PREDICTION OF FLOW DURATION CURVES FOR USE IN HYDROPOWER ANALYSIS AT UNGAGED SITES IN KOSRAE, FSM

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WERI

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

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ABSTRACT

The cost and availability of energy resources is one key factor in the economic development of and quality of life in any developing country. This is especially true in Kosrae, Federated States of Micronesia (FSM), where nearly all of the energy produced is from costly, non-renewable, and potentially environmentally damaging fossil fuel (oil) resources. The cost of fuel to operate the local power plant has risen dramatically over the past years and no doubt will continue to rise in the future. With these increases of fuel costs, it becomes more and more important to explore other means of providing energy to the islands power grid.

Kosrae is blessed with an abundance of surface water resources and because of the extreme topography of the island many of these streams have very high slopes. This combination of abundant streamflow and high stream gradient or slope is ideal for the application of run-of-river-hydropower development. This kind of hydropower development has the least environmental impact and is generally less capital intensive than typical hydropower plants built in conjunction with high dams with large amounts of water storage.

In order to explore the feasibility of using hydropower as an additional energy source for Kosrae, it is necessary to be able to define the variability of flow available in the streams where the hydropower plants might be constructed. 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 Kosrae, as in most locations, is that streamflow information is not available for all possible sites where development could occur. In the FSM this problem is even more acute since the streamflow gaging network has been abandoned for almost 20 years. What is needed is a means of predicting the variability of flow at ungaged locations that are likely to become candidate sites for future hydropower development.

This project has developed a means of predicting flow duration curves at ungaged sites in Kosrae. All of the major streams of the island were divided into stream reaches, or homogenous sections of a stream, that have similar flow properties. These reaches were identified on maps developed from the comprehensive Geographic Information System (GIS) map inventory of Kosrae available at the Water and Environmental Research Institute (WERI). Various statistical and analytical methods were applied to the existing streamflow data and physical characteristics of the reaches in order to predict the streamflow in each stream reach.

The final results of this project are a series of maps of the streams of Kosrae with each stream reach identified. The maps will be available for use in the free GIS program ARC Explorer. The user will be able to find the average flow for each stream reach. An Excel application was also developed to perform a preliminary power production and economic analysis for any new proposed site based on the average flow information and the statistical flow duration data developed in the project. The GIS maps, ARC Explorer program and Excel application are available on a CD which is included at the back of this report.

KEYWORDS: Hydropower, Flow Duration Curves, Streams

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INTRODUCTION

The cost and availability of energy resources is one key factor in the economic development and quality of life of any developing country. This is especially true in Kosrae, Federated States of Micronesia (FSM), where nearly all of the energy produced is from costly, non-renewable, and potentially environmentally damaging fossil fuel (oil) resources. The cost of fuel to operate the local power plant has risen dramatically over the past years and no doubt will continue to rise in the future. With these increases of fuel costs, it becomes more and more important to explore other means of providing energy to the island's power grid.

Kosrae is blessed with an abundance of surface water resources and because of the extreme topography of the island many of these streams have very high slopes. This combination of abundant streamflow and high stream gradient or slope is ideal for the application of run-of-river-hydropower development. This kind of hydropower development has the least environmental impact and is generally less capital intensive than typical hydropower plants built in conjunction with high dams with large amounts of water storage. While in general hydropower plants are high in first cost, but the cost per kilowatt hour of energy production is lower than fossil fuel plants and the annual power costs have the advantage of remaining relatively stable over the life of the project. Another advantage is the hydropower plant can be operated in a running reserve capacity and therefore can be called on to easily assist in supplying peak demands that occur at various times of the day.

In order to explore the feasibility of using hydropower as an additional energy source for Kosrae, it is necessary to be able to define the variability of flow available in the streams where the hydropower plants might be constructed. 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 streamflow data measured at the point of interest. The problem in Kosrae, as in most locations, is that streamflow information is not available for all possible sites where development could occur. In the FSM this problem is even more acute since the streamflow gaging network has been abandoned for almost 20 years. What is needed is a better means of predicting the variability of flow at ungaged locations that are likely to become candidate sites for future water resources development.

The flow duration curve provides us with a means of representing the variability of flow at a proposed hydropower 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 the flows in streams.

This project has developed a means of predicting flow duration curves at ungaged sites in Kosrae. All of the major streams of the island were divided into stream reaches, or homogenous sections of a stream, that have similar flow properties. These reaches were identified on maps developed from the comprehensive Geographic Information System (GIS) map inventory of Kosrae available at the Water and Environmental Research Institute (WERI). Various statistical and analytical methods were applied to the existing streamflow data and physical characteristics of the reaches in order to predict the streamflow in each stream reach.

The final results of this project are a series of maps of the streams of Kosrae with each stream reach identified. The maps will be available for use in the free GIS program ARC Explorer. The user will be able to find the average flow for each stream.

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, ARC Explorer program and Excel application are available on a CD which is included at the back of this report.

STUDY AREA

As shown in Figure 1, the Island of Kosrae is located in the Western Pacific approximately 2,600 miles South East of the Island of Japan. Kosrae is a state in the Federated States of Micronesia (FSM). The more detailed map in Figure 2 shows the many streams on the island. The land area of the island is approximately 42 square miles. Rainfall on the island ranges from 185 to 260 inches. The topography of almost the entire island is highly mountainous intersected with many fast flowing streams making it an ideal area for hydropower development.

As of 2010 the population of the island is approximately 6600 (2010 census). The island is served by the Kosrae Utilities Authority (KUA). The KUA provides power to the island. The vast majority of the power produced on the island is by a thermal (fuel oil) power plant.

Figure 1. Kosrae Island location map

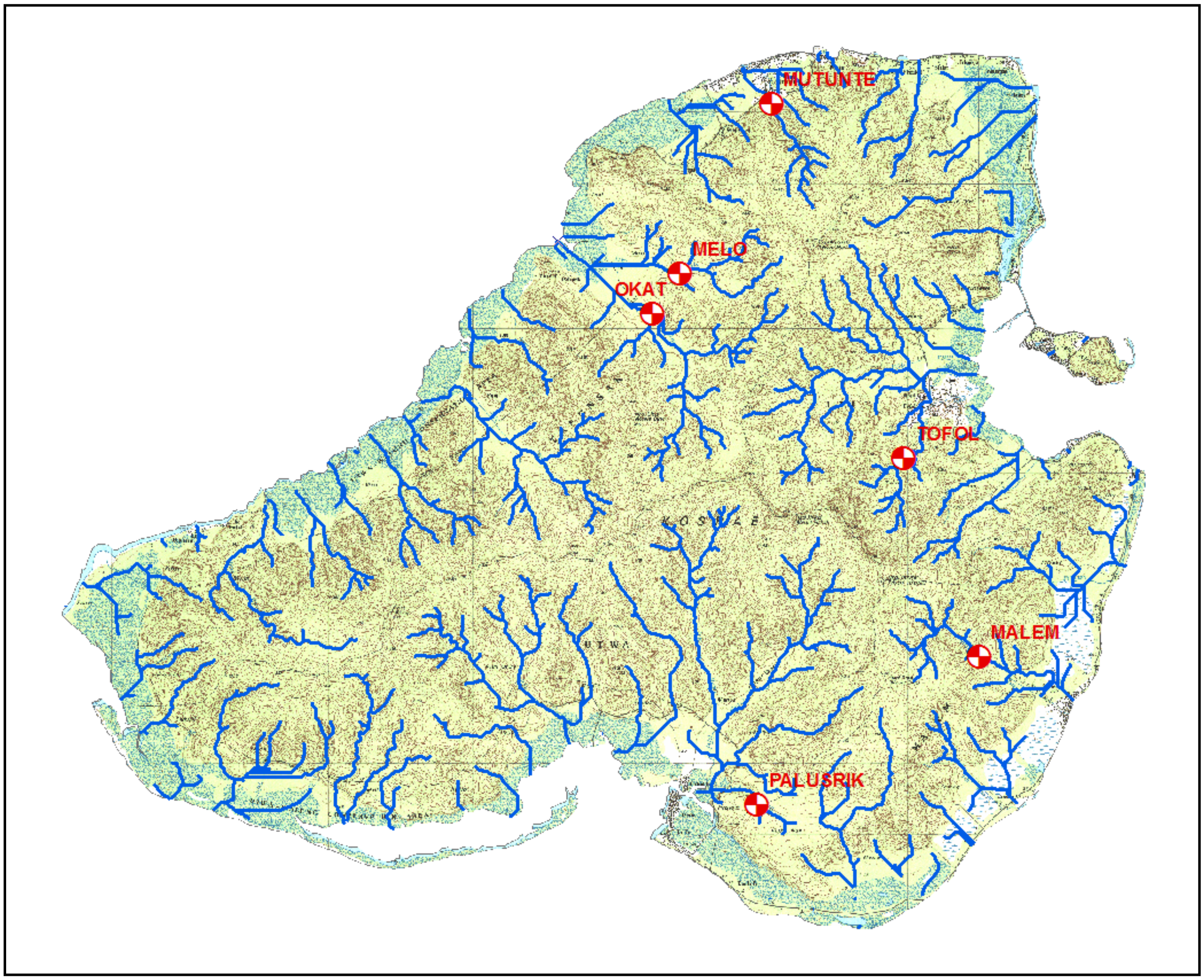

Figure 2. Island of Kosrae showing streams

OBJECTIVES

The overall objective of this project was to develop flow durations curves for reaches of Kosrae's streams. These flow duration curves are essential for studying future hydropower development in the streams and will also be useful in making studies of low flow requirements and availability of water for various surface water developments and to study the impacts of mans 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 Kosrae.

2. Develop techniques, based on average stream flow, for transferring the flow duration curve information available at the gaged locations to ungaged sites in Kosrae.

3. Develop estimates of average flow for Kosrae's streams.

4. Divide Kosrae’s streams into homogenous stream reaches with similar flow characteristics and assign an average flows to each reach.

5 Develop a set of GIS based maps showing the location of all stream reaches along with the average flows available and make these maps available in a free to use GIS program.

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. In 2010 the authors of this report performed a similar study for the Island of Pohnpei. (Heitz & Khosrowpanah, 2010)

Beginning in June of 2003, WERI researchers (Khosrowpanah et al., 2005) assembled a network of rain gages on Pohnpei Island which lies North of Kosrae. They found that earlier charts of Pohnpei’s mean annual rainfall using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly, 1994) were quite accurate. For that reason the maps developed by the PRISM techniques for the Island Of Kosrae were used in this study. Rainfall amounts varied from 185 inches around the island’s shoreline to 260 inches in the high mountain peaks.

METHODS AND PROCEDURES

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

PHASE I
Develop Flow Duration Curves for Each Gage Site

The first step was to gather all the available daily streamflow data for Kosrae's streams into computer spreadsheet format. This was accomplished using WERI's Earth Info CD-ROM data base and accompanying data accessing programs. Figure 3 shows the location of the United States Geological Survey (USGS) stream gage sites that were used in the study. Figure 4 provides information on the period of record for each of the gages.

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 5 shows a typical flow duration curve for the Toful River in Kosrae. 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 Kosrae. In addition to the duration values, the average annual runoff was determined for each gage site. Figure 6 shows a complete set of duration curves for all of the gage sites in Kosrae.

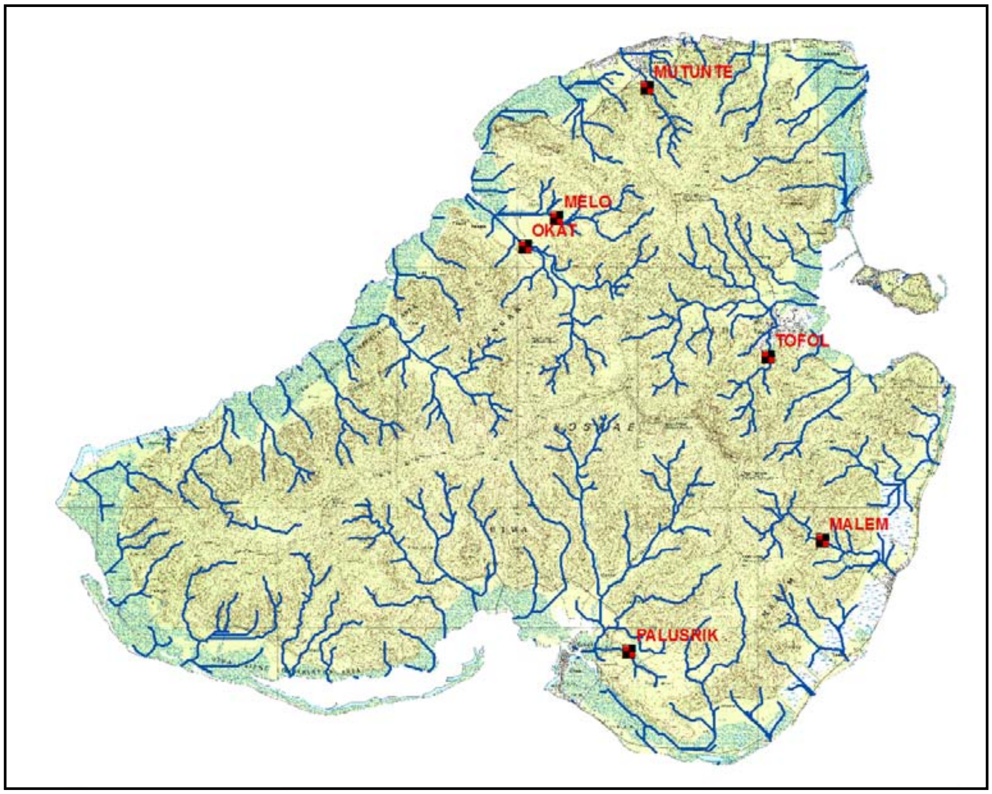

Figure 3. Location of USGS stream gage sites

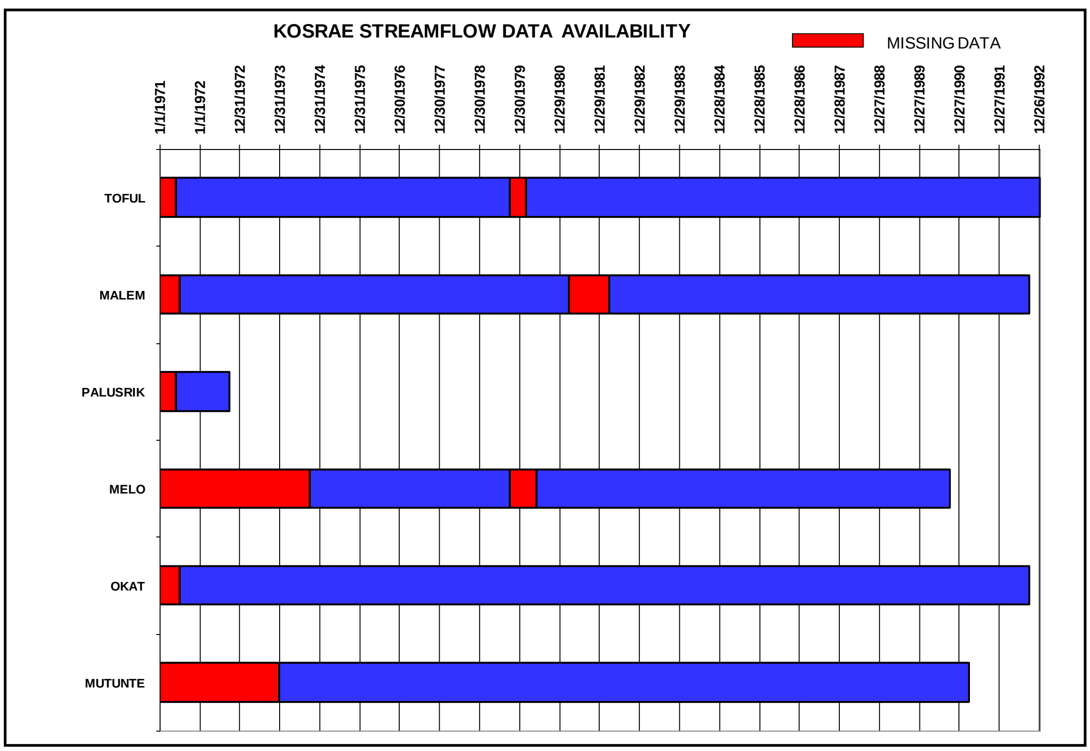

Figure 4. Availability of streamflow data from USGS gages on Kosrae

LOW	HIGH	IN BIN	NUMBER GREATER	% GREATER
0	0.02	0	6545	100.0000%
0.02	0.3	152	6393	97.6776%
0.3	0.75	360	6033	92.1772%
0.75	1	266	5767	88.1131%
1	1.25	208	5559	84.9351%
1.25	1.5	321	5238	80.0306%
1.5	1.75	192	5046	77.0970%
1.75	2	339	4707	71.9175%
2	2.25	355	4352	66.4935%
2.25	2.6	425	3927	60.0000%
2.6	3	345	3582	54.7288%
3	3.5	419	3163	48.3270%
3.5	4	369	2794	42.6891%
4	4.5	311	2483	37.9374%
4.5	5	290	2193	33.5065%
5	5.75	350	1843	28.1589%
5.75	6.75	393	1450	22.1543%
6.75	8	299	1151	17.5859%
8	10	396	755	11.5355%
10	15	373	382	5.8365%
15	50	367	15	0.2292%
50	122	15	0	0.0000%
	TOTAL	6545		

Table 1. Flow duration table for Toful River, Kosrae, FSM

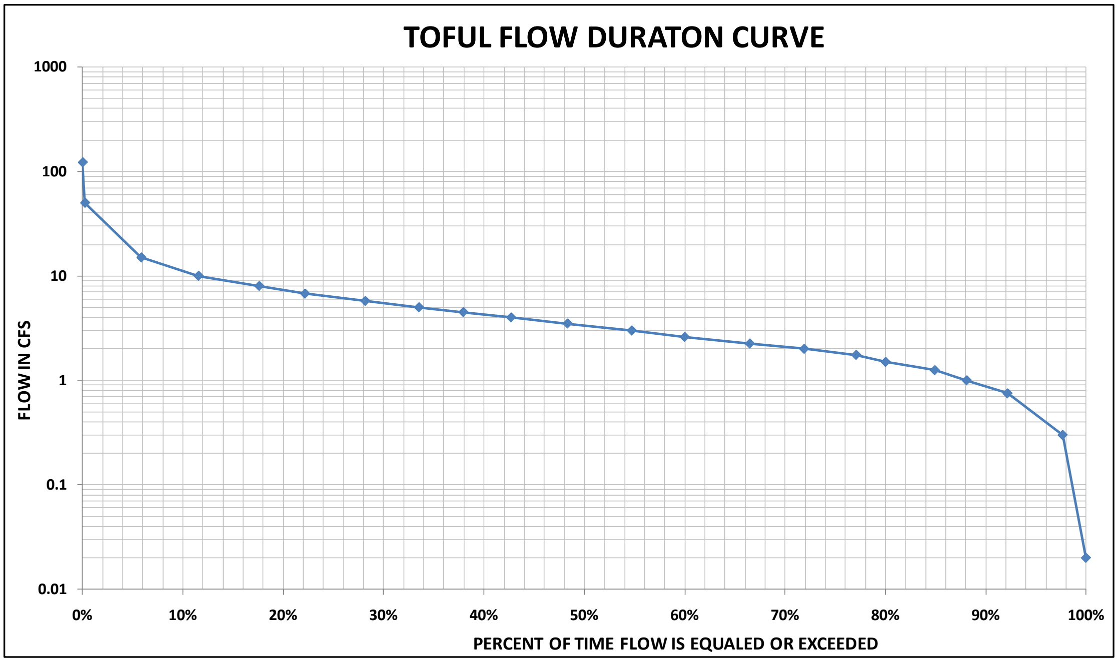

Figure 5. Flow duration curve for Toful river, Kosrae State, FSM

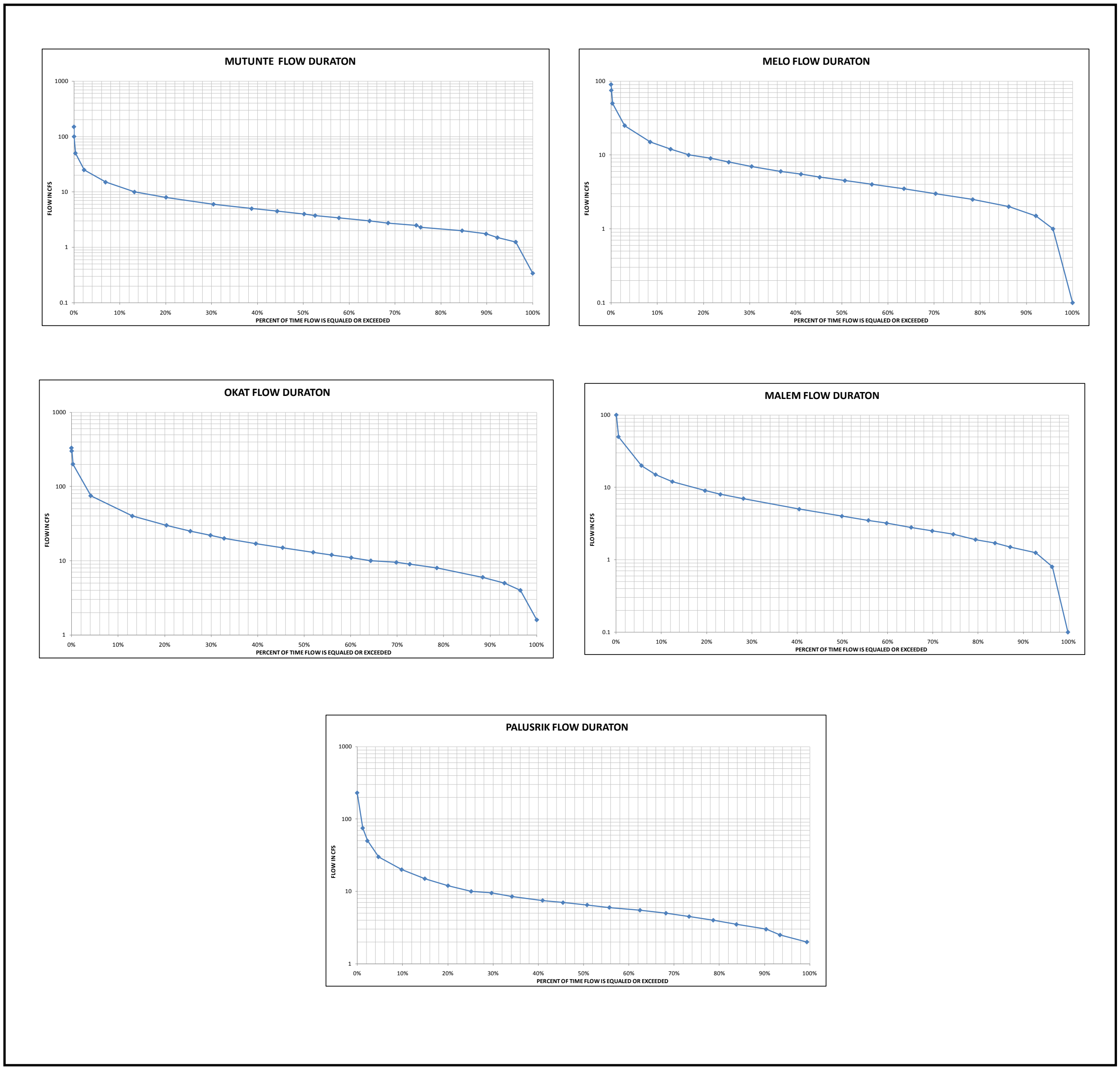

Figure 6. Duration curves for Mutunte, Melo, Okat, Malem, and Palusik Rivers

PHASE II
Prediction of Duration Curves at Ungaged Sites

Phase II involved the application of a technique to predict duration curves at ungaged sites in Kosrae. This step is important because many of the potential hydropower sites in Kosrae 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 percents. 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(30), Q(50), and Q(30) from each of the duration curves developed in Phase I. These particular exceedance values were chosen because these percentages are important in the sizing of hydropower plants. 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. An example of the resulting parametric curves is shown in Figure 7.

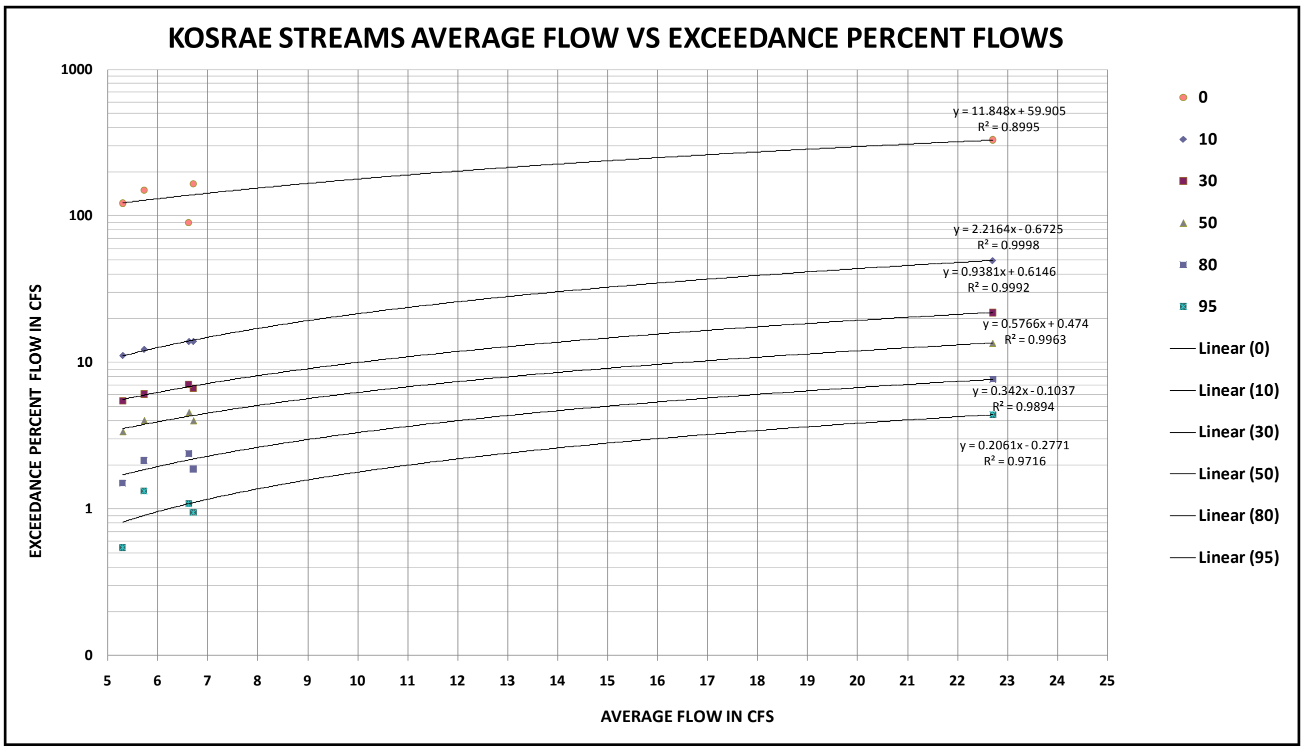

Figure 7. Parametric flow duration curves

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. These equations were used later to predict actual flows at ungaged sites or stream reaches. Figure 8 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 18 cfs.

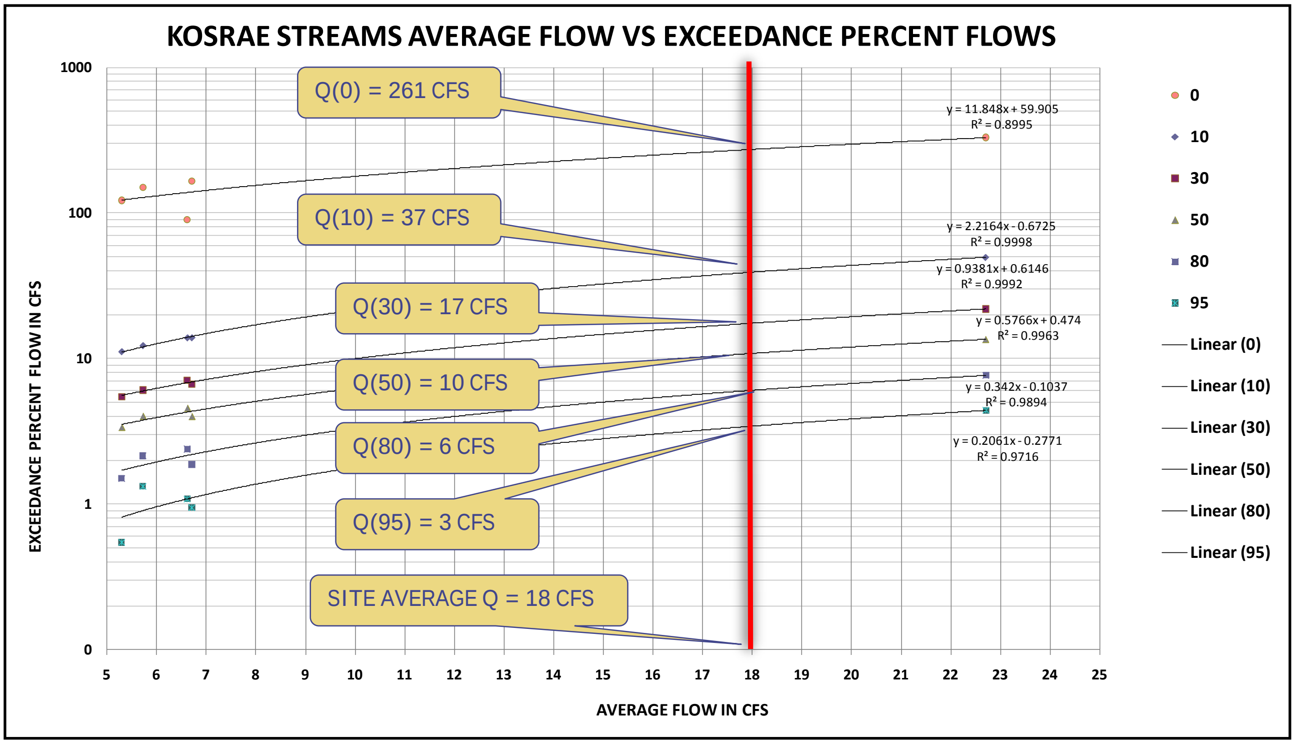

Figure 8. Use of parametric flow duration curves to predict flow duration values at an ungaged site with an average flow of 18 cfs

PHASE III
Develop 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 Kosrae'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 product was grid based 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 sites or reaches.

The steps required to redevelop the average flow values are:

1. Develop a 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 and stream segments (reaches) from DEM data
6. Determine average flows in stream reaches

DEVELOPMENT OF ELEVATION GRID

The grid Coverage and shape file names provided in the following explanations correspond to those provided in the table of contents in the ArcGIS map file (mxd file) that is provided on the CD located in the envelope in the back of this report. The first step in the development of the various GIS maps for the study was to obtain the latest USGS topographic map of Kosrae to use as a base map for all of the other maps. This map was provided by Digital Data Services of Lakewood Colorado. They purchased the latest topographic map of Kosrae from the USGS and digitized and geo-referenced this map. The next step was to overlay the digital line graphics (DLG) contour maps that were available from the USGS on to the new USGS topographic map. These contours were developed from older maps and were somewhat offset from the new topographic base map. The contours lines were shifted until they fit the contours on the new topographic map. The Contour to Raster Tool of the Spatial Analyst Toolbox was used to develop the elevation grid from the contour lines. A five meter by five meter grid size was used. This grid file is sometimes known as a Digital Elevation Model or DEM. Figure 9 shows the DEM for Kosrae. Note that the green colors are the highest elevations and the colors from yellow to brown show lower and lower elevations. In order to be useful for our analyses this DEM 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. Once the DEM was filled the FILLED DEM 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. This tool assigned the direction that water would flow from each of the FILLED DEM grid cells resulting in a FLOW DIRECTION grid. 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 10 shows the results of the accumulation function. The lighter colors show the areas of highest accumulations. These correspond to the small streams and rivers.

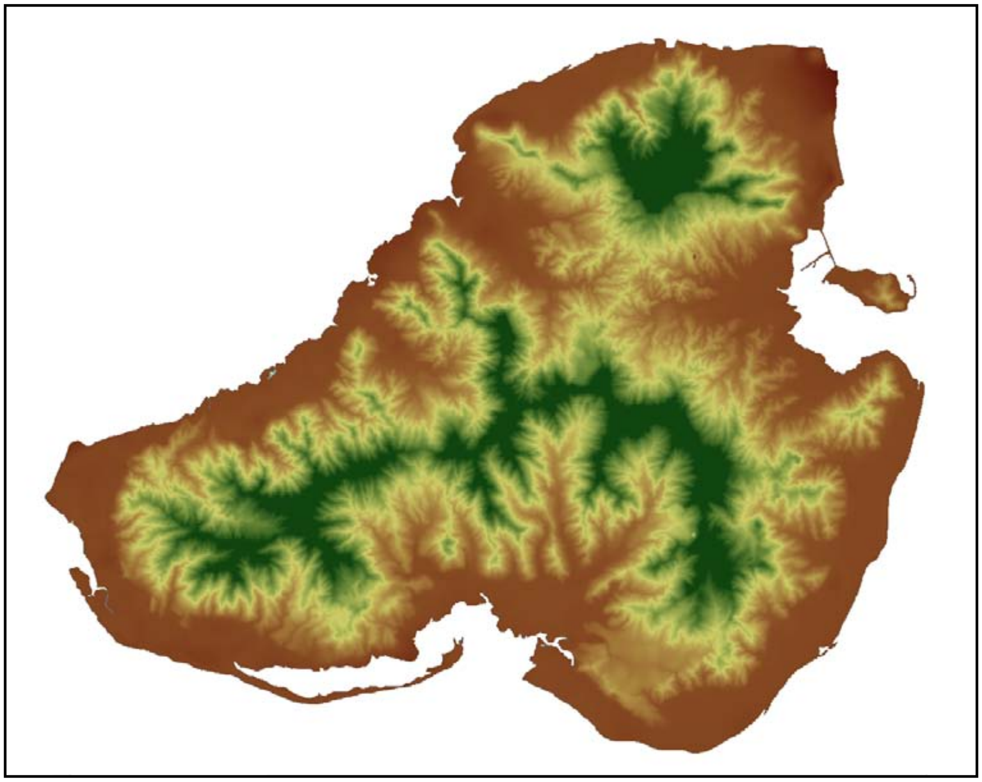

Figure 9. Digital elevation model for Kosrae Island

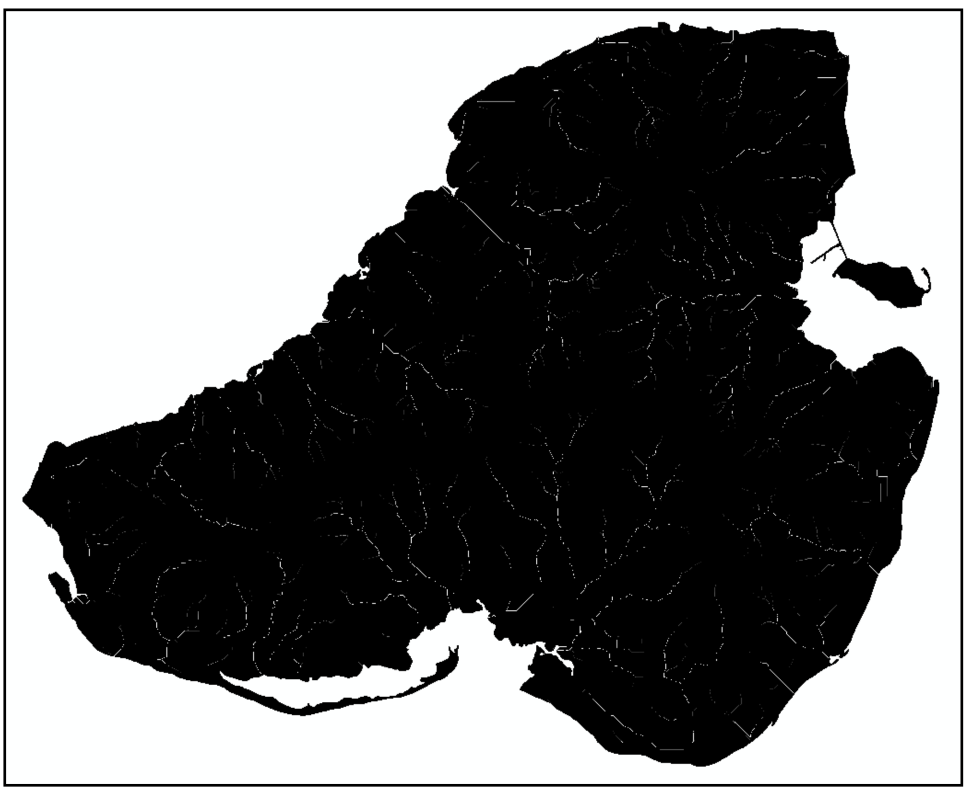

Figure 10. Flow accumulation grid map for Kosrae Island

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 Pohnpei (Lander & Khosrowpanah, 2005) had revealed that mean annual rainfall predicted using the University of Oregon PRISM (Daly, 1994) technique were found to be quite accurate. The Kosrae PRISM map is available at: http://www.prism.oregonstate.edu/products/viewer.phtml?file=/pub/prism/pacisl/graphics/ppt/Normals/kosrae_ppt_1971_2000.14.jpg. This jpeg was laid over the base USGS topographic map and stretched to fit the island outline. Average annual precipitation contour lines were manually drawn on the stretched jpeg, (PRISM RAINFALL CONTOURS). These contours are shown in Figure 11.

The Topo to Raster Tool of the Spatial Analysis Toolbox was applied to the PRISM RAINFALL CONTOURS to get a Grid of average annual rainfall for the island. This grid will be referred to as PRISM RAIN and is shown in Figure 12.

DEVELOPMENT OF AVERAGE ANNUAL PRECIPITATION INPUT AND AVERAGE ANNUAL FLOW GRIDS

The first step was to combine the FLOW DIRECTION grid file previously developed and the PRISM RAIN average annual rainfall grid. The result was a new grid map called RAINFALL ACCUMULATIONS 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, PRISM RAIN, 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. Proper conversions factor were applied to the RAINFALL ACCUMULATION grid using the Spatial Analyst Raster Calculator so that the resulting values were in units of cubic feet per second (cfs) average annual flow. The grid file is name PRECIPITATION INPUT CFS and is shown in Figure 13.

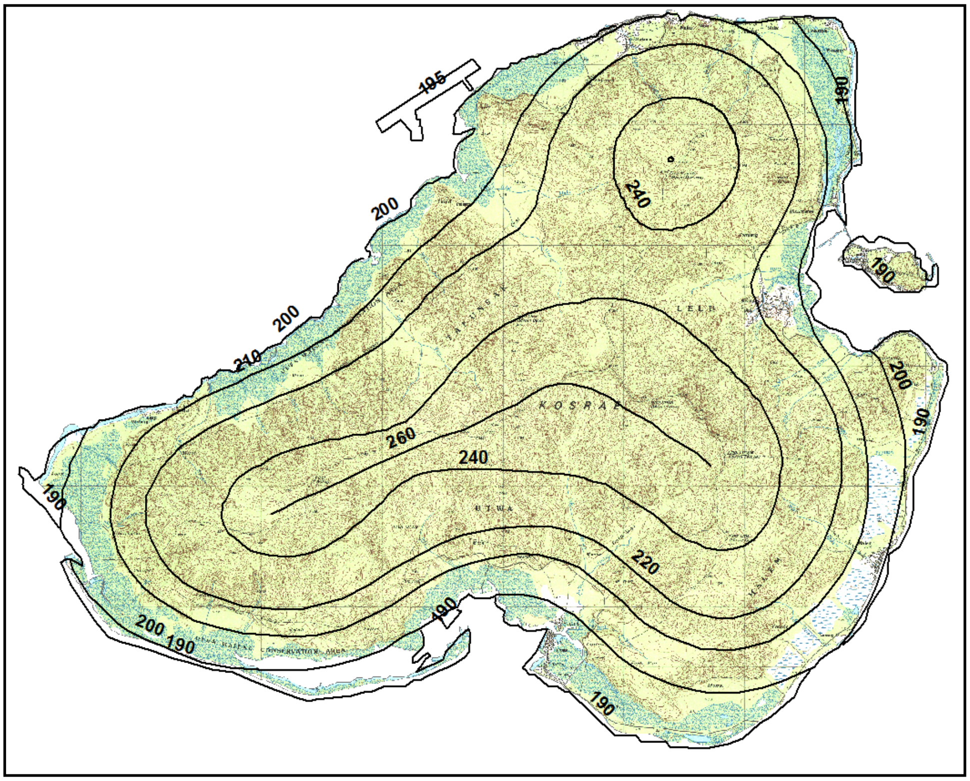

Figure 11. Average annual rainfall contours in inches

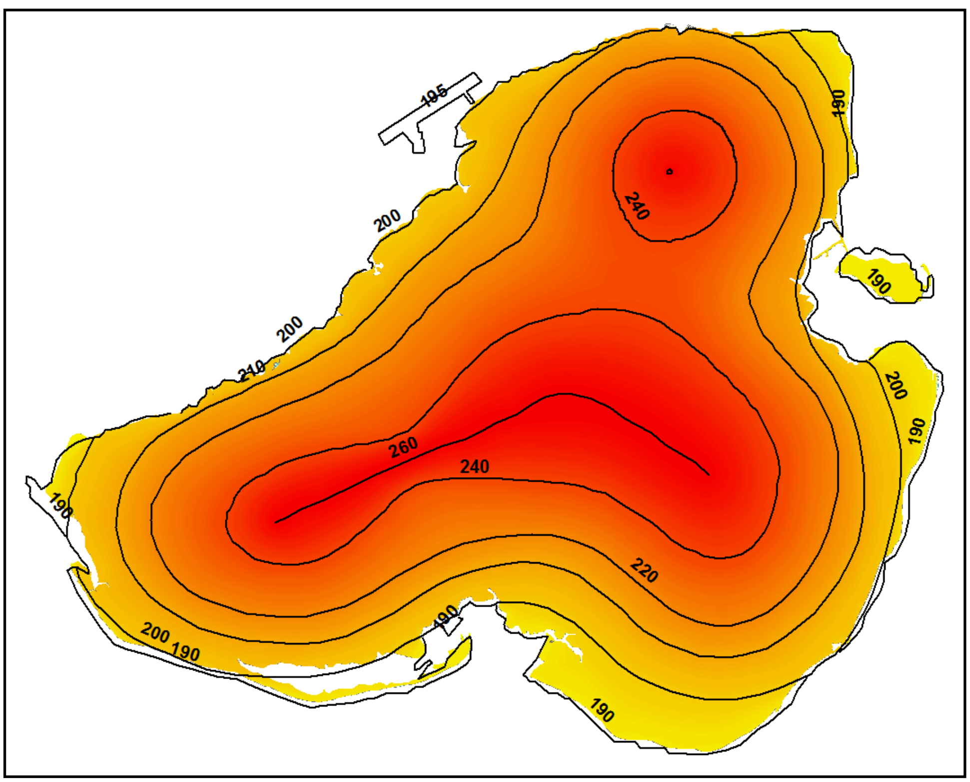

Figure 12. Average annual rainfall grid map with rainfall contours in inches

One can think of this 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 13 shows the results of this final accumulation. Again the light colors represent the higher values of rainfall accumulation in the larger stream channels. Figure 14 shows the same map enlarged on an area near the location of the Toful river stream gage. The cell in white nearest the gage site has a value 8.8 cfs. This represents the average flow at that location assuming no losses. This process is repeated for each stream flow gage location shown in Figure 15. Table 2 shows the Precipitation Input for all of the gage stations. 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.

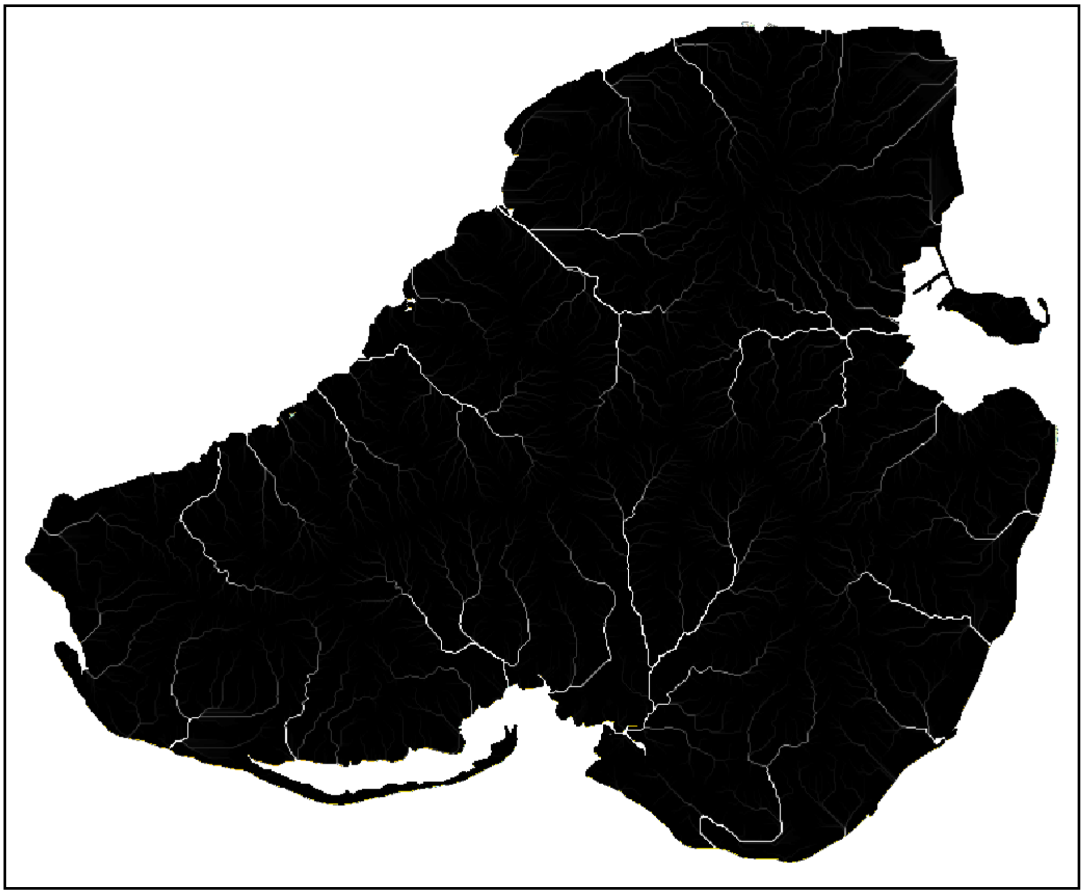

Figure 13. Precipitation input or average annual rainfall accumulation grid

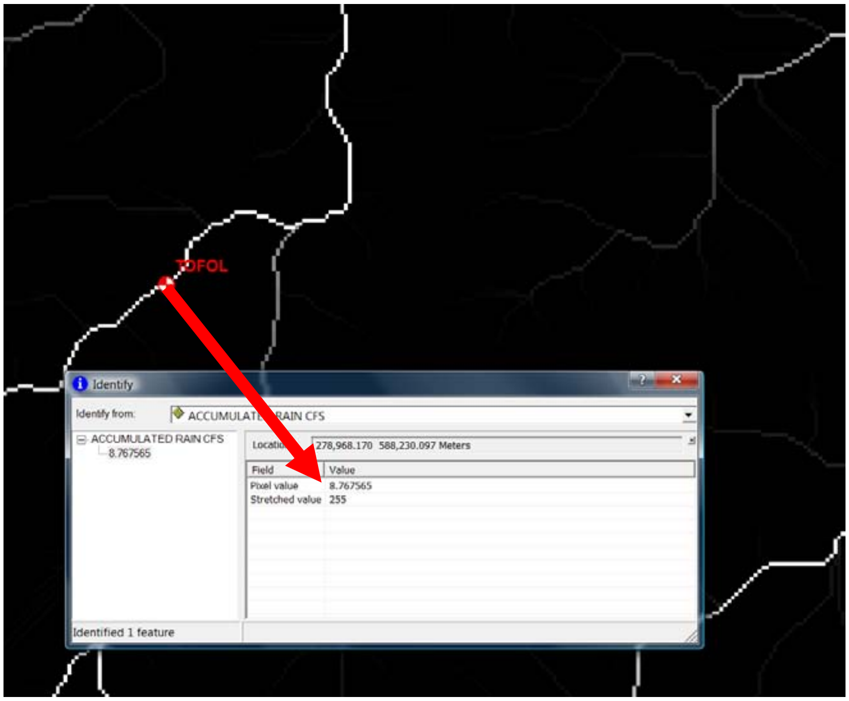

Figure 14. Precipitation input grid in the area near the Toful river stream gage site

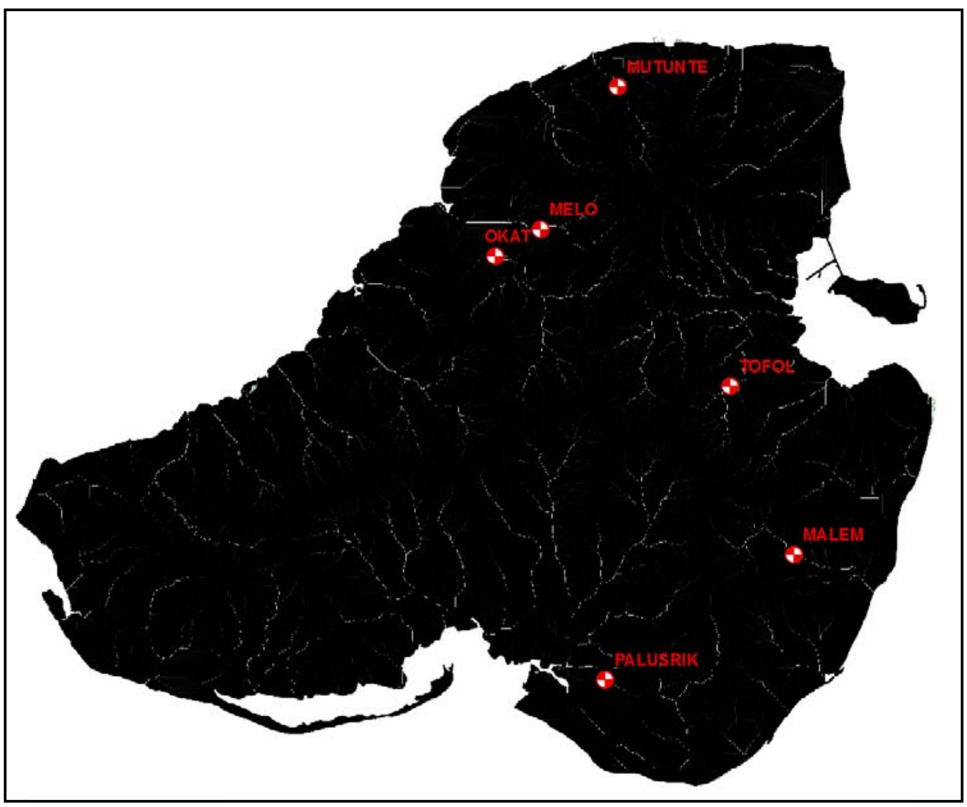

Figure 15. Streamflow measuring sites and precipitation input grid

USGS GAGE NAME	AVERAGE FLOW (CFS)	PRECIPITATION INPUT (CFS)	RUNOFF FACTOR	DRAINAGE AREA (SQ. MILES)
TOFUL	5.29	8.77	0.60	0.48
MALEM	6.71	13.78	0.49	0.77
MELO	6.62	10.37	0.64	0.59
OKAT	22.71	29.77	0.76	2.14
MUTUNTE	5.72	9.7	0.59	0.54
		AVERAGE	0.62	

Table 2. Average runoff and precipitation input (average rainfall accumulation) for Kosrae's stream gage stations

Next we developed a method of predicting runoff factors for ungaged sites in Kosrae. This factor was applied to the Precipitation Input Grid Map (PRECIPITATION INPUT CFS) that was developed previously to predict the average flow at the ungaged sites. If we plot the precipitation input versus the computed runoff factor for each of the stream flow gage station we get the plot show in Figure 16. If we fit a linear curve to the data we get the equations shown in Figure 16. Please note that data from the Palusrik Gage was not included in the analysis because only just over one year of data was available from that site.

The regression equation is applied to the PRECIPITATION INPUT CFS grid using the grid Raster Calculator Tool of the Spatial Analyst Toolbar resulting in the grid (RUNOFF FACTORS). If we multiply the RUNOFF FACTORS grid by the PRECIPITATION INPUT CFS grid, again using the Raster Calculator Tool, the results is an average annual flow map for all streams on the island (AVERAGE RUNOFF CFS). Figure 17 shows the AVERAGE FLOW CFS grid for the area near the Toful River gage station. A GIS function called "Identify" applied to the cells shown in white near the gage reveals a predicted average annual flow of 5.0 cfs. This is very close to the actual average annual flow measured at the site of 5.2 cfs. The AVERAGE FLOW CFS 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 bar to obtain a new grid (AVERAGE FLOW ONLY IN STREAMS) which contains only average flow values in the stream grid cells.

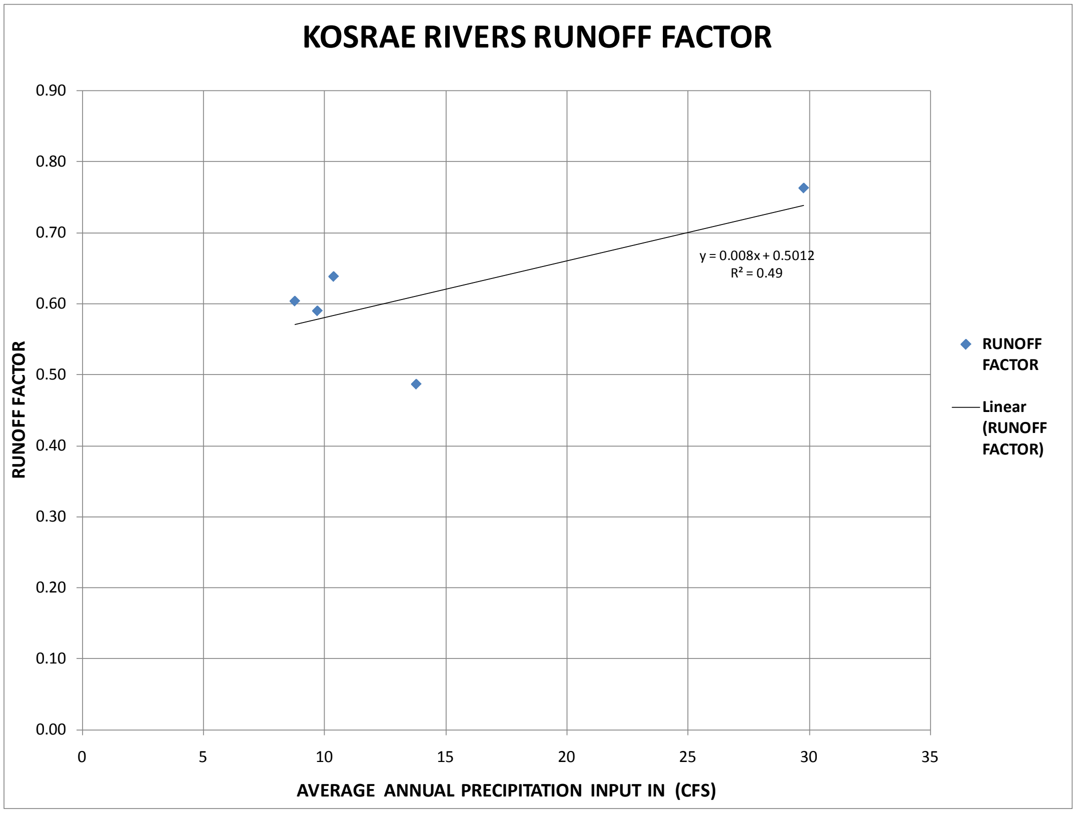

Figure 16. Runoff factor vs. precipitation input for Kosrae Rivers

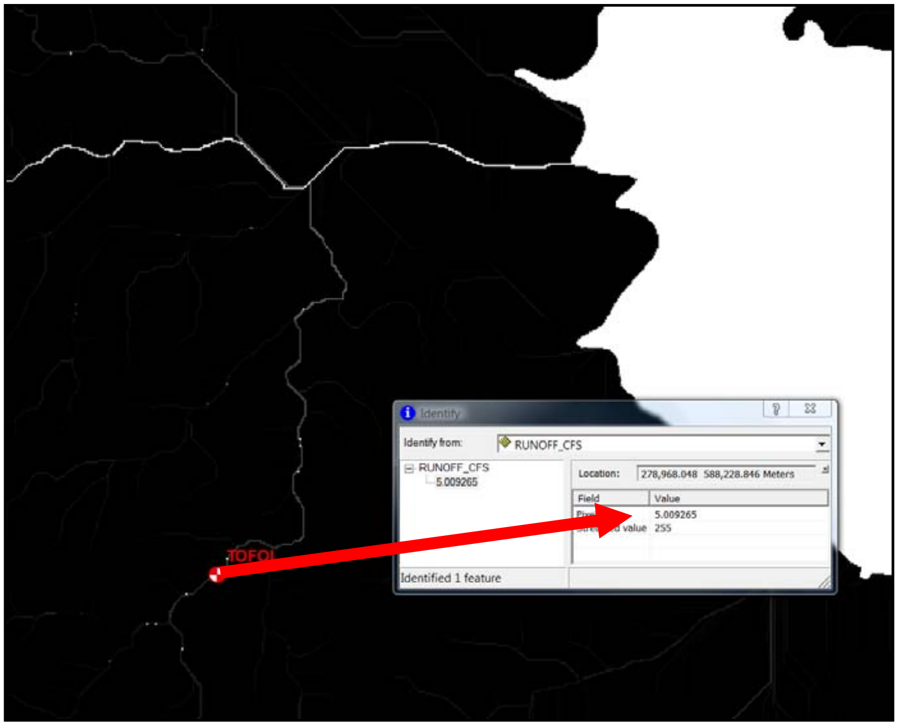

Figure 17. Average flow grid near the Toful river stream gage site

PHASE IV
Stream Reach Delineation and average flow

In Phase IV we divided Kosrae's streams into homogenous stream reaches with similar flow characteristics. After examining the available USGS Digital Line Graphics (DLG) hydro-coverage available for the USGS Kosrae Topographic Map it was determined that a more complete network of streams should be developed. This was done starting with the ACCUMULATION grid coverage 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 3000 was determined to give a reasonable stream network definition for our study. What this means is that all cells in the ACCUMULATION grid with cell values of 3000 or greater will be included in the stream network. The Raster Calculator Tool of the Spatial Analyst Toolbar was applied to the ACCUMULATION grid to eliminate all cells with accumulations less than 3000. The resulting grid was called ACCUMULATIONS GREATER THAN 3000. 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 3000 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 used 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. 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 Raster to Polyline tool of the Conversions 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) will be used in the next step to determine the mean flows in each reach segment.

In the next step the average flow in each of the cells in a stream reach was averaged and a new grid was developed containing the average flow 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 AVERAGE FLOW ONLY IN STREAM grid for Input Value Field. The statistics type chosen was mean. The resulting grid (REACH MEAN FLOWS) contains the average flow values for all reaches in Kosrae's watersheds. The final step is to convert the REACH MEAN 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 looses the accuracy of the flow values calculated the MEAN REACH FLOW grid file was first multiplied by 100 (MEAN REACH FLOW X 100) then turned into an integer (MEAN REACH FLOW X 100 INTEGER) using the Times and Integer tools of the Raster Math tools in the 3d Analyst Toolbox.

The final step was to change the integer MEAN 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 mean flow values. The Raster to Polyline tool of the Conversions Toolbox was applied to the MEAN REACH FLOW X 100 INTEGER to create the polyline shape file (MEAN FLOW IN REACH). A new field was added to the shape files attribute table. This field was titled MEAN_FLOW. Values for this field are computed using the field calculator by dividing the grid code field (flowsX100 integer) by 100 to get the correct mean value for each reach. Figure 18 shows the entire set of streams that was developed. Figure 19 shows a close up view of individual stream reaches on the Toful River.

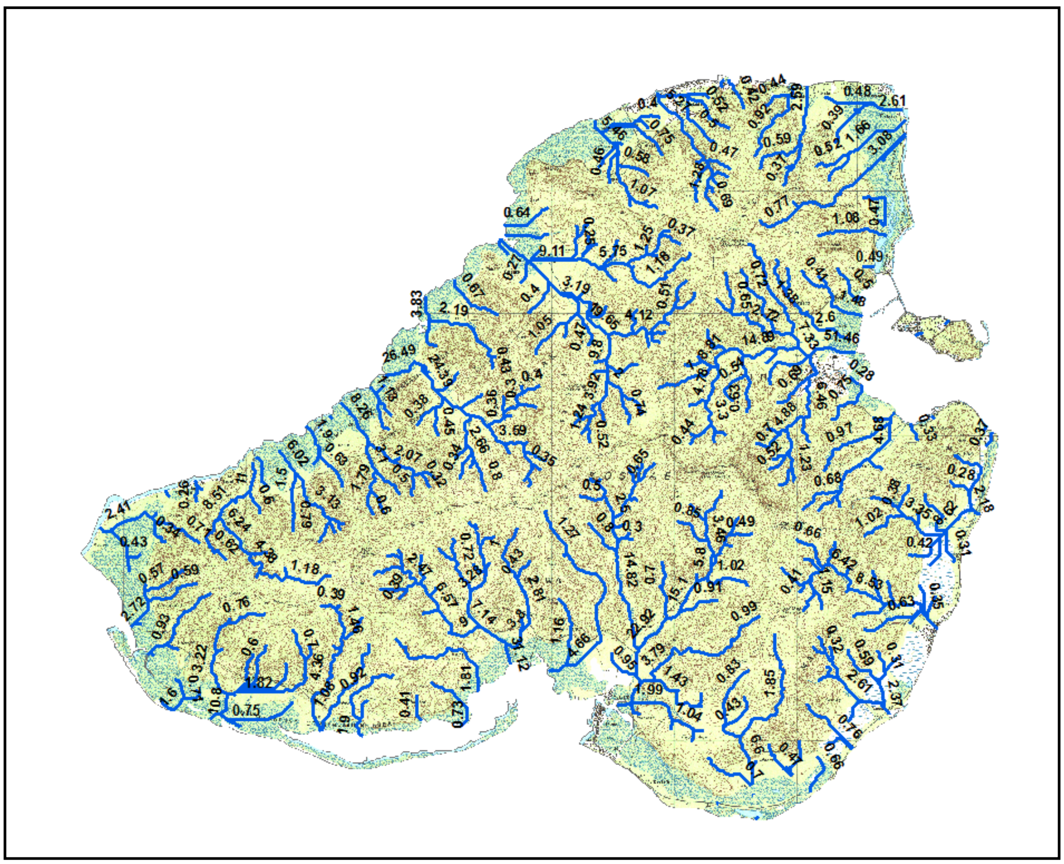

Figure 18. Kosrae streams and average flows in cfs from stream reach delineations

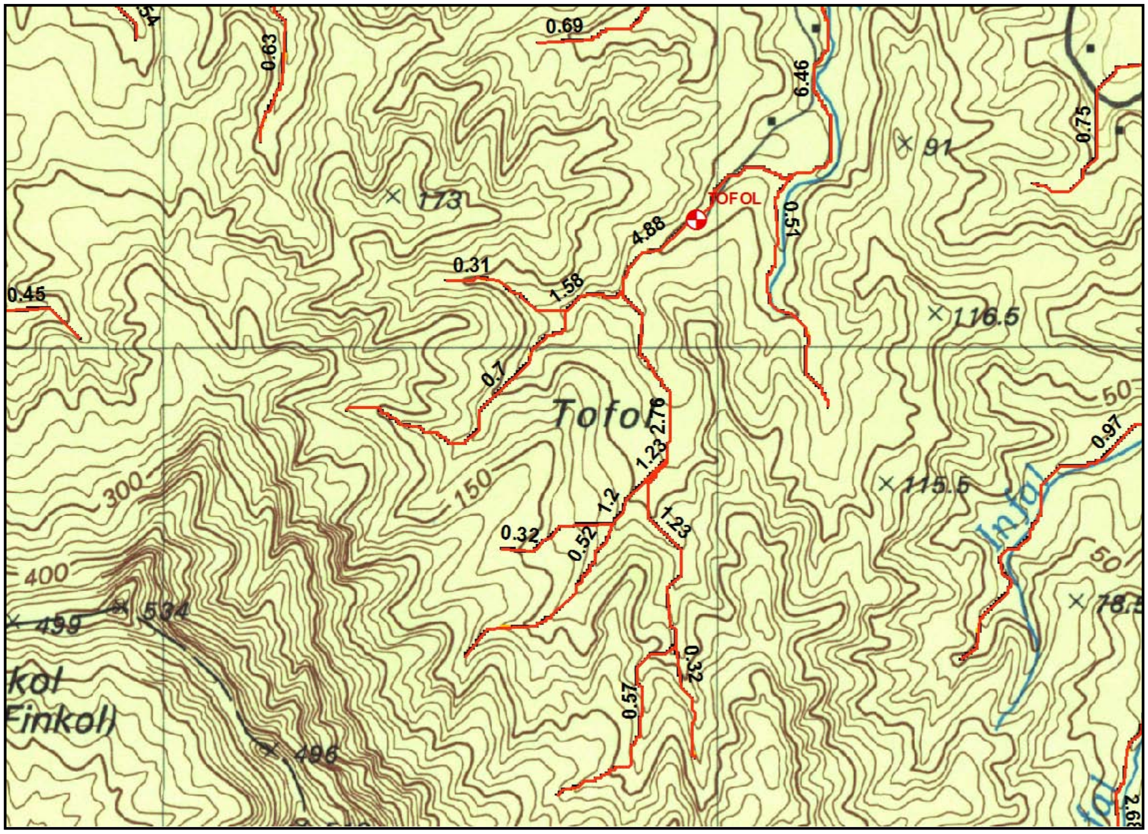

Figure 19. Individual stream reaches on the Toful River showing average annual flow in cfs for the midpoint each reach

The stream reaches shown in Figures 18 and 19 were developed from a grid elevation model of the island. This reaches although much more detailed than the streams shown on the USGS topographic maps, do not always exactly match the stream lines shown on the map. To make it easier for the user who requires only data on the streams shown on the topographic map, an average annual flow attribute was added to the attribute table of the Digital line graphs (DLGs) of the streams (RIVERS USGS DLG). The average flow values for each stream segment were manually taken from the computed average flow grid (AVERAGE FLOW CFS). The RIVERS USGS DLG shape file is shown in Figure 20.

Figure 20. Kosrae stream reaches from USGS topographic map with average annual; flows in cfs

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 Kosrae 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 21. 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 22, 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 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. A copy of the Excel Workbook is provided on the CD accompanying this report. This application can be used by those interested in carrying out their own analysis at any potential hydropower site in Kosrae.

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

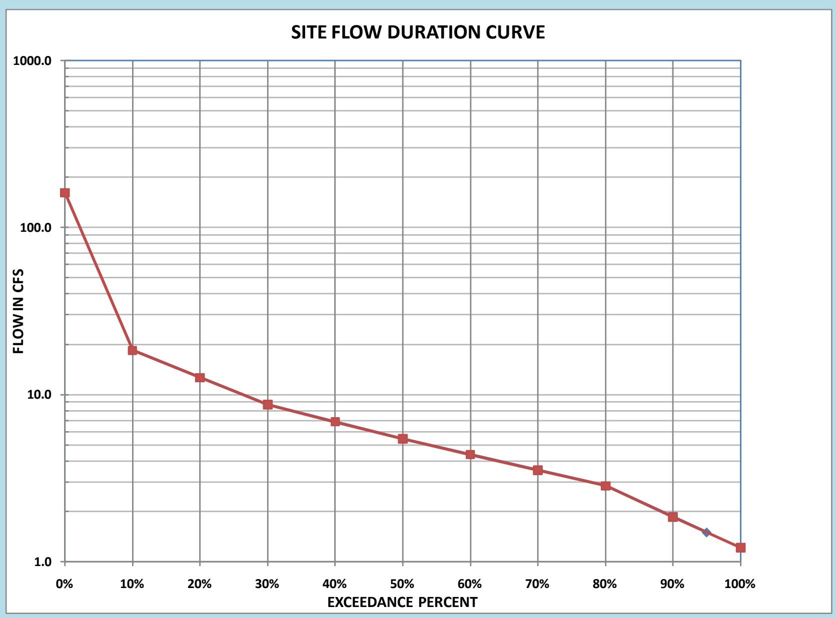

Figure 21. Hydrology worksheet of hydropower analysis application

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

TURBINE PARAMETERS

	DESIGN	MINIMUM	MAX EFF (%)		FLOW RATIO	EFFICIENCY RATIO
Q TURBINE 1=	10	8	0.83	1.	0	0
Q TURBINE 2=	5	3	0.83	2.	0.6	0.7
Q TURBINE 3=	2	0.5	0.83	3.	0.8	0.8
				4.	0.9	0.95
GENERATOR EFFICIENCY= 0.9				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	GROSS HEAD	AVAIL FLOW	FLOW TURBINE 1	FLOW TURBINE 2	FLOW TURBINE 3	FLOW UNUSED	POWER TURBINE 1	POWER TURBINE 2	POWER TURBINE 3	POWER TOTAL	ENERGY TOTAL
%	CFS	FT	CFS	CFS	CFS	CFS	CFS	KW	KW	KW	KW	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	BORROWING PERIOD =	30	YRS
COST TURBINE 2 =	$1,000	$/KW	INTEREST RATE =	12	%
COST TURBINE 3 =	$1,000	$/KW	CONSTRUCTION PERIOD =	1	YRS
PENSTOCK COST =	$100	$/FT	TAXES =	3.5	% 1st COST
OTHER COSTS =	$50,000	$	INSURANCE =	0.15	% 1st COST
ENERGY VALUE =	$0.50	$/KWH			
CAPACITY BENEFIT=	$100	$/KW			

ECONOMICS RESULTS

FIRST COSTS		ANNUAL COSTS		ANNUAL BENEFITS	
TURBINE COST =	$171,971	INTEREST AND PRINCIPLE=	98,690	ENERGY BENEFIT =	$266,788
PENSTOCK COST =	$528,000	TAX COST =	26,249		
OTHER COST COST =	$50,000	INSURANCE COST =	1,125	CAPACITY BENEFIT =	$17,197
CONSTRUCTION INTEREST =	$44,998	O&M COST =	6,613		
TOTAL COST =	$794,969	TOTAL ANNUAL COST =	132,677	TOTAL NET ANNUAL BENEFIT =	$283,985
ANNUAL COST =	$98,690			NET BENEFITS =	$151,308
				B/C =	2.140

Figure 22. Hydropower output, turbine sizing and economic feasibility worksheet of hydropower analysis application

RESULTS

This study has provided a means to evaluate the hydroelectric potential at sites and on reaches of streams in Kosrae, FSM. In order to accomplish this, average flows were developed for stream reaches on all Kosrae's major streams. A means of computing flow duration curves from these average flows was also developed.

A hydropower planning spreadsheet workbook application is provided in which average flows are input along with various hydraulic and economics parameters. A power potential and economic analysis is then performed. This analysis provides preliminary estimates of the feasibility of developing a hydroelectric project at a particular site. The workbook is available as part of the data package for this project.

The average flow data is made available through a GIS map of the stream reaches on all the major streams on Kosrae. The data for this map is available for use with the free GIS application Arc Explorer. This average flow data is useful for other applications beyond just estimating hydroelectric potential. When coupled with the hydrology worksheet in the spreadsheet application, flow duration curves can be estimated for any stream in Kosrae. This information could be used for in-stream flow requirement studies or other studies investigating man impact on the natural flow patterns in the streams.

SUMMARY AND CONCLUSIONS

The information provided in this report and its accompanying GIS data bases can be most helpful to those interested in establishing new hydroelectric facilities on Kosrae. Hydroelectric power can provide electric power with minimal environmental impact and can also provide a hedge against rising fuel oil prices. While first costs of hydroelectric facilities are generally higher than fossil fuel plants, the operating costs of the hydro facilities are always significantly lower. Kosrae is blessed with an abundance of stream flow resources. Hydroelectric power, as a clean renewable resource, should be seriously considered for any new power system expansions in Kosrae.

This study has developed means of predicting average flows and flow duration curves for most of Kosrae's streams. One key starting point in making these predictions is an accurate normal annual precipitation (NAP) map. A previous study showed that the existing NAP map developed using the PRISM method agreed well with a new array of rain gages that were stationed around the island of Pohnpei. This study used maps developed by the same PRISM procedure. While this is good, any new long term precipitation records should be compared with the existing NAP maps so that improvements in these maps can be made. Any improvements in predicting NAP distribution will improve the estimates of average annual flow and flow durations made by this project.

The second important starting point is the measured stream flow data. The data that was available was very limited. The longest record, which was for the Toful River was only twenty one years in length. The USGS gage network has been inactive for almost 18 years. Any new projects that establish long term recording of streamflow data would be most helpful in improving the estimates made by this study. It would be particularly helpful if the old stream gage stations were re-commissioned to extend the existing records.   Also establishing some completely new sites might improve the geographic distribution of stream gage sites thus leading to improved estimates.

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