stream segments or stream reaches.

The steps required to develop the average flow and duration curve values were:

1. Develop a usable grid based model of elevation (Digital Elevation Model or DEM)
2. Develop a grid based model of the accumulation of cells using the DEM.
3. Develop a grid of average annual precipitation
4. Develop a grid model of average annual precipitation input and average annual flow
5. Define streams, stream reaches and stream segments from the DEM data
6. Determine average flows in stream segments and reaches and flow variability in all stream segments.

### DEVELOPMENT OF ELEVATION GRID

The grid coverages and shape file names provided in “All Caps” in the following explanations correspond to those provided in the table of contents in the ArcMap map file (South Guam Flow Variability for CD.mxd) that is available from the WERI web site: http://www.weriguam.org/. Because of the large size of the grid files only the final results grids files are provided. The grid files used in computational steps to get these final results files are not provided but their titles are shown in the following explanations in parentheses.

The first step in the development of the various GIS maps for the study was to obtain the latest USGS topographic map and satellite imagery of Guam to use as base maps for all of the other maps. These maps, (GUAM QUAD MAP and GUAM SATELLITE IMAGE), were provided from the extensive GIS map inventory of Guam available at WERI. A 1 meter resolution Light Detection and Ranging (LIDAR) based Digital Elevation Model (DEM), “baredem_1gu_projected Raster”, was also provided from the WERI GIS map inventory. This DEM served as the basis for the elevation data used in the study. Figure 10 shows the DEM for Southern Guam. Note that the red colors are the highest elevations and the colors from yellow to green show lower and lower elevations. In order to be useful for our analyses, the DEM used cannot have any local water flow sinks (non-outlets). The Fill Tool of the Spatial Analyst Toolbox was used to assure that there were no sinks in the DEM. Because of computational time complications with the GIS weighted accumulation function the 1 m x 1 m filled DEM was resampled with 2m x

2m resolution. The 2m x 2m Filled DEM (ELEVATIONS WITH CULVERTS 2M) was used in the remaining Spatial Analyst functions that are applied.

DEVELOPMENT OF FLOW ACCUMULATION GRID

Next we applied the Flow Direction tool of the Spatial Analyst Toolbox to the filled DEM. This tool assigned the direction that water would flow from each of the filled DEM grid cells resulting in a grid called “Flow Direction”. Next we applied the Flow Accumulation Tool of the Spatial Analyst Toolbox. By examining the flow direction from each cell from the “Flow Direction” grid this Spatial Analyst function determines how many upstream cells flow into each cell resulting in a new grid called “Flow Accumulation”. Figure 11 shows the “Flow Direction” grid and a portion of the “Flow Accumulation” grid. The red squares show the areas of highest accumulations. These correspond to the small streams and rivers. The flow accumulation grid was transformed to square mile units using the spatial analyst Raster Calculator and then resampled to a 4 m by 4m grid. This aggregation was required in order to develop a polyline map of small segments of the streams showing the drainage areas for each segment. The polyline map (DRAINAGE AREA MI^2) was developed using the raster to polyline tool of the ArcToolbox. The small stream segment map that shows the drainage area is shown in Figure 12. The small stream segment polyline file is much smaller in size and much easier to access on the GIS screen than the larger grid files.

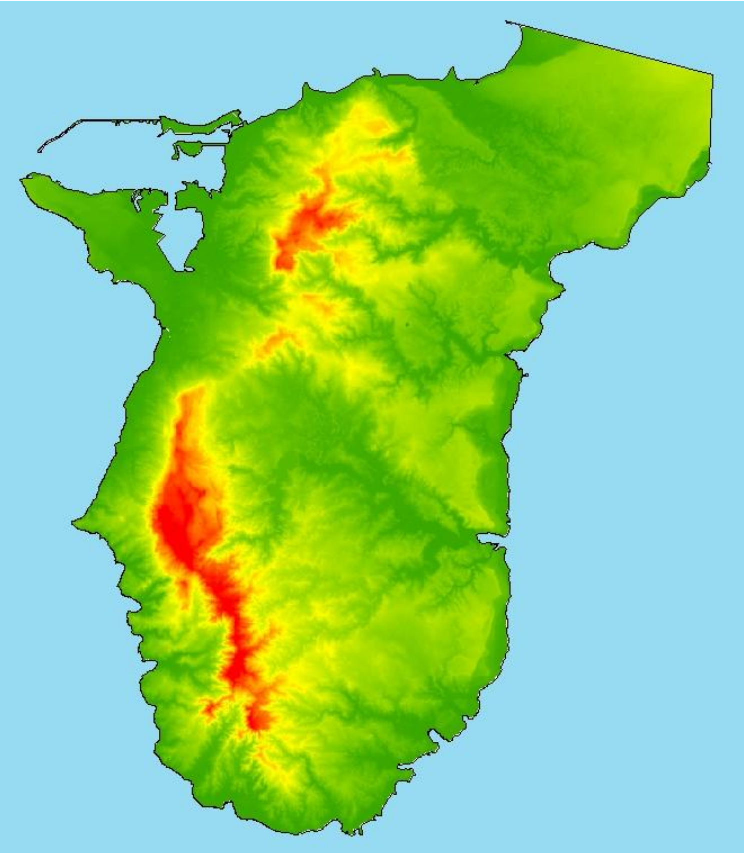


Figure 10. Digital elevation model for South Guam

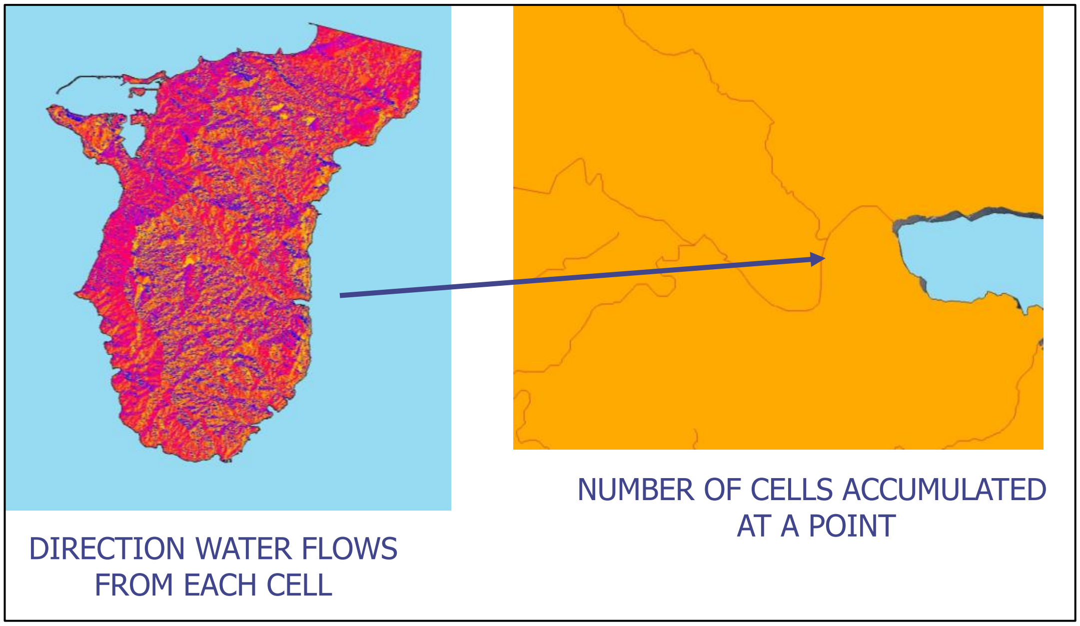
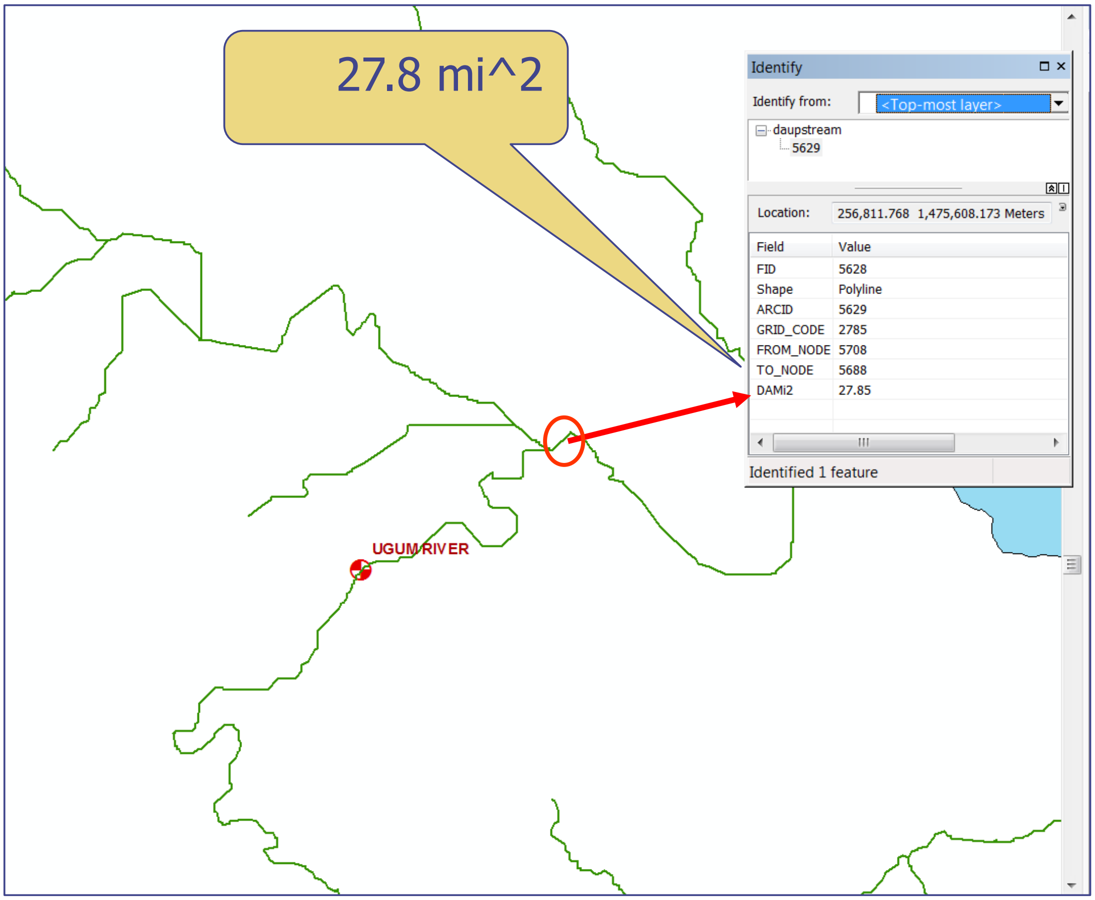


Figure 11. Flow direction and flow accumulation grids for South Guam



Identify from: <Top-most layer>

daupstream
5629

Location: 256,811.768 1,475,608.173 Meters

| Field | Value |
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| Shape | Polyline |
| ARCID | 5629 |
| GRID_CODE | 2785 |
| FROM_NODE | 5708 |
| TO_NODE | 5688 |
| DAMi2 | 27.85 |

Identified 1 feature

Figure 12. Small stream segment polyline map showing upstream drainage area

## DEVELOPMENT OF AN AVERAGE RAINFALL GRID

The next step was to develop a rain grid that represents the average annual rainfall amount falling into each grid cell. A previous study in Guam, (Lander and Guard, 2003), had developed average annual precipitation lines for all of Guam. These lines with some corrections recommended by Lander were manually traced onto A GIS map (RAINFALL ISOLINES INCHES). These contours are shown in Figure 13.

The Topo to Raster Tool of the Spatial Analysis Toolbox was applied to the average annual rainfall contours (RAINFALL ISOLINES INCHES) to get a Grid of average annual rainfall for the island. This grid will be referred to as (AVERAGE RAINFALL GRID INCHES) and is shown along with the rainfall isolines in Figure 14.

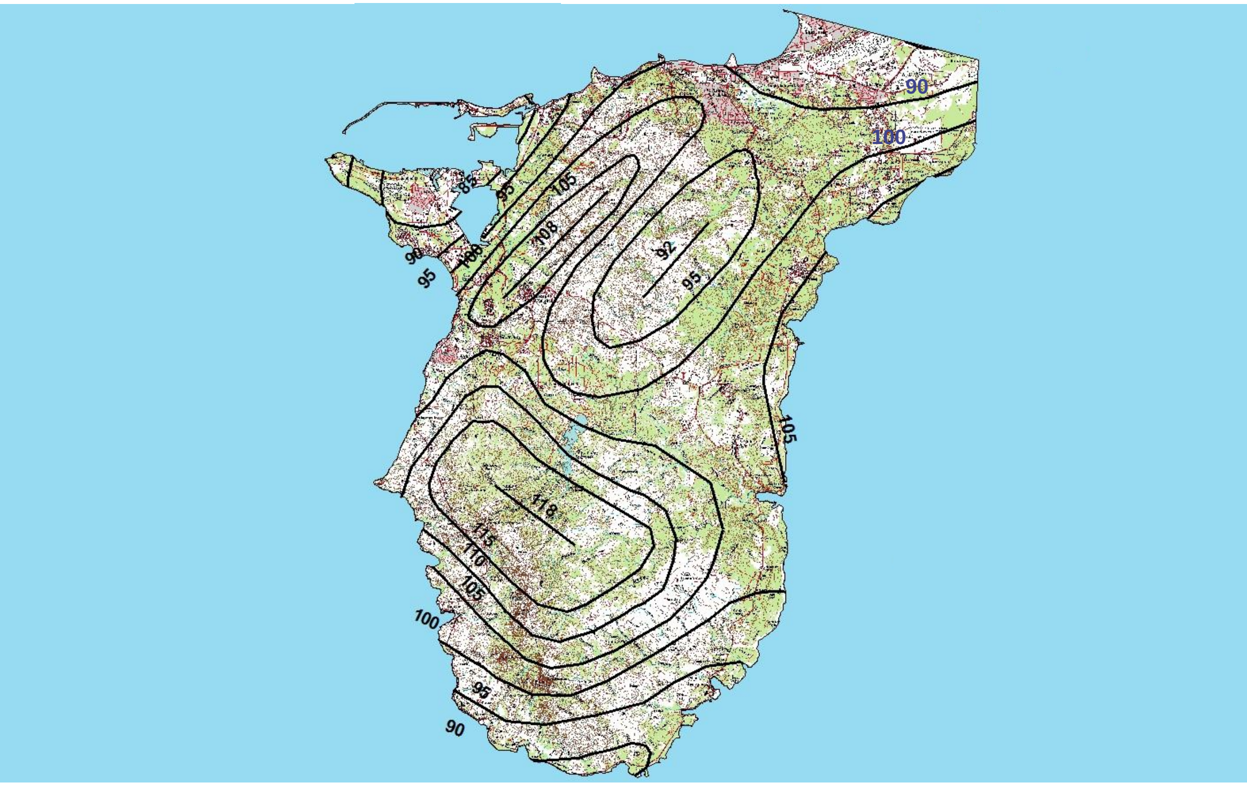


Figure 13. South Guam average annual rainfall contours in inches

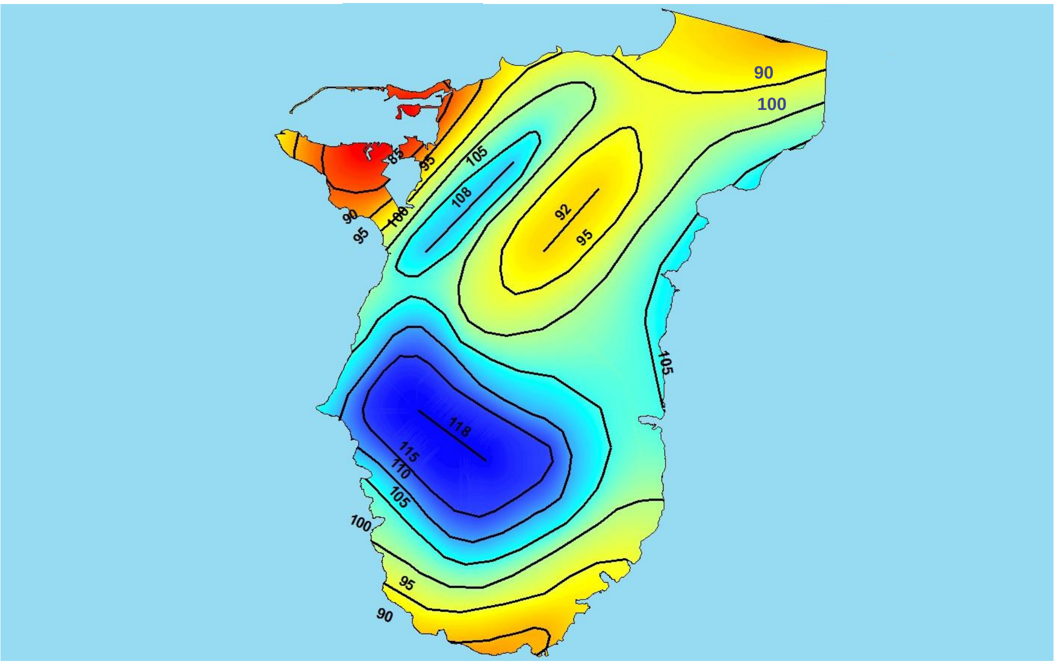


Figure 14. South Guam average annual rainfall grid map with rainfall contours in inches

## DEVELOPMENT OF AVERAGE ANNUAL PRECIPITATION INPUT AND AVERAGE ANNUAL FLOW GRIDS

The first step in this phase was to combine the flow direction grid previously developed and the average annual rainfall grid (AVERAGE RAINFALL GRID INCHES). The result was a new grid map that shows the total average annual amount of rainfall accumulating in each cell. To accomplish this step the Accumulation Tool of the Spatial Analyst Toolbox was applied. The rainfall grid was used as the input weight raster in the "Accumulation" function. The Accumulation tool sums up the total accumulation of rainfall traveling down gradient through the islands stream systems resulting in a “Rainfall Accumulation Grid”.

Proper conversions factors were applied to the “Rainfall Accumulation Grid” using the Spatial Analyst Raster Calculator so that the resulting precipitation input grid were in units of cubic feet per second (cfs) of average annual flow. First the average rainfall depth is multiplied by the area of the cell to get the volume of rain in the cell in cubic feet. The accumulated volumes are then divided by the number of seconds in a year. The resulting grid, “Rainfall Accumulation Grid CFS” shows the average annual flow required to equal the total volume of rain falling upstream in one year.

The rainfall accumulation grid was divided by the flow accumulation grid resulting in the average precipitation upstream of points along the streams. This grid was resized to a 4 m by 4m grid. The resulting grid file “Average Precipitation Inches” is shown in figure 15. This aggregation was required in order to apply the raster to polyline tool of the ArcToolbox to develop a polyline map (AVERAGE RAINFALL UPSTREAM INCHES) of small portions of the streams showing the upstream average rainfall for each stream segment.  A portion of the small stream segment map that shows the average annual upstream rainfall is shown in Figure 16.  The small stream segment polyline file is much smaller in size and much easier to access on the GIS screen than the larger grid files.

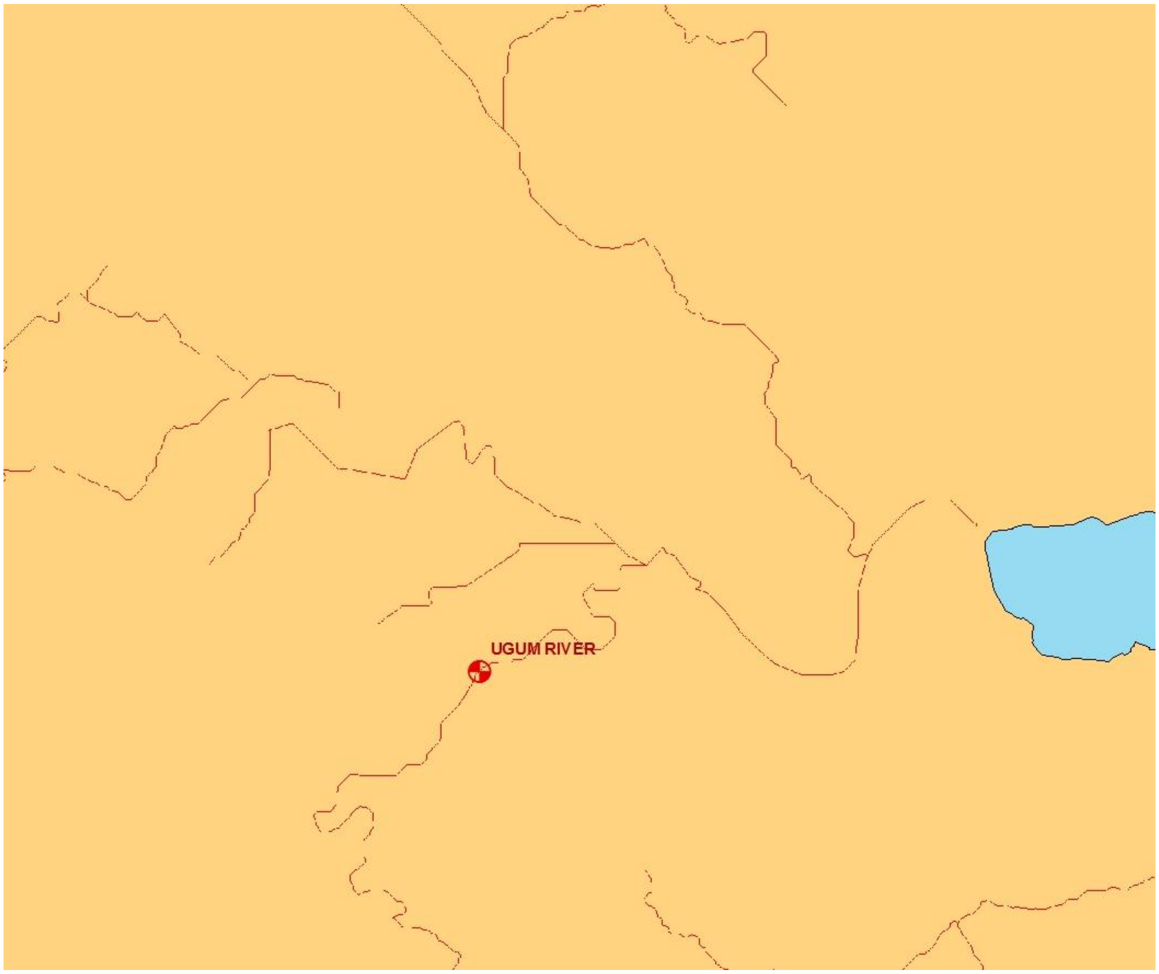
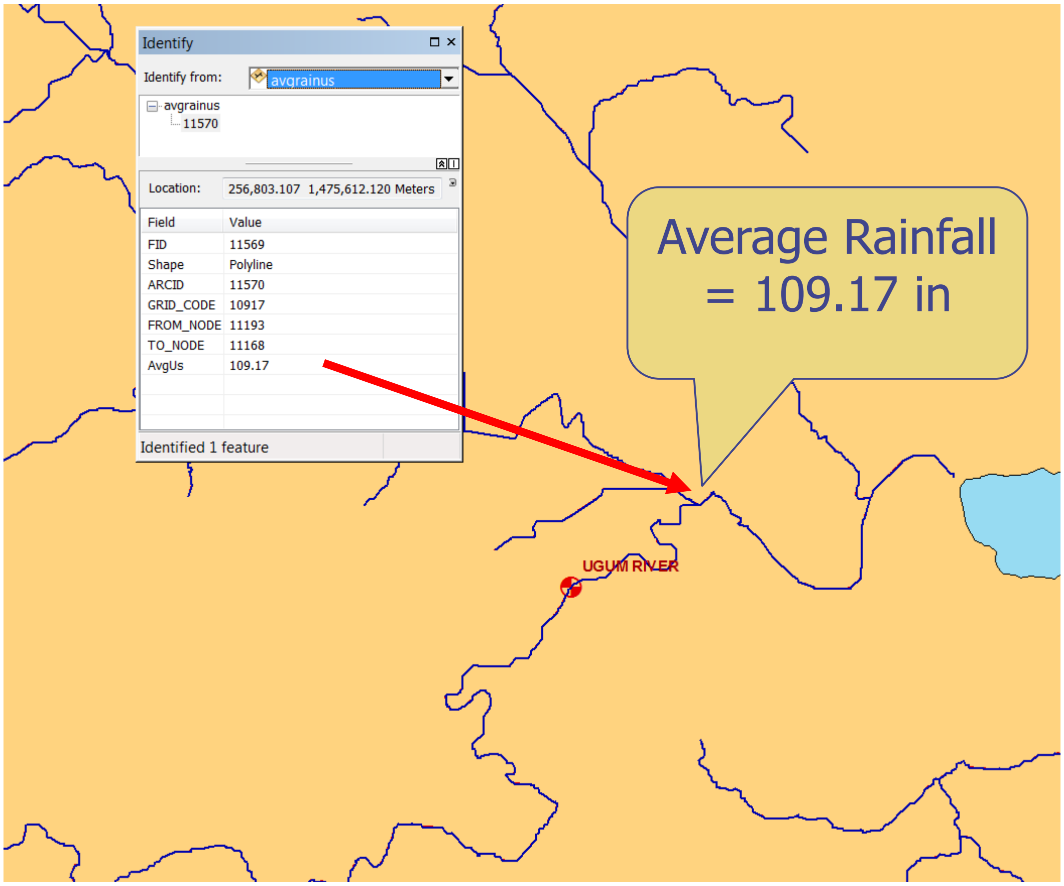


Figure 15.  Precipitation input or average annual rainfall accumulation grid



Location: 256,803.107 1,475,612.120 Meters

| Field | Value |
|---|---|
| FID | 11569 |
| Shape | Polyline |
| ARCID | 11570 |
| GRID_CODE | 10917 |
| FROM_NODE | 11193 |
| TO_NODE | 11168 |
| AvgUs | 109.17 |

Figure 16. Small stream segment polyline map showing upstream average rainfall

One can think of grid "Rainfall Accumulation Grid in CFS" as the average flow that would occur in the streams if there were no losses in the hydrologic system. This precipitation input value is sometimes referred to as the precipitation area product as it is the product of the average annual precipitation in a watershed times the area of the watershed. Figure 17 shows and enlarged area of the results of this final accumulation on the Ugum River near Talofofo, Guam. Again the light colors represent the higher values of rainfall accumulation in the larger stream channels. Figure 18 shows the same map enlarged on an area near the location of the "Ugum River Near Talofofo" stream gage. The cell in blue nearest the gage site has a value 59.29 cfs. This represents the average flow at that location assuming no losses. The precipitation input is determined for each stream flow gage location shown in Figure 19. Table 3 shows the Precipitation Input for all of the gage stations.

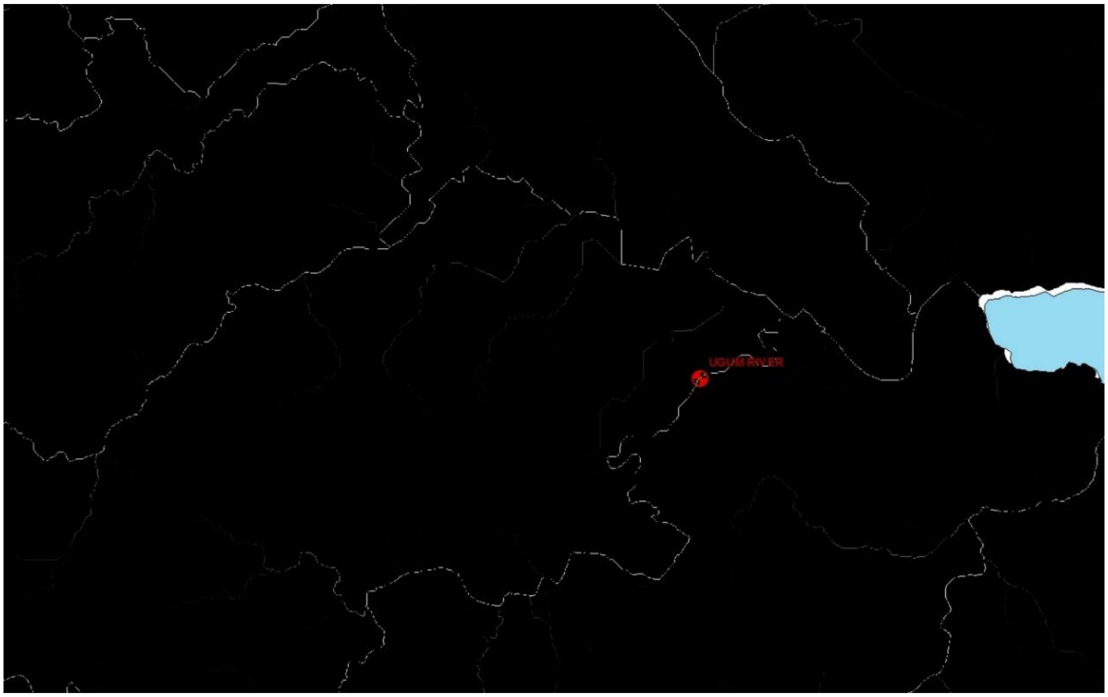
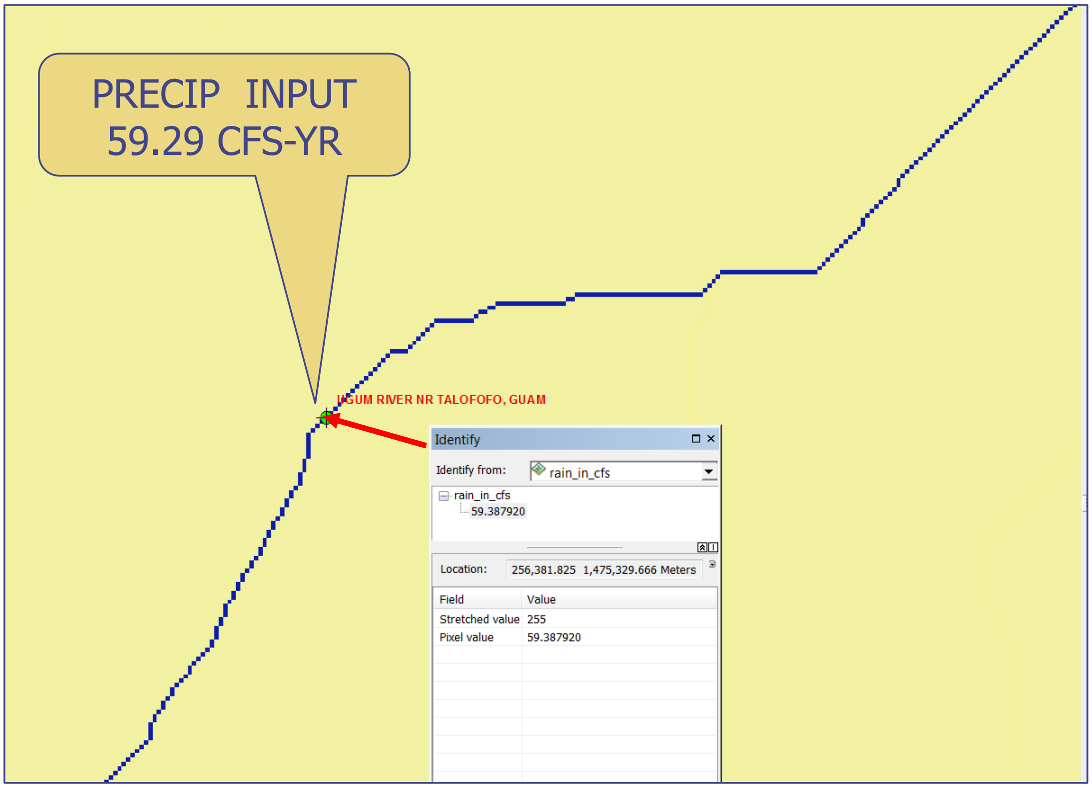


Figure 17. Precipitation input or average annual rainfall accumulation grid


PRECIP INPUT
59.29 CFS-YR

Identify from: rain_in_cfs

rain_in_cfs
59.387920

Location: 256,381.825 1,475,329.666 Meters

| Field | Value |
|---|---|
| Stretched value | 255 |
| Pixel value | 59.387920 |

Figure 18. Precipitation input grid in the area near the Ugum River near Talofofo stream gage site

Figure 19. Streamflow measuring sites and precipitation input grid

| STREAM GAGE | PRECIPITATION INPUT (CFS) | AVERAGE FLOW (CFS) | RUNOFF FACTOR | DRAINAGE AREA (SQ. MILES) |
|---|---|---|---|---|
| **UMATAC** | 16.66 | 8.62 | 0.52 | 2.08 |
| **IMONG** | 16.50 | 10.22 | 0.62 | 1.91 |
| **PAGO** | 40.88 | 26.40 | 0.65 | 5.67 |
| **YLIG** | 46.51 | 28.56 | 0.61 | 6.51 |
| **FINILE** | 2.04 | 1.40 | 0.68 | 0.26 |
| **INARAJAN** | 33.44 | 17.46 | 0.52 | 4.32 |
| **TINAGO** | 14.76 | 5.73 | 0.39 | 1.91 |
| **GUESS** | 7.09 | 3.02 | 0.43 | 0.93 |
| **UGUM NR TALOFOFO** | 59.29 | 29.77 | 0.50 | 7.05 |

Table 3. Average runoff and precipitation input (average rainfall accumulation) for Guam's stream gage stations used in the analysis

A runoff factor is computed for each gage station. This factor is the ratio of the average annual flow at the station to the average annual precipitation input. If we plot the precipitation input versus the average annual flow for each of the stream flow gage station we get the plot show in Figure 20. If we fit a linear curve to the data we get the equation shown in Figure 20.

The regression equation shown in Figure 20 was applied to the precipitation input grid using the grid Raster Calculator Tool of the Spatial Analyst Toolbar. The resulting grid is an average annual flow map for all streams on the island.

The average annual flow grid file was multiplied by the “streams = 1 or no data” grid (developed in Phase IV) using the Raster Calculator of the Spatial Analyst Tool. This new grid (AVERAGE FLOW CFS) contains only average flow values in the stream grid cells. Figure 21 shows the (AVERAGE FLOW CFS) grid for the area near the Ugum River gage station. A GIS function called "Identify" applied to the cells shown in red near the gage reveals a predicted average annual flow of 31.4 cfs. This grid was resized to a 4 m by 4m grid. This aggregation was required in order to apply the grid to polyline function to develop a polyline map of small portions of the streams showing the average flow for each stream segment. The small stream segment map that shows the average annual average flow, (FLOWS IN STREAM SEGMENTS CFS), is illustrated in Figure 22. The small stream segment polyline file is much smaller in size and much easier to access on the GIS screen than the larger grid files. The stream segment attribute file contains the average flow for the segment plus the exceedance percentage flows derived from the parametric duration curves.

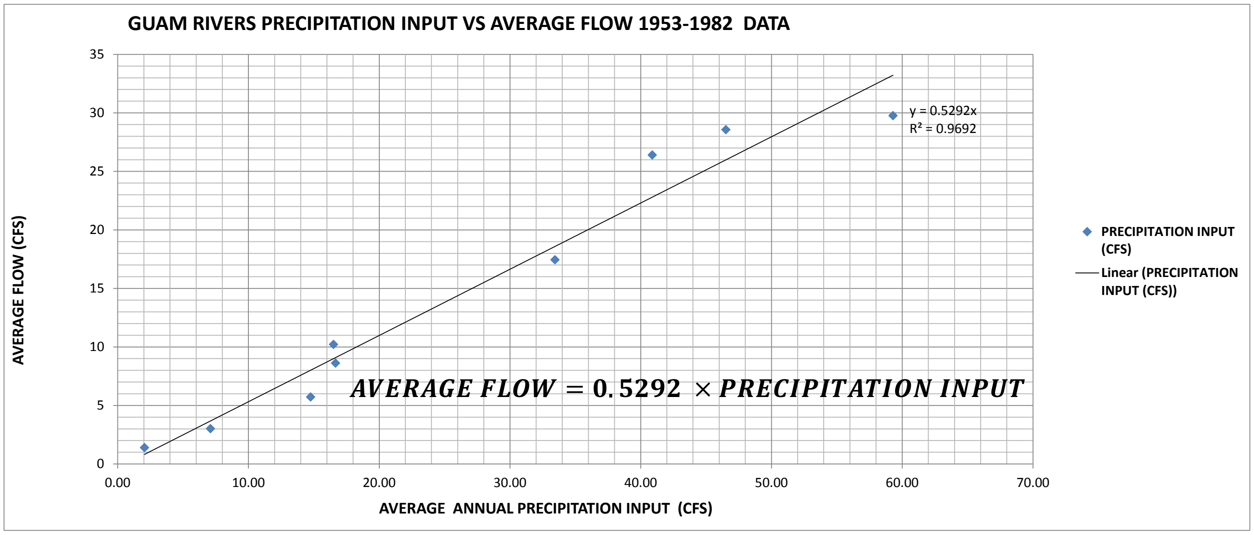
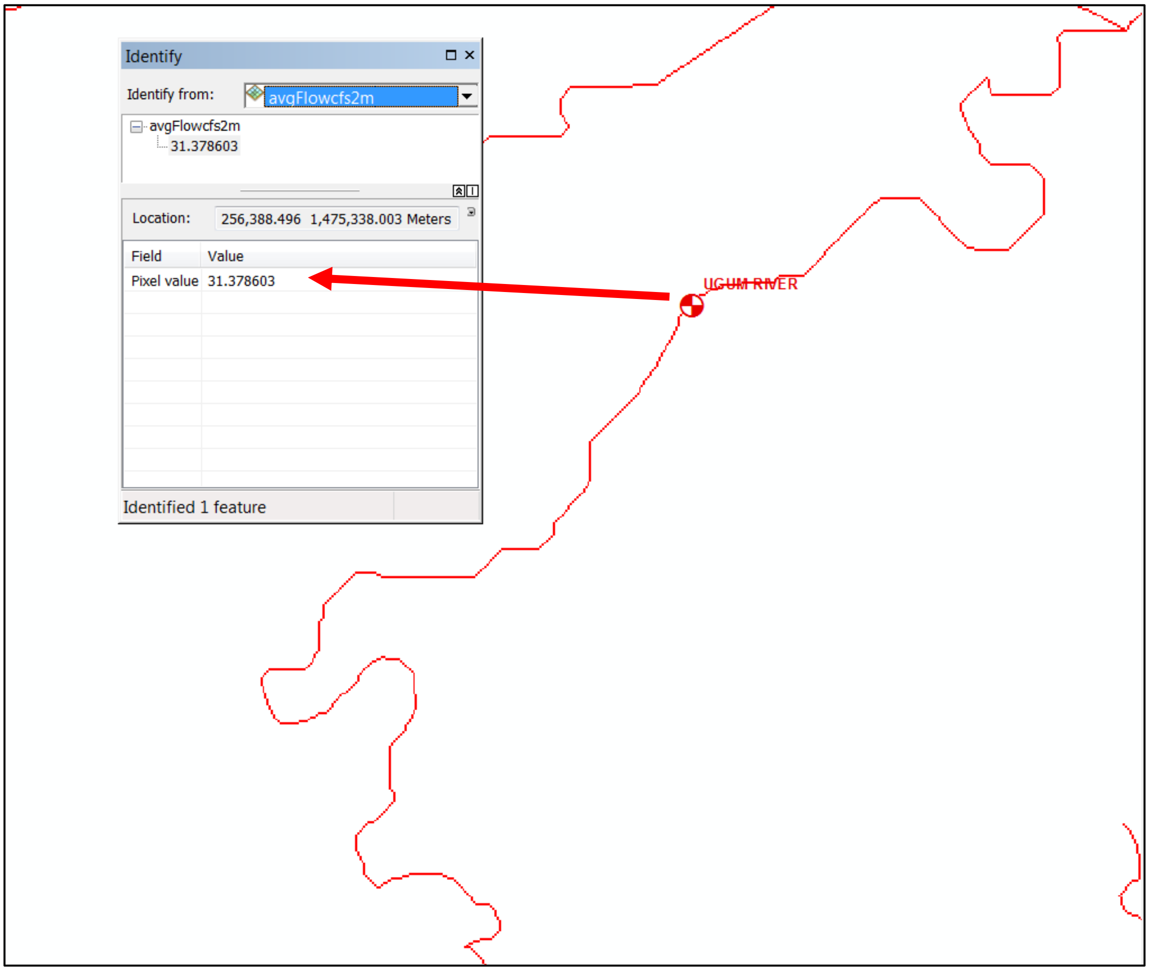


Figure 20. Average flow vs precipitation input for Guam's rivers



Identify from: avgFlowcfs2m

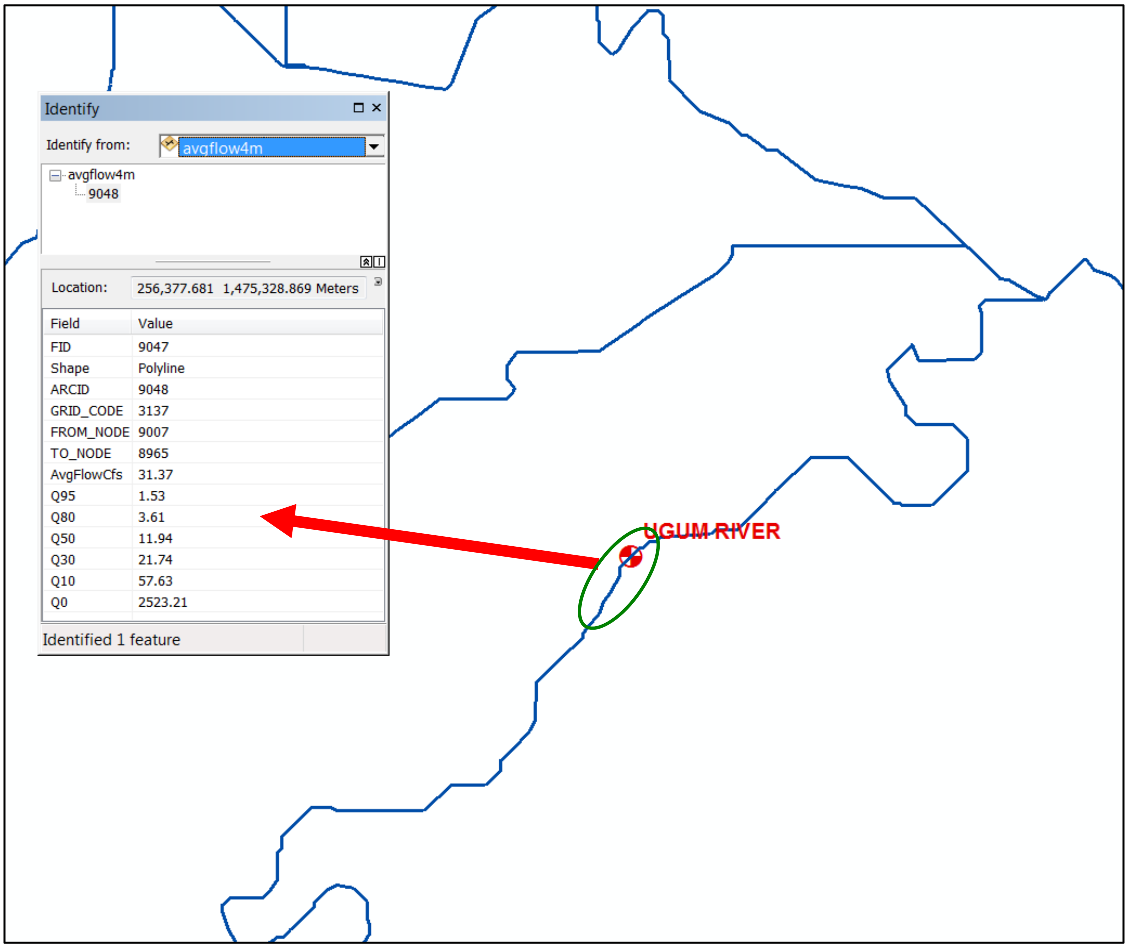
avgFlowcfs2m
31.378603

Location: 256,388.496 1,475,338.003 Meters

| Field | Value |
|---|---|
| Pixel value | 31.378603 |

Identified 1 feature

Figure 21. Average flow grid near the Ugum river stream gage site



Identify from: avgflow4m

Location: 256,377.681 1,475,328.869 Meters

| Field | Value |
|---|---|
| FID | 9047 |
| Shape | Polyline |
| ARCID | 9048 |
| GRID_CODE | 3137 |
| FROM_NODE | 9007 |
| TO_NODE | 8965 |
| AvgFlowCfs | 31.37 |
| Q95 | 1.53 |
| Q80 | 3.61 |
| Q50 | 11.94 |
| Q30 | 21.74 |
| Q10 | 57.63 |
| Q0 | 2523.21 |

Identified 1 feature

Figure 22. Small stream segment polyline map showing average and exceedance percent flows

## PHASE IV
## Stream Reach Delineation and Reach Average Flow Estimates

In Phase IV we divided Guam's streams into stream reaches based on stream order. This was done starting with the "Flow Accumulation" grid discussed earlier and required extensive spatial analyst processing as will be described below. The first step in the process was to specify the headwater definition for the new stream network. A minimum accumulation of cells count of 64,700 was determined to give a reasonable stream network definition for our study. What this means is that all cells in the "Flow Accumulation" grid with cell values of 64,700 or greater will be included in the stream network. The 64,700 cell accumulation value corresponds to a drainage area of 0.1 square miles or 64 acres when applied to the 2 meter by 2 meter grid used in this study. The Raster Calculator Tool of the Spatial Analyst Toolbar was applied to the "Flow Accumulation" grid to eliminate all cells with accumulations less than 64,700. This grid file was divided by itself using the Raster Calculator tool of Spatial Analysis toolbar to obtain a new Grid that contains ones in all cells where the accumulations are greater than

64,700 and “no data” in all other cells” This file will be used later to select only cells from a particular raster data set that are included in the identified streams.  This new grid file was named “streams=one or no data”.

Next the Stream Order Tool of the Spatial Analyst Toolbox was applied to the “streams=one or no data” grid. to define a grid where the stream order of each stream reach was defined.  The farthest upstream segment or reach was defined as first order. When two first order reaches came together the next downstream segment was defined as second order.  When two second order reaches come together the next downstream reach was third order etc etc. This process continues downstream through the stream system. The resulting grid file was called “Stream Order”.  Next the stream order grid was processed using the Stream to Feature tool of the Hydrology Toolbox.  This resulted in a line shape file “Streams For Arcid” with a separate line (thus a separate ARCID) for each line segment in the stream network.  These separate ARCIDs were used later in finding the average reach flows.

The next step was to change the previously developed polyline shape file “Streams For Arcid” back to a grid file where each grid segment contains the ARCID of the stream segment.  This was accomplished using the Polyline to Raster tool of the Conversions Toolbox.  The resulting grid file “Stream Grid With Arcid” was used in the next step to determine the mean flows in each reach segment.

In the next step the median of the average flow in each of the cells in a stream reach was determined and a new grid was developed containing this median for each reach.  This step used the Zonal Statistics tool of the Spatial Analyst Toolbox.  Input to the tool included “Stream Grid With ARCID” for the Input Feature Zone data, with the Zone Field being Value and the (AVERAGE FLOW CFS) grid for the Input Value Field.  The statistics type chosen was median.  The resulting grid “Reach Median Flows” contains the median average annual flow values for all reaches in Guam’s watersheds.  The “Mean” Zonal Statistics tool was also used, but because of technical issues was unable to provide reasonable values.  The results of the Median Zonal Statistics analysis seemed to be much more reasonable.  The final step is to convert the “Reach Median Flows” grid file to a polyline shape file.  In order to do this ARCMAP requires that the starting grid file must have only integers as values.  In order to not lose the accuracy of the flow values calculated, the “Reach Median Flows” grid file was first multiplied by 100 then turned into an integer “Median Reach Flow x 100 Integer” using the Times and Integer tools of the Raster Math tools in the Spatial Analyst Toolbox.

The final step was to change the “Median Reach Flow x 100 Integer” grid to a polyline shape file.  This was done in order to make the stream reaches easier to see on the map and to provide for easy labeling of the median flow values.  The Raster to Polyline tool of the Conversions Toolbox was applied to the “median reach flow x 100 integer” grid to create the polyline shape file (STREAM REACHES).  A new field was added to the shape files attribute table.  This field was titled “medianFlow”.  Values for this field were computed using the field calculator by dividing the grid code field (flowsX100 integer) by 100 to get the correct median value for each reach.   Figure 23 shows the entire set of streams that were developed.  Figure 24 shows a close up view of individual stream reaches on the Ugum River. The flow value is the median value of the reach average annual flow for the reach.

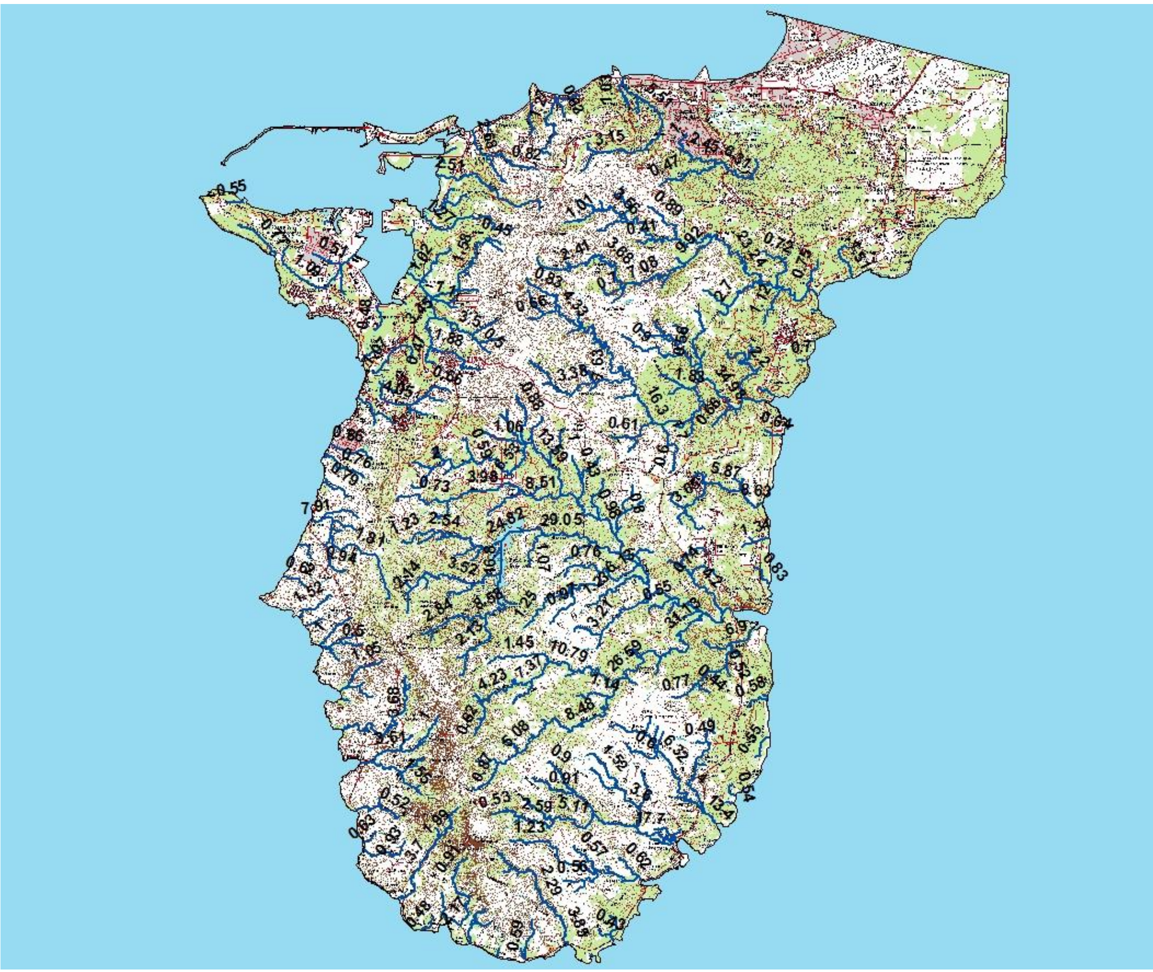
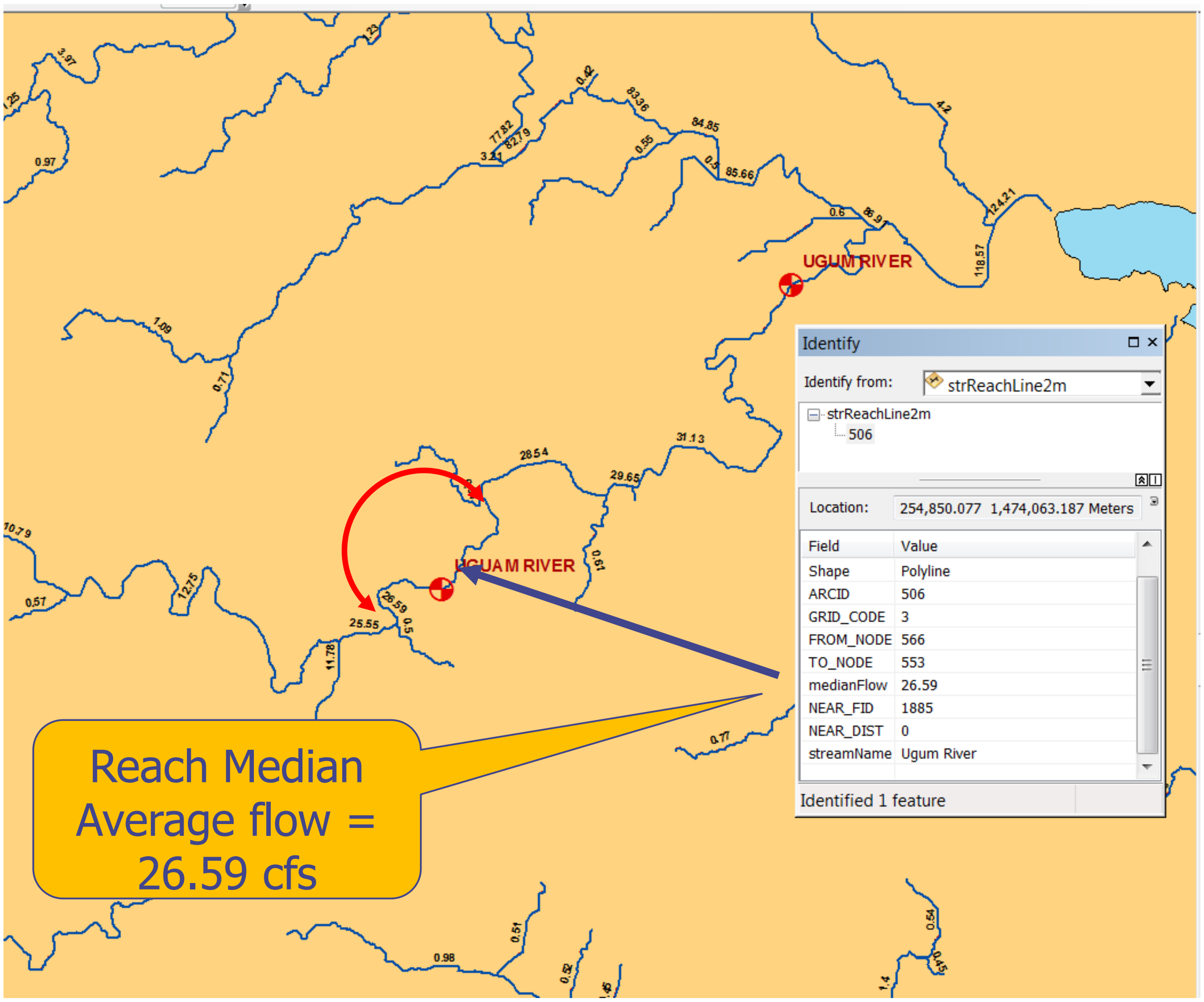


Figure 23. Guam streams and median reach flows in cfs from stream reach delineations



Identify

Identify from: strReachLine2m

strReachLine2m
506

Location: 254,850.077 1,474,063.187 Meters

| Field | Value |
|---|---|
| Shape | Polyline |
| ARCID | 506 |
| GRID_CODE | 3 |
| FROM_NODE | 566 |
| TO_NODE | 553 |
| medianFlow | 26.59 |
| NEAR_FID | 1885 |
| NEAR_DIST | 0 |
| streamName | Ugum River |

Identified 1 feature

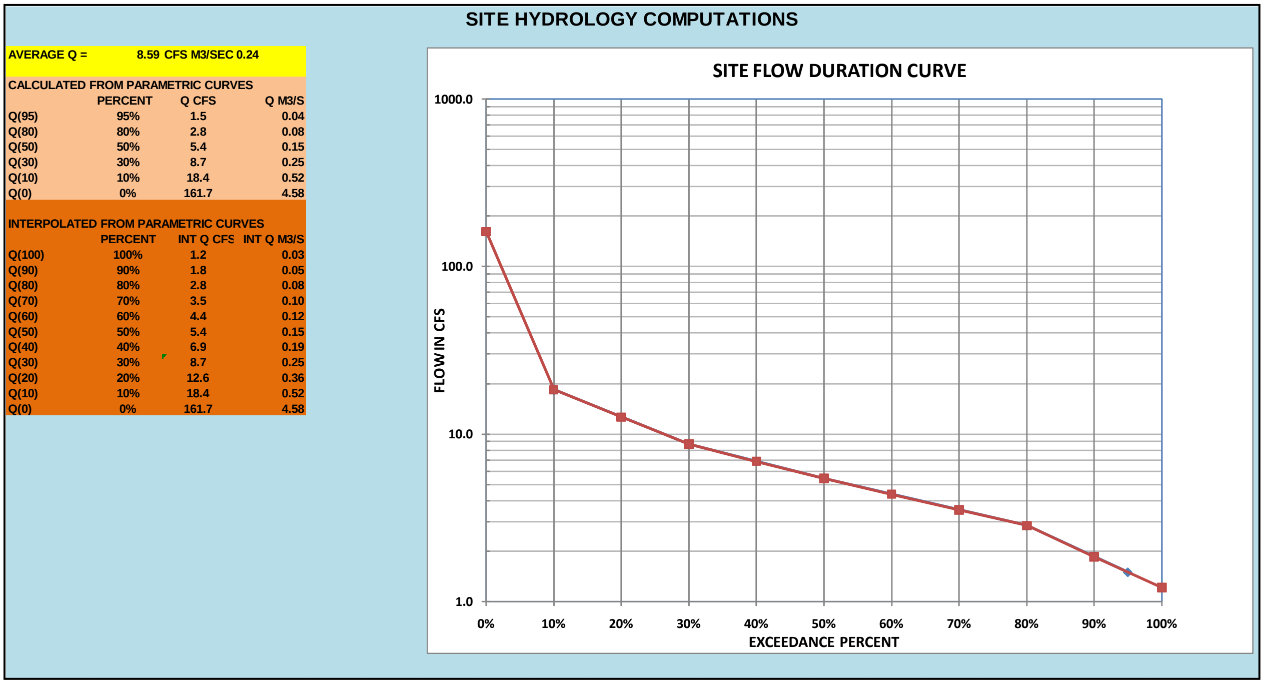
Reach Median Average flow = 26.59 cfs

Figure 24. Individual stream reaches on the Ugum River showing estimated median average annual flow in cfs for the reach

# PHASE V

## Hydro Power Production and Economic Analysis

In this Phase of the work a means of calculating the power potential and economic feasibility of potential hydropower sites in Guam was developed. A previously developed spreadsheet program (Heitz, 1982) was used as a basis for the new hydro power potential Excel application. The first worksheet of the application is shown in Figure 25. Input to this sheet is the potential site's average annual flow which comes from the previously described GIS maps. The application computes the flow duration values using the parametric duration curves described earlier. The application also plots the flow duration curve for the selected site. The second worksheet of the application, shown in Figure 26, computes the power production and economics of the site based on the flow duration curves computed on the first worksheet and the input site head, turbine sizing information and economic considerations. This application allows the user to explore various turbine sizing and economic considerations to determine the preliminary feasibility of developing a hydropower facility at a particular site. A copy of the Excel Workbook is available from the WERI web site: http://www.weriguam.org/. This application can be used by those interested in carrying out their own analysis at any potential hydropower site in Guam.



SITE HYDROLOGY COMPUTATIONS

AVERAGE Q = 8.59 CFS M3/SEC 0.24

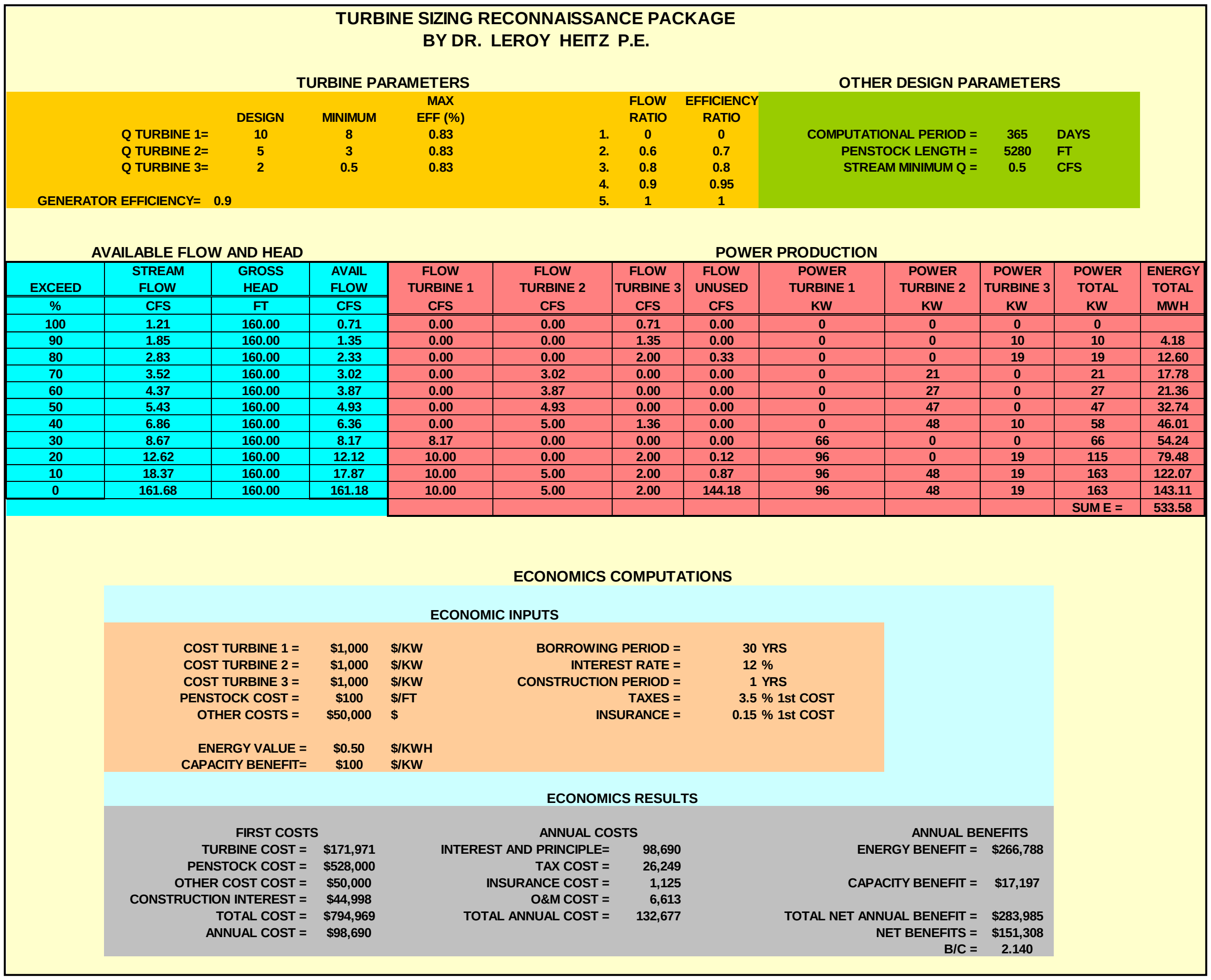
CALCULATED FROM PARAMETRIC CURVES

| | PERCENT | Q CFS | Q M3/S |
|---|---|---|---|
| Q(95) | 95% | 1.5 | 0.04 |
| Q(80) | 80% | 2.8 | 0.08 |
| Q(50) | 50% | 5.4 | 0.15 |
| Q(30) | 30% | 8.7 | 0.25 |
| Q(10) | 10% | 18.4 | 0.52 |
| Q(0) | 0% | 161.7 | 4.58 |

INTERPOLATED FROM PARAMETRIC CURVES

| | PERCENT | INT Q CFS | INT Q M3/S |
|---|---|---|---|
| Q(100) | 100% | 1.2 | 0.03 |
| Q(90) | 90% | 1.8 | 0.05 |
| Q(80) | 80% | 2.8 | 0.08 |
| Q(70) | 70% | 3.5 | 0.10 |
| Q(60) | 60% | 4.4 | 0.12 |
| Q(50) | 50% | 5.4 | 0.15 |
| Q(40) | 40% | 6.9 | 0.19 |
| Q(30) | 30% | 8.7 | 0.25 |
| Q(20) | 20% | 12.6 | 0.36 |
| Q(10) | 10% | 18.4 | 0.52 |
| Q(0) | 0% | 161.7 | 4.58 |

Figure 25. Site hydrology worksheet of hydropower analysis application



TURBINE SIZING RECONNAISSANCE PACKAGE
BY DR. LEROY HEITZ P.E.

TURBINE PARAMETERS

| | DESIGN | MINIMUM | MAX EFF (%) |
|---|---|---|---|
| Q TURBINE 1= | 10 | 8 | 0.83 |
| Q TURBINE 2= | 5 | 3 | 0.83 |
| Q TURBINE 3= | 2 | 0.5 | 0.83 |

GENERATOR EFFICIENCY= 0.9

| | FLOW RATIO | EFFICIENCY RATIO |
|---|---|---|
| 1. | 0 | 0 |
| 2. | 0.6 | 0.7 |
| 3. | 0.8 | 0.8 |
| 4. | 0.9 | 0.95 |
| 5. | 1 | 1 |

OTHER DESIGN PARAMETERS

COMPUTATIONAL PERIOD = 365 DAYS
PENSTOCK LENGTH = 5280 FT
STREAM MINIMUM Q = 0.5 CFS

AVAILABLE FLOW AND HEAD / POWER PRODUCTION

| EXCEED % | STREAM FLOW CFS | GROSS HEAD FT | AVAIL FLOW CFS | FLOW TURBINE 1 CFS | FLOW TURBINE 2 CFS | FLOW TURBINE 3 CFS | FLOW UNUSED CFS | POWER TURBINE 1 KW | POWER TURBINE 2 KW | POWER TURBINE 3 KW | POWER TOTAL KW | ENERGY TOTAL MWH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 | 1.21 | 160.00 | 0.71 | 0.00 | 0.00 | 0.71 | 0.00 | 0 | 0 | 0 | 0 | |
| 90 | 1.85 | 160.00 | 1.35 | 0.00 | 0.00 | 1.35 | 0.00 | 0 | 0 | 10 | 10 | 4.18 |
| 80 | 2.83 | 160.00 | 2.33 | 0.00 | 0.00 | 2.00 | 0.33 | 0 | 0 | 19 | 19 | 12.60 |
| 70 | 3.52 | 160.00 | 3.02 | 0.00 | 3.02 | 0.00 | 0.00 | 0 | 21 | 0 | 21 | 17.78 |
| 60 | 4.37 | 160.00 | 3.87 | 0.00 | 3.87 | 0.00 | 0.00 | 0 | 27 | 0 | 27 | 21.36 |
| 50 | 5.43 | 160.00 | 4.93 | 0.00 | 4.93 | 0.00 | 0.00 | 0 | 47 | 0 | 47 | 32.74 |
| 40 | 6.86 | 160.00 | 6.36 | 0.00 | 5.00 | 1.36 | 0.00 | 0 | 48 | 10 | 58 | 46.01 |
| 30 | 8.67 | 160.00 | 8.17 | 8.17 | 0.00 | 0.00 | 0.00 | 66 | 0 | 0 | 66 | 54.24 |
| 20 | 12.62 | 160.00 | 12.12 | 10.00 | 0.00 | 2.00 | 0.12 | 96 | 0 | 19 | 115 | 79.48 |
| 10 | 18.37 | 160.00 | 17.87 | 10.00 | 5.00 | 2.00 | 0.87 | 96 | 48 | 19 | 163 | 122.07 |
| 0 | 161.68 | 160.00 | 161.18 | 10.00 | 5.00 | 2.00 | 144.18 | 96 | 48 | 19 | 163 | 143.11 |
| | | | | | | | | | | | SUM E = | 533.58 |

ECONOMICS COMPUTATIONS

ECONOMIC INPUTS

COST TURBINE 1 = $1,000 $/KW
COST TURBINE 2 = $1,000 $/KW
COST TURBINE 3 = $1,000 $/KW
PENSTOCK COST = $100 $/FT
OTHER COSTS = $50,000 $

ENERGY VALUE = $0.50 $/KWH
CAPACITY BENEFIT= $100 $/KW

BORROWING PERIOD = 30 YRS
INTEREST RATE = 12 %
CONSTRUCTION PERIOD = 1 YRS
TAXES = 3.5 % 1st COST
INSURANCE = 0.15 % 1st COST

ECONOMICS RESULTS

FIRST COSTS
TURBINE COST = $171,971
PENSTOCK COST = $528,000
OTHER COST COST = $50,000
CONSTRUCTION INTEREST = $44,998
TOTAL COST = $794,969
ANNUAL COST = $98,690

ANNUAL COSTS
INTEREST AND PRINCIPLE= 98,690
TAX COST = 26,249
INSURANCE COST = 1,125
O&M COST = 6,613
TOTAL ANNUAL COST = 132,677

ANNUAL BENEFITS
ENERGY BENEFIT = $266,788

CAPACITY BENEFIT = $17,197

TOTAL NET ANNUAL BENEFIT = $283,985
NET BENEFITS = $151,308
B/C = 2.140

Figure 26. Hydropower output, turbine sizing and economic feasibility worksheet of hydropower analysis application

## TECHNICAL ISSUES THAT REQUIRED REMEDIATION

The 1 meter resolution LIDAR derived elevation DEM that provided elevation data that formed the basis for this study proved to provide accurate ground elevations with very fine resolution. One issue that arose involved the GIS derived stream locations where the stream crossed through roadway embankments. In the LIDAR data the tops of the embankments were shown as the correct ground elevations as that was the ground surface exposed to the LIDAR sensor. In stream location delineation using GIS it is necessary to see the elevation of the stream invert as it passes through the embankment in order to derive the correct stream crossing location. If this elevation is not available the GIS stream location procedure requires that the channel behind the embankment be filled until the water can pass over the embankment areas and continue downstream. This filling causes the location of stream to move sometimes great distances from the actual embankment crossing point at the bridge or culvert provided.

To remedy this problem we physically lowered the elevation of the 1 meter resolution LIDAR derived grid at each of the embankment crossing points. A polyline was drawn at each of the crossing point. An embankment elevation reduction was assigned to the polyline. The reduction assigned was determined by the difference between the top of the embankment and the downstream stream channel elevation. This polyline was buffered by 10 meters in order to derive a polygon that contained the required elevation reduction. This polygon file was then changed to a grid file that matched the 1 meter LIDAR data. The elevation reduction grid was then subtracted from the original elevation data, and further processed, as described earlier, to get the stream delineations. This procedure resulted in much improved stream channel locations throughout the South Guam study area.

Other issues arose due to the extreme size of the 1 meter resolution South Guam LIDAR data. The file size for this elevation grid was 6.23 Gb. The FILL, FLOW DIRECTION, and FLOW ACCUMULATION GIS Watershed Functions worked fine although processing time was lengthy. These functions required one half to one hour of processing using a standard PC with an I7 processor and 16 GB of memory. Problems arose when trying to perform a weighted accumulation based on the rainfall grid. Even after more than 12 hours of processing time the weighted accumulation failed to finish. A check on the internet revealed that this is a common problem when the WEIGHTED ACCUMULATION function is applied to large grid files using the ARCGIS 10 program. We resized the original 1 meter by 1 meter grid to 2meters by 2 meters and the long processing time for the WEIGHTED ACCUMULATION was eliminated. The smaller grid file could be processed in approximately 1 hour.

A second issue arose when attempting to create polylines along the streams from the average rainfall, Drainage area, and average flow grids. When starting with the 2m the program was unable to process the whole grid file because the number of polylines exceeded the limit allowed by the program. In order to complete this processing we resized the grids to 4 meter by 4 meter and averaged the gridded values for average rainfall, drainage area, and average flow.

The processing ran to completion and the polylines were at an adequate resolution and the values were precise enough for the purposes of this project.

## RESULTS

The results of this project was the development of a means of predicting flow duration curves at ungaged sites in Guam. All of the major streams in Southern Guam were divided into stream reaches. These reaches were based on “Stream Order” of the stream segment. The reaches were identified on maps developed from the detailed Geographic Information System (GIS) map inventory of Guam available at WERI. Various statistical and analytical methods, as described in the previous methods section, were applied to the existing streamflow data along with the physical characteristics of the reaches in order to predict the streamflow variability in each stream reach. More detailed average flows and exceedance percentage flows were also provided for smaller stream segments for all South Guam streams. Average annual rainfall upstream and drainage area were also developed for each of the stream segments.

An Excel application was also developed to perform a preliminary power production and economic analysis for any new proposed site. Those wishing to explore the feasibility of hydro power at a particular site will be able to enter the average flow and available head (hydraulic drop) information into the simple spreadsheet application which will be provided as part of the study. This application will allow the user to explore various turbine sizing and economic considerations to determine the preliminary feasibility of developing a hydropower facility at a particular site.

The GIS maps, and Excel application are available from the WERI web site:
http://www.weriguam.org/.
The GIS maps include the following for all the streams of Southern Guam:

1. Background Satellite Image of Guam
2. USGS Topographic Background map of Guam
3. Two meter by two meter grid files for the following:
    a. Drainage area upstream in South Guam Streams
    b. Average rainfall upstream in South Guam Streams
    c. Estimated Average Annual flow in South Guam Streams
    d. Average rainfall on south Guam
4. Polyline shape files which include
    a. Average annual rainfall Isolines for South Guam
    b. Average Drainage Area for stream segments of South Guam streams
    c. Average rainfall upstream for stream segments of South Guam streams
    d. Average flow and exceedance percentage flows for stream segments of South Guam streams. These shape files are also provided in “kmz” format for use with the Google Earth Program.
    e. Median average annual flow for stream reaches (based on steam order) for South Guam streams

The average flow, exceedance percentage flows, drainage area and average rainfall data provided are useful for many different hydrologic investigations. 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 all need the data that has been developed.

It is important to note that the average flows and exceedance percentage flow values are based on natural non-regulated flow conditions. Flows provided for the Maagas and Talofofo Rivers downstream of Fena Reservoir will need further adjustment to account for the regulation provided by Fena Reservoir and the treatment facility located at the reservoir. Similar adjustments will be required to flows in the Ugum River downstream of the diversion to Guam Waterworks Authority's Ugum water treatment facility.

## 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.

This study has developed means of predicting average flows and flow duration curves for most streams in South Guam. One key starting point in making these predictions is an accurate normal annual precipitation (NAP) map. A study by Lander and Guard provided us with the latest estimates of the distribution of annual rainfall in Southern Guam.

The second important starting point is the measured stream flow data. The data that was available was felt to be adequate for the purposes of this study. As time goes on and new data is gathered at existing and new sites, it will be possible to improve on the estimates of average flow and exceedance percentage flows made by this study

## ACKNOWLEDGMENT

The authors would like to thank Dr. Mark Lander for his help in providing updates to the South Guam average precipitation map. Also thanks are in order to Dr. Nathan Habana who provided access to the Guam 1m by 1 m LIDAR data and the Satellite imagery the formed the basis for the GIS portions of the study. Special thanks to the WERI Director, Dr. Shahram Khosrowpanah and the funding agency "the US Geological Survey".

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