

**River Channel Morphology Model – A tool for analyzing and extrapolating river
channel bathymetry**

by

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TABLE OF CONTENTS

Section 1 - Introduction	1
Section 2 - River Channel Morphology Model.....	3
Section 3 - Analysis of Residuals from RCMM	43
Section 4 - Application of RCMM to the Lower Brazos Priority Segment.....	50
Section 5 – Summary and Future Work.....	53

Section 1 - Introduction

Introduction

An ArcGIS toolset (River Channel Morphology Model) is developed for extrapolating the three-dimensional structure of river channels in the form of cross-sections and profile-lines. Cross-sections are bed profiles across the flow, and profile-lines are bed profiles along the flow. The River Channel Morphology Model (RCMM) describes only the mean surface for the channel bed. The description of channel bed is based on the meandering shape of the channel planform and hydraulic geometry relationships. This report describes the step-by-step procedure to implement the River Channel Morphology Model (RCMM) for creating a three-dimensional structure for river channels. The scope of work for the year 2004 is addressed in sections 3 and 4. For more details on RCMM theory and its application, the reader is referred to Merwade and Maidment (2004) provided with the CD-ROM at the end of this report.

Scope of work for 2004

For the year 2004, the following two tasks were identified in the scope of work:

- Task 1: Studying local scale variations in the channel bathymetry
- Task 2: Application of RCMM to the lower Brazos priority segment

In task 1, it was proposed to filter the observed bathymetry data from the RCMM output so that the filtered residuals can be separated into pools and riffles. To get a clear indication of pools or riffles from the filtered data, it is necessary that RCMM captures all the trends (longitudinal and lateral) in the channel bathymetry. It is found that although RCMM captures the large lateral trends in the channel bathymetry, the model needs to incorporate additional factors such as slope, geology, local terrain, etc to provide a complete description of the mean surface. Therefore, the work for task 1, presented in section 3 of this report, includes a preliminary analysis of residuals, and discussion of an approach for studying the local scale variations in the channel bathymetry by adopting geostatistical methods.

In task 2, it was proposed to apply RCMM to the lower Brazos priority segment. The work for task 2, presented in section 4 of this report, includes application of RCMM to the lower Brazos priority segment downstream of SH 21 near Bryan, TX. The flow and elevation data at four USGS gaging stations are used to rescale the RCMM output, and describe the three-dimensional channel bathymetry for the lower Brazos priority segment. It is found that although RCMM is capable of describing the channel bathymetry for a segment that is approximately 470 km long, the results must be used with caution. The hydraulic geometry relationships predict the average width and depth reasonably well, but the elevation data from USGS gaging stations must be supplemented by some local measurements to get meaningful results from RCMM.

Report Outline

This report is organized into five sections. In the second section, a tutorial is provided with step-by-step instructions for using RCMM. The third section provides a brief discussion on analysis of residual data for incorporating local scale variations (pools and riffles) in RCMM. In the fourth section, the application of RCMM for the lower Brazos priority segment is discussed. Section five provides a summary with some ideas for future work.

A CD-ROM is provided with the report containing the following two items:

Tutorial.zip: This zip file contains the RCMM toolset (RCMM.dll) and the data necessary for implementing the tutorial described in section two.

CRWR_04-08.pdf: This pdf document is a copy of the CRWR online report available at <http://www.crwr.utexas.edu/reports/2004/rpt04-8.shtml>. The fifth chapter in *CRWR_04-08.pdf* provides the theoretical background and development of RCMM. It also includes the application of RCMM to the study sites along the Brazos, Guadalupe and Sulphur Rivers, all in Texas.

Section 2 - River Channel Morphology Model

Introduction

This section describes the step-by-step procedure to implement the River Channel Morphology Model (RCMM) for creating a three-dimensional structure for river channels in the absence of detailed channel bathymetry. The section is organized in the form of a tutorial using an example dataset along the Brazos River. For a detailed discussion on RCMM theory, the reader is referred to Merwade and Maidment (2004) provided with the CD-ROM.

Goal

The goal of this exercise is to use RCMM to create a three-dimensional structure for the main stem of the Brazos River between the Richmond and Rosharon gaging stations by using the centerline from the National Hydrography Dataset (NHD) and cross-section information from the United States Geological Survey (USGS). In addition, some other functions of RCMM that are useful for extracting the three-dimensional structure of the channel to run the HEC-RAS model are explored.

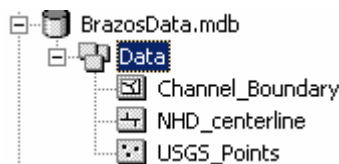
Data and Software Requirements

The data required for this tutorial, and other necessary files, are located in the Tutorial.zip file provided with the CD. Copy the zip file, and unzip it to save the contents in a local folder (Tutorial folder).

RCMM needs at least the following two feature classes populated:

1. A **point feature class** containing at least two points, each located upstream and downstream from the area of interest. The point feature class must have channel width, depth and bank elevation attributes. These attributes can be populated by using the information from the USGS gaging stations or from any other sources.
2. A **polyline feature class**, typically the FlowLine feature class from NHD.

The raw data can be found in BrazosData.mdb. Open ArcCatalog, and browse to the data as shown below:



The BrazosData.mdb has three feature classes:

- 1) **Channel_Boundary** is a polygon feature class digitized using aerial photographs of the study area.
- 2) **NHD_centerline** is a polyline feature class that contains NHD FlowLine features for the main stem of the Brazos River from Richmond to Rosharon gaging station.
- 3) **USGS_Points** is a point feature class with two points identifying the locations of the gaging stations.

This tutorial requires **ArcGIS 9.0** (ArcView and ArcInfo) desktop version with Spatial Analyst and 3D Analyst extensions.

Building the RCMM Database

To use RCMM, a geodatabase must be created with the required feature classes. The following table shows the data requirements for RCMM.

Feature Class	Feature type
ReferencePoints	Point
Centerline	PolylineZM/PolylineM
ChannelBoundary	Polygon
BoundarySegments	Polyline
Thalweg	PolylineZM
CrossSections	PolylineZM
ProfileLines	PolylineZM

The RCMM structure is stored in a schema (RCMM_Schema.xml) that can be applied to an empty geodatabase to create all the feature classes necessary for using RCMM. In ArcCatalog, create an empty personal geodatabase in the tutorial folder (Right click → *New* → *Personal Geodatabase*), and name it as Brazos_RCMM.mdb.

Brazos_RCMM.mdb can be populated by applying the RCMM schema (RCMM_Schema.xml), which is stored in the tutorial folder. Open RCMM_Schema.xml with internet explorer to see the geodatabase structure with all the feature classes as shown below (Note: the xml file will look different if opened with other browsers):

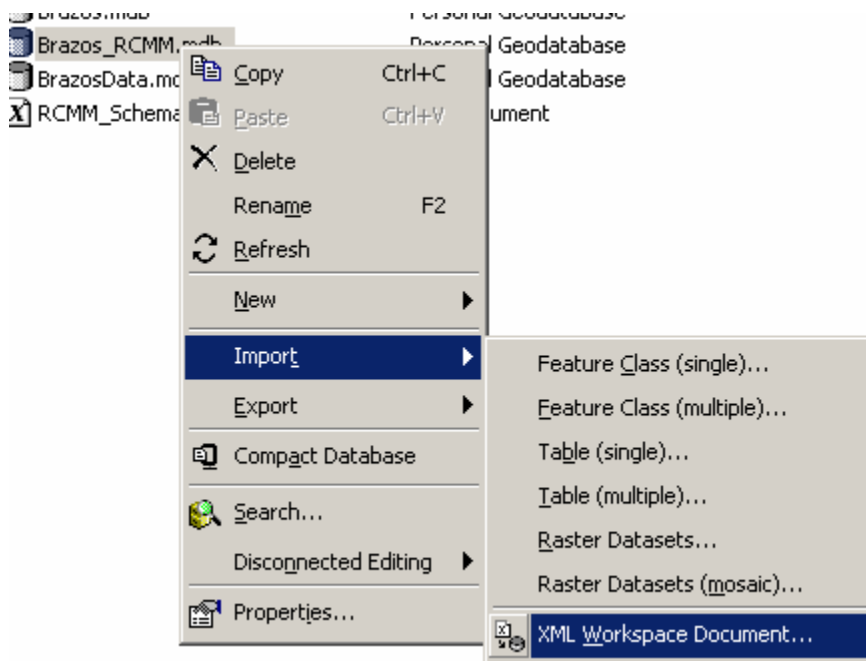
```

- <esri:Workspace xmlns:esri="http://www.esri.com/schemas/ArcGIS/9.0"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xmlns:xs="http://www.w3.org/2001/XMLSchema">
- <WorkspaceDefinition xsi:type="esri:WorkspaceDefinition">
  <WorkspaceType>esriLocalDatabaseWorkspace</WorkspaceType> ← Geodatabase type
  <Version />
  <Domains xsi:type="esri:ArrayOfDomain" />
- <DatasetDefinitions xsi:type="esri:ArrayOfDataElement">
  - <DataElement xsi:type="esri:DEFeatureDataset">
    <CatalogPath>/FD=RCMM</CatalogPath> ← Feature dataset name
    <Name>RCMM</Name>
  - <Children xsi:type="esri:ArrayOfDataElement">
    - <DataElement xsi:type="esri:DEFeatureClass">
      <CatalogPath>/FD=RCMM/FC=ChannelBoundary</CatalogPath>
      <Name>ChannelBoundary</Name> ← Feature class name
      <DatasetType>esriDTFeatureClass</DatasetType>
      <DSID>5</DSID>
      <Versioned>>false</Versioned>
      <CanVersion>>false</CanVersion>
      <HasOID>>true</HasOID>
      <OIDFieldName>OBJECTID</OIDFieldName>
    - <Fields xsi:type="esri:Fields">
      - <FieldArray xsi:type="esri:ArrayOfField">
        - <Field xsi:type="esri:Field">
          <Name>OBJECTID</Name> ← Field name
          <Type>esriFieldTypeOID</Type> ← Field type
          <Nullable>>false</Nullable>

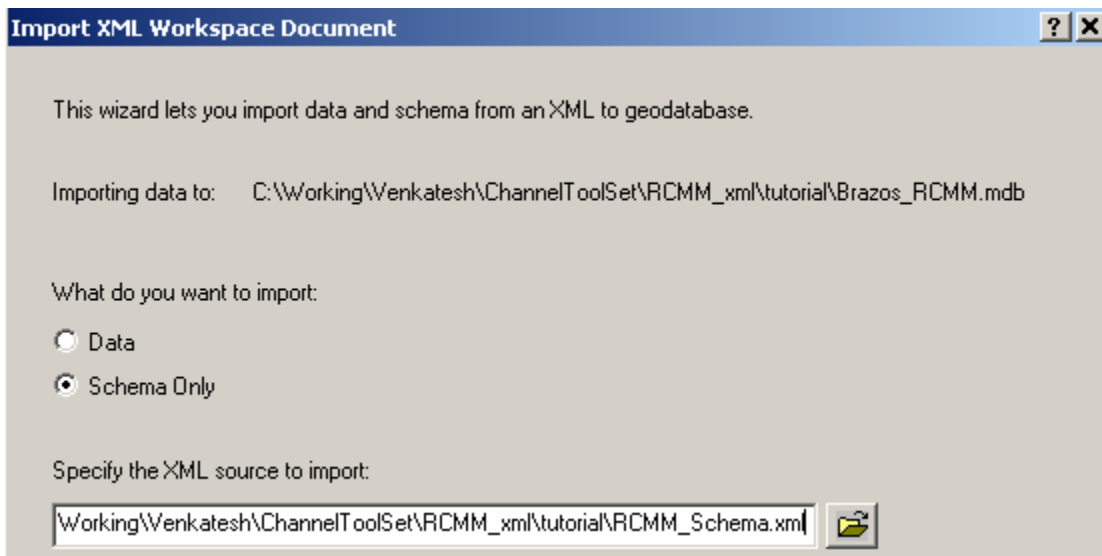
```

A geodatabase schema mainly consists of definition of objects such as feature datasets, feature classes and tables, and relationships among them. For example, the RCMM_Schema.xml contains the definition of all the feature classes and its associated fields necessary for this tutorial. When a schema is applied to a geodatabase, the geodatabase gets populated with the feature classes and other information (eg. relationships, tables) stored in the schema document. This process saves time in creating a structured geodatabase manually.

Before applying the schema, make sure ArcMap is closed An open ArcMap session sometimes causes conflicts resulting in errors during the schema import process. To apply the RCMM schema to Brazos_RCMM.mdb, from ArcCatalog right click on Brazos_RCMM.mdb → *Import* → *XML Workspace Document* as shown below:

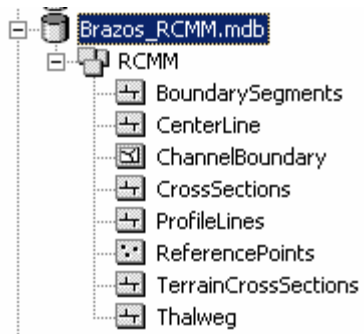


Choose the import *Schema Only* option, and browse to RCMM_Schema.xml as shown below:

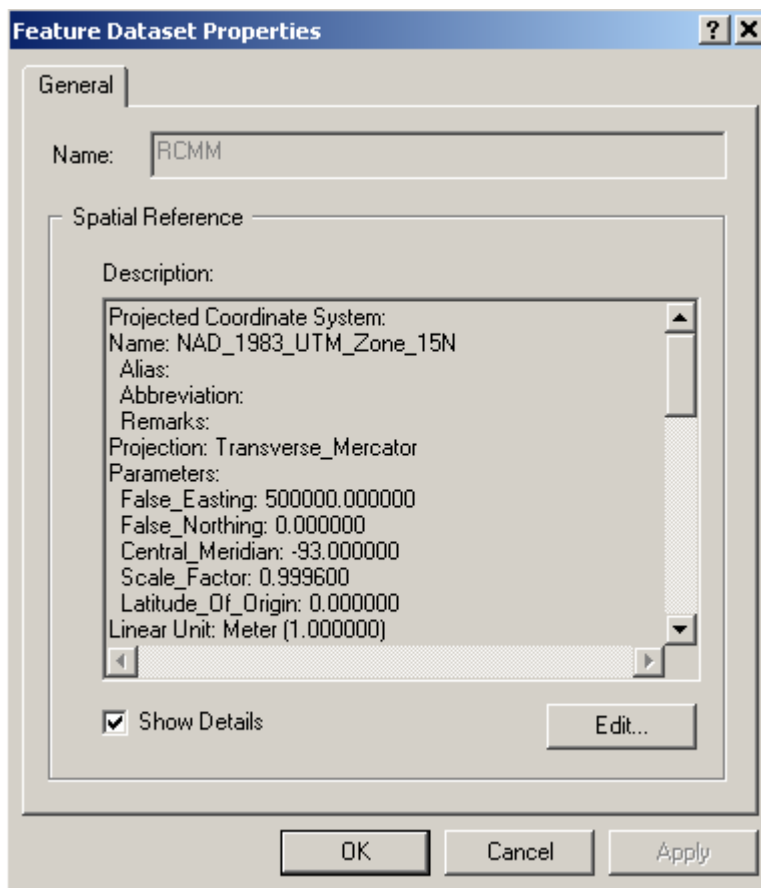


Click *Next*, and then *Finish* to complete the schema import process.

Refresh the ArcCatalog view by going to *View*→*Refresh*. Click on Brazos_RCMC.mdb to see the new feature classes added to the geodatabase by the schema as shown below:



Right click on the RCMM feature dataset to see its properties. The properties window will show that the spatial reference is already defined (NAD_1983_UTM_Zone_15N).

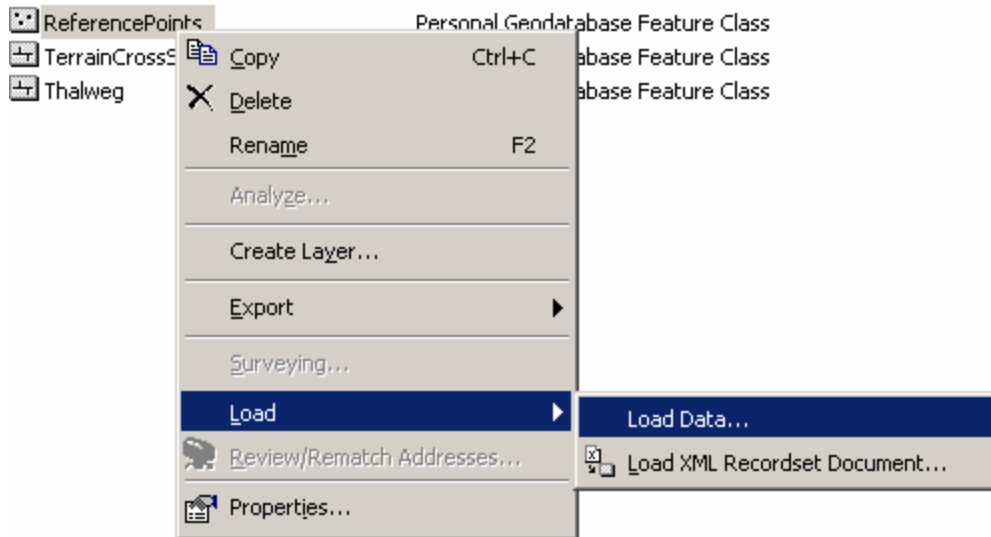


This spatial reference is fine for the Brazos dataset, but may have to be changed for other datasets. The spatial reference can be imported from other existing datasets, or can be selected from a predefined coordinate system. It is absolutely necessary to have the spatial reference defined for the geodatabase before employing the RCMM toolset.

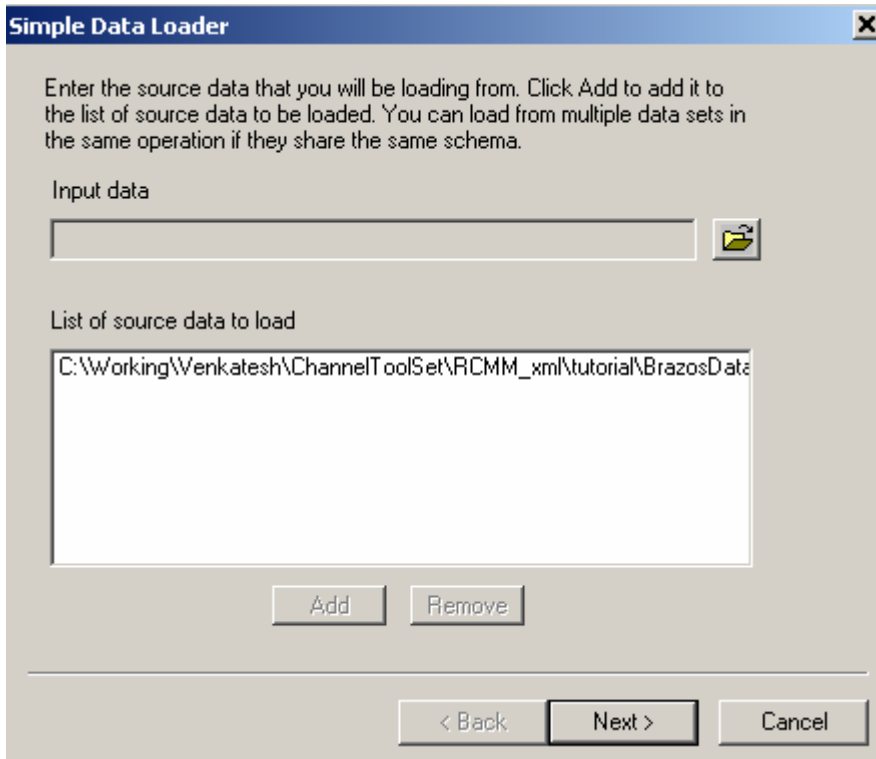
Since all the feature classes in Brazos_RCMM.mdb are empty, the next step is to import the existing data from BrazosData.mdb to Brazos_RCMM.mdb.

Importing Existing Data to the RCMM geodatabase

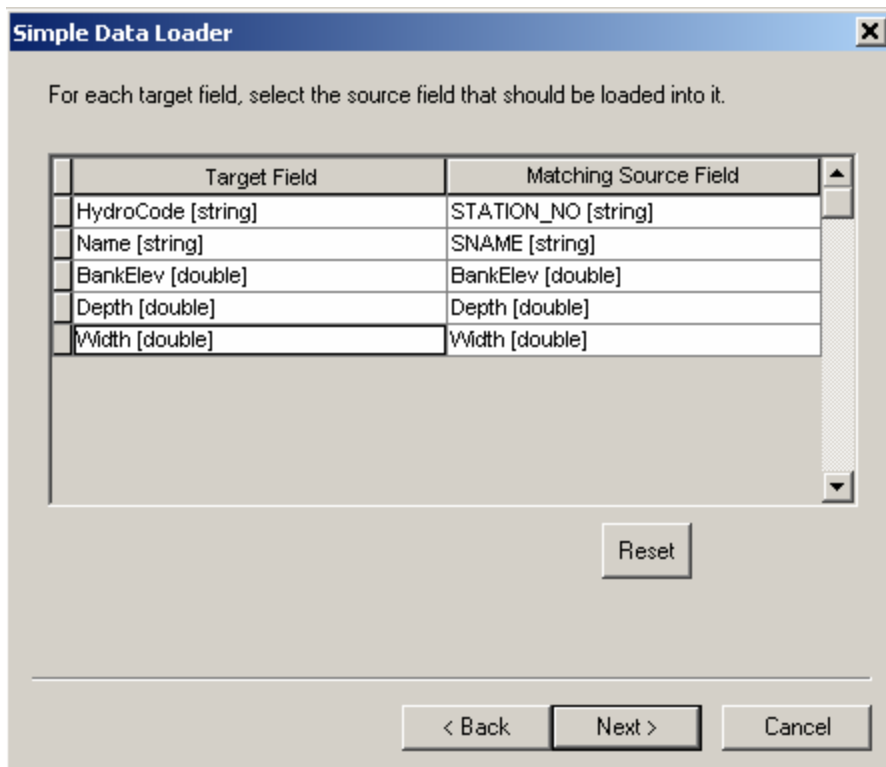
This section describes importing of existing data (Channel Boundary, NHD Centerline and USGS Points) from BrazosData.mdb to the newly created Brazos_RCMM.mdb geodatabase. The order in which the data are imported is not important. The USGS_Points feature class in BrazosData.mdb contains the two reference points along the Brazos River, and therefore should be exported to the ReferencePoints feature class. Right click on ReferencePoints → *Load* → *Load Data* as shown below:



Browse to the USGS_Points feature class located in BrazosData.mdb, and click *Add*, and then *Next* as shown below:

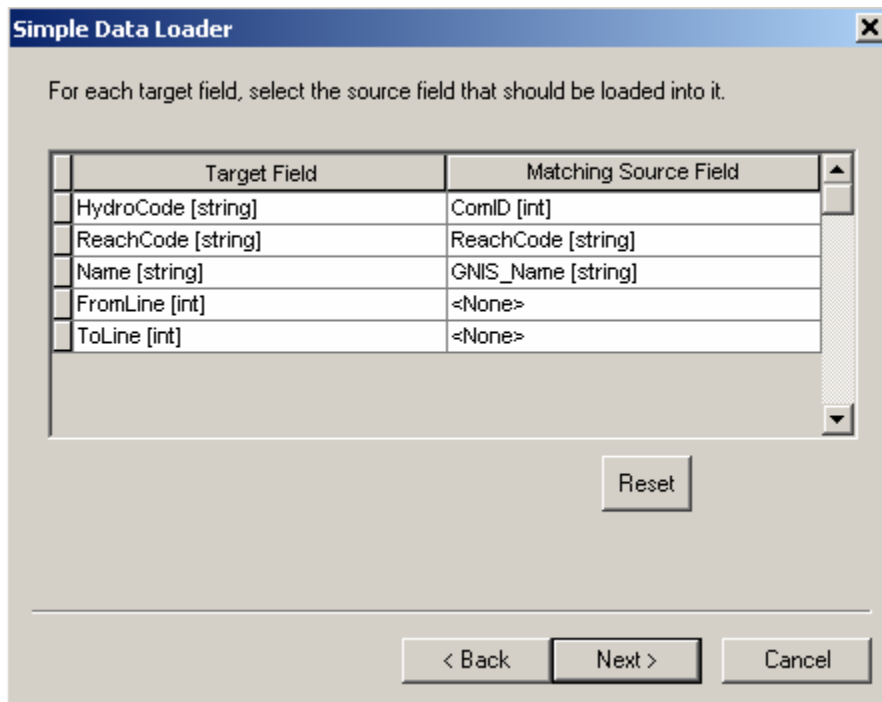


Choose *Next* in the Simple Data Loader window to get the following window (Note: The order in which the fields appear in the following window may vary for different computers. This order, however, is not important):



Match HydroCode with STATION_NO, NAME with SNAME, BankElev with BankElev, Depth with Depth, and Width with Width. Click *Next*, choose *Load all of the source data* option, click *Next* and then *Finish* to load the data from USGS_Points to the ReferencePoints feature class.

Repeat the loading process for NHD_centerline from BrazosData.mdb to the Centerline feature class in Brazos_RCMM.mdb.



Match HydroCode with ComID, ReachCode with ReachCode, and Name with GNIS_Name. Since there are no matching fields for FromLine and ToLine in NHD_centerline, leave the Matching Source Field as None. Click *Next*, choose *Load all of the source data* option, click *Next* and then *Finish* to load the data from NHD_centerline to the Centerline feature class.

Finally, load the data from Channel_Boundary in BrazosData.mdb to the ChannelBoundary feature class in Brazos_RCMM.mdb. Note, there are not any target fields or source fields for this feature class.

Populating the attributes of the ReferencePoints feature class

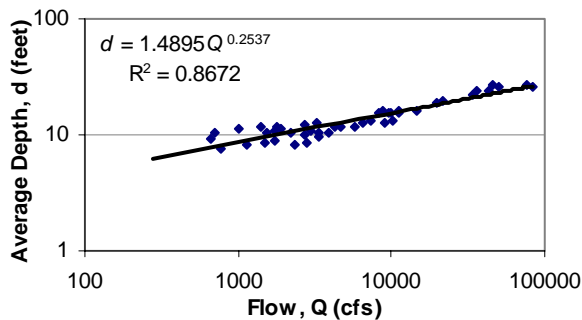
To develop the channel morphology in areas without data, RCMM uses the average values of depths, widths and bank elevations at upstream and downstream locations (reference points) from the area of interest. The computation of average values of depth, width, and bank elevation at the reference points along the channel is a prerequisite for the application of RCMM. For this exercise, these values are already computed and

stored as attributes in the ReferencePoints feature class. This section briefly describes how the average values of depth, width and bank elevation can be computed for the reference points using the USGS gaging station data.

To compute the depth, width and bank elevation, it is ideal to have measured cross-sections at reference points, but if measured cross-sections are not available, the average values of depth, width and bank elevation can be computed from the USGS gaging station data. The USGS performs occasional measurements of cross-sections at its gaging stations to update the stage-discharge rating curves, and these data can be downloaded from the link below:

<http://nwis.waterdata.usgs.gov/usa/nwis/measurements>

For this tutorial, the study area is bounded by the Richmond gaging station upstream (# 08114000) and by the Rosharon gaging station downstream (#08116650). Using the USGS measurements, the average values of depth, width and bank elevation at any point along a river channel can be computed by developing hydraulic geometry relationships. Hydraulic geometry relationships relate flow with average values of depth, width and velocity. The following figure shows the hydraulic geometry relationship between flow and average depth at the Richmond gaging station (Merwade and Maidment, 2004).



For any given flow at the Richmond gaging station, the average depth can be calculated by using the relationship shown in the above figure. The bank elevation is computed by getting the stage from the stage discharge relationship, and adding it to the gage datum. The width can be computed either by using hydraulic geometry relationships or by digitizing the boundary from aerial photographs. RCMM uses the left bank (looking downstream from Richmond to Rosharon gaging station) of the river channel to generate the thalweg and cross-sections, and using the boundary digitized from an aerial photograph provides a better description of the channel morphology. Therefore, it is recommended to have the channel boundary digitized from aerial photographs. The boundary polygon imported into the ChannelBoundary feature class was digitized using aerial photographs. If aerial images are unavailable for the study area, RCMM has a tool to create the boundary using the centerline.

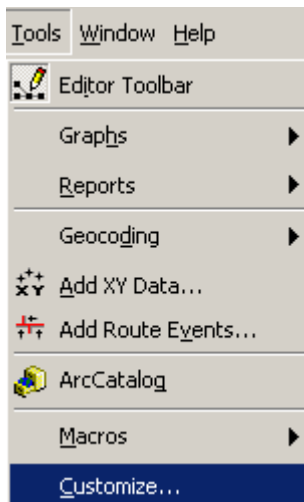
At the Richmond gaging station, for a 2-year return period flow of 55800 ft³/s (estimated using the flow duration curve with peak flow data from 1903 to 2001), the average values of depth, width and bank elevations are 7.3m, 109m and 18.4, respectively. Similarly, for a 2-year return period flow of 51600 ft³/s (estimated using the flow duration curve with

peak flow data from 1967 to 2001) at the Rosharon gaging station, the average values of depth, width and bank elevations are 11m, 101m and 12.2, respectively.

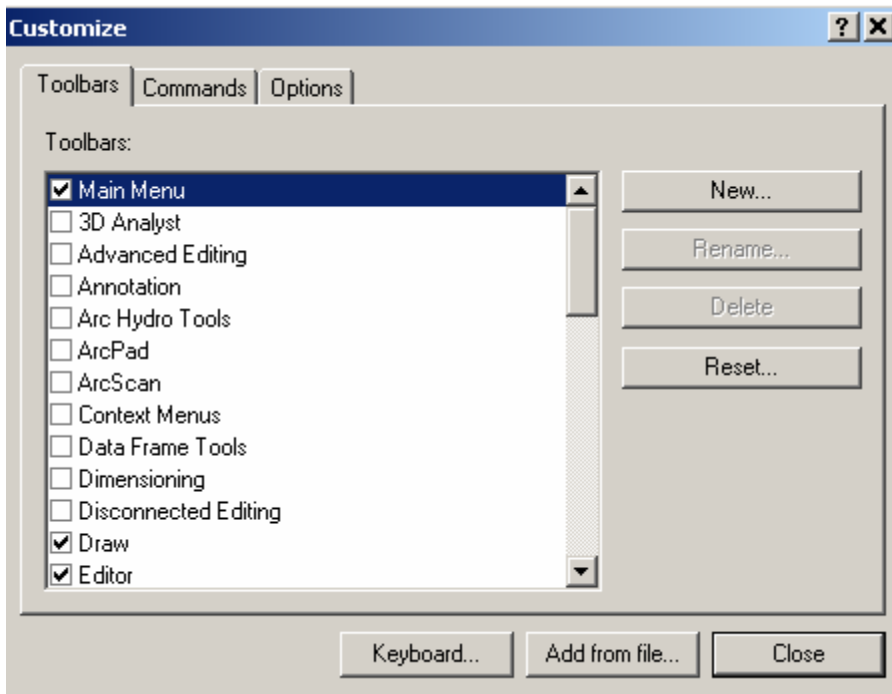
In summary, preprocessing for RCMM involves applying the RCMM schema to an empty geodatabase, loading existing data, digitizing the boundary for the area of interest (optional) and computing the depth, width, and bank elevation at reference points. If the area of interest is long (more than 10 miles), manual digitization of the boundary is a cumbersome task. There is a tool under development that will automatically delineate the channel banks using aerial photographs. The following sections demonstrate the application of RCMM for creating three-dimensional structure of river channels.

RCMM Toolbar

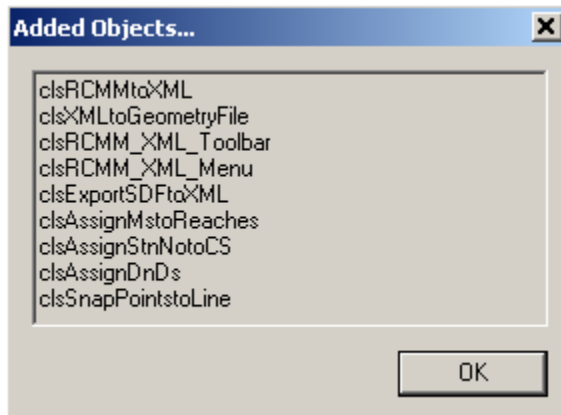
RCMM toolbar is a DLL (dynamic link library) file compiled by using Visual Basic and ArcObjects (interfaces for customizing ArcGIS applications). RCMM toolbar can be used in ArcMap by adding it as a custom tool. Open an ArcMap session, and save the document as RCMM_tutorial.mxd. Load the RCMM Toolbar into the map document by clicking on *Tools* → *Customize..* as shown below (Note: adding a toolbar to an ArcMap document may require administrative access to the computer):



In the Customize window, click on *Add from file...*, and browse to RCMM.dll located in the Tutorial folder.



Upon successful addition of all objects in the DLL file (shown below), click *OK*. If no objects are added to the window, most probably access to the system folder was denied, and an administrative login is required to load the toolbar.



Close the customize window, and a dockable toolbar named RCMM Toolbar should appear on the map document as shown below:

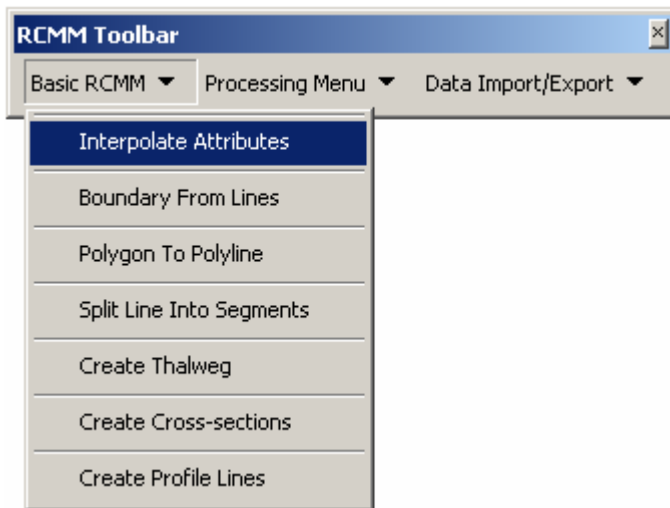


Save the ArcMap document. The RCMM toolbar has three menu buttons: (a) Basic RCMM, (b) Processing Menu and (c) Data Import/Export. The Basic RCMM menu has functions to build the three-dimensional structure (cross-sections and profile lines) for

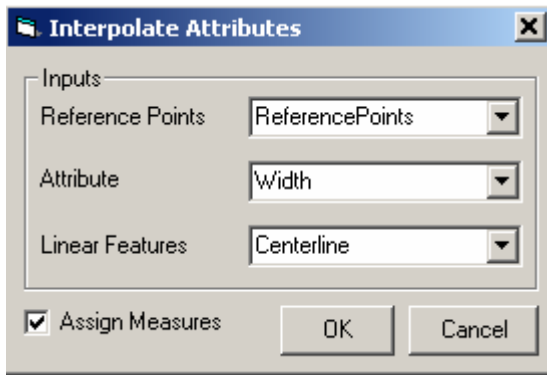
river channels using the ReferencePoints and Centerline feature classes. The Processing Menu has functions for the general analysis of river morphology data, and the Data Import/Export menu has functions for exchanging data from geodatabase files to XML files, XML files to HEC-RAS geometry files, and HEC-RAS output to XML files. The applications of some of the functions in the RCMM toolbar are discussed in the following sections.

Creating Boundary using the Centerline (Optional)

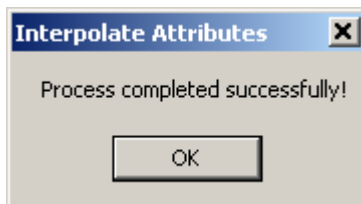
This task can be skipped if the boundary for the study area already exists. Add ReferencePoints, Centerline and ChannelBoundary from RCMM_Brazos.mdb to the map document. Although the ChannelBoundary feature class has one boundary polygon in it, the goal of this task is to demonstrate the utility of RCMM to create the boundary polygon in the absence of other sources such as aerial photographs. To create the channel boundary using the centerline, the centerline feature class must have a channel width assigned to each feature (note that the centerline features do not have width attributes). Channel widths can be assigned to the centerline features by using the Interpolate Attributes tool, which calculates the width by linearly interpolating the width attribute from the ReferencePoints feature class. Lookup the attribute table for ReferencePoints to make sure the width attribute is populated. Click on *Basic RCMM* → *Interpolate Attributes* as shown below:



Choose ReferencePoints for Reference Points, Centerline for Linear Features, and Width for Attribute. Leave the Assign Measures option checked. This option assigns a measure attribute to each feature in the Centerline feature class with respect to the overall length of the reach, which is useful for linear referencing.



Click *OK*, and the process should finish within 2-4 seconds (for the tutorial dataset). Click *OK* on the process completion message box (shown below).

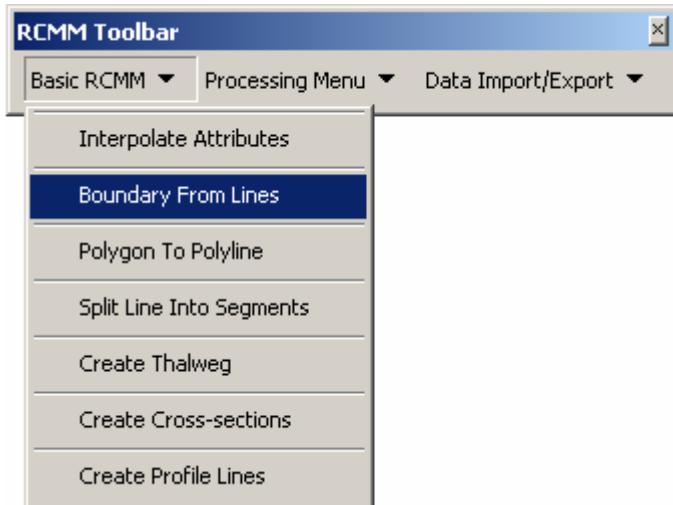


Open the attribute table for the Centerline feature class, and it should now have two extra attributes (Width and Measure) as shown below:

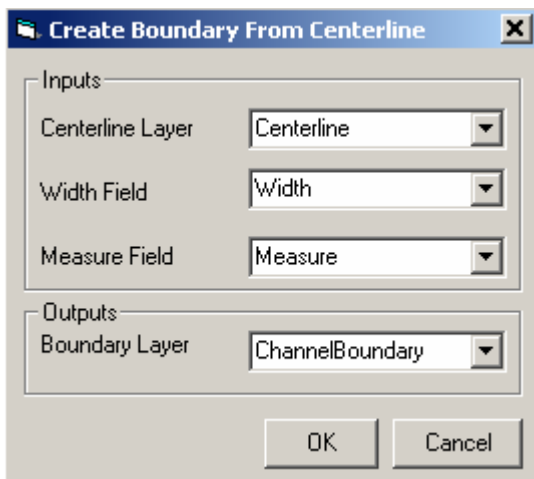
	Name	FromLine	ToLine	SHAPE_Len	Width	Measure
	Brazos River	<Null>	<Null>	1806.789239	109	903.3946
	Brazos River	<Null>	<Null>	3859.162546	108.8062	3736.9268
	Brazos River	<Null>	<Null>	2265.713066	108.4006	6798.8083
	Brazos River	<Null>	<Null>	2191.278762	108.1055	9027.3042
	Brazos River	<Null>	<Null>	1157.705363	107.8837	10701.7963
	Brazos River	<Null>	<Null>	1158.037942	107.7304	11859.6679
	Brazos River	<Null>	<Null>	2025.716636	107.5195	13451.5452

The Width field contains linearly interpolated values of widths (between the reference points) for each centerline feature. The Measure field contains the distance from the midpoint of each centerline feature to the starting point of the most upstream feature in the centerline feature class. The values stored in the Measure attributes are in map units, which is meters in this case. After each centerline feature has a width attribute associated with it, the centerline feature class can be used to create the channel boundary.

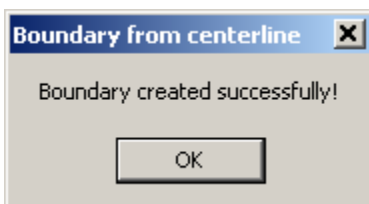
Click on *Basic RCMM* → *Boundary From Lines* as shown below:



Choose Centerline for Centerline Layer, Width for Width Field, Measure for Measure Field, and ChannelBoundary for Boundary Layer. The measure field is used to process the centerline features in a sequential fashion from upstream to downstream.



Click OK. The create boundary tool takes about 2-4 seconds to complete. Click *OK* on the process completion window as shown below.

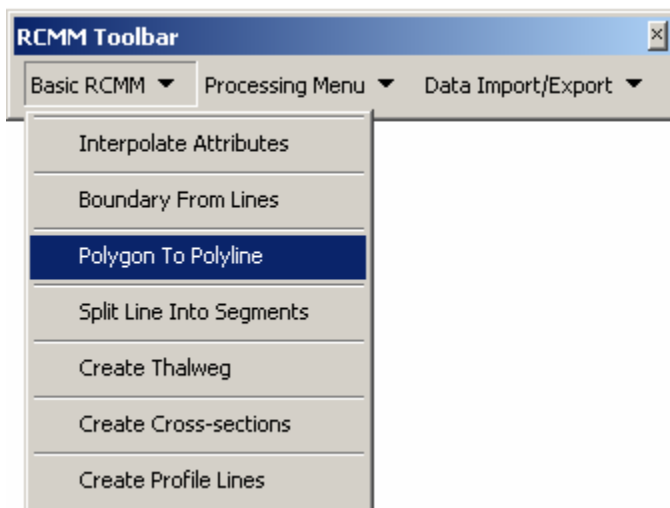


The boundary is added to the ChannelBoundary feature class. The channel boundary is created by offsetting each centerline feature by a distance of 0.5 times the width on each side. Compare the new boundary polygon with the one that already exists (created by digitizing aerial photographs) in the ChannelBoundary feature class. Compare both

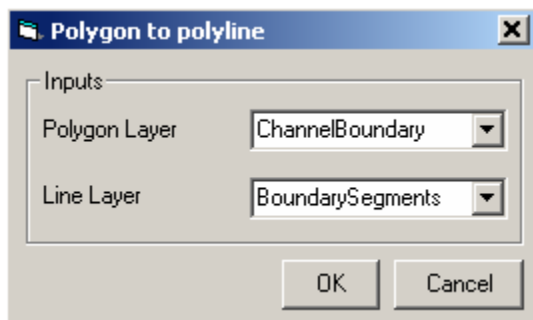
polygons to see the difference between the boundary created by an automatic process and by manual digitization. The digitized polygon is 15-20 percent wider than the polygon created by RCMM at almost all locations, and therefore, manual digitization of channel boundary using aerial photographs is recommended. Retain the digitized polygon for further analysis and discard the polygon created by RCMM by deleting it (deleting a feature requires the map document in edit mode). Save the ArcMap document.

Creating thalweg

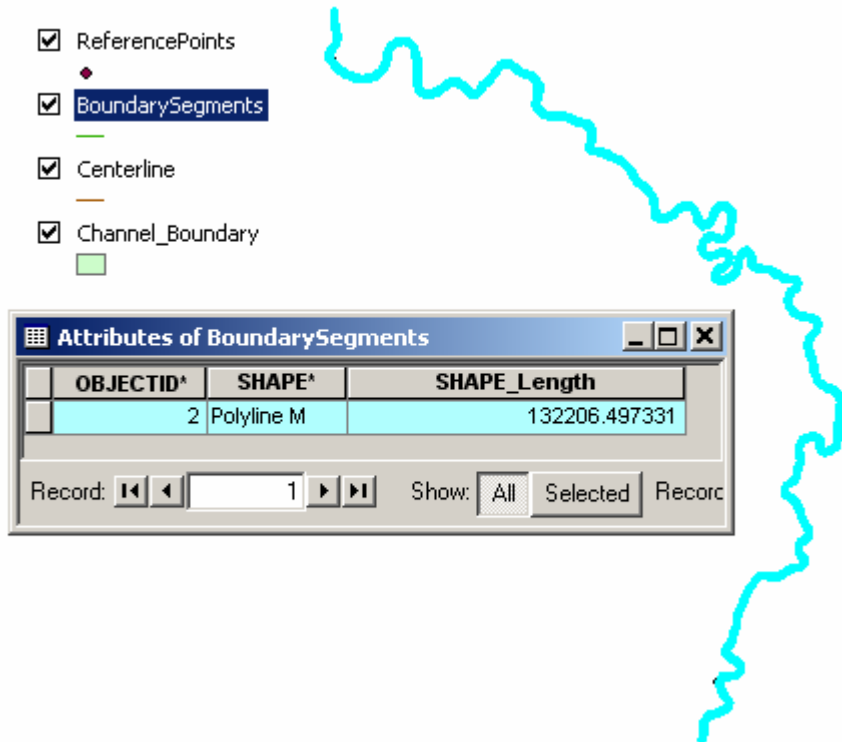
RCMM uses the left bank (looking downstream) to create the thalweg. Therefore, the boundary polygon first has to be converted to a boundary polyline, and then the polyline must be split to extract the left bank. Add BoundarySegments from Brazos_RCMM to the ArcMap document. Click on *Basic RCMM*→*Polygon To Polyline* as shown below:



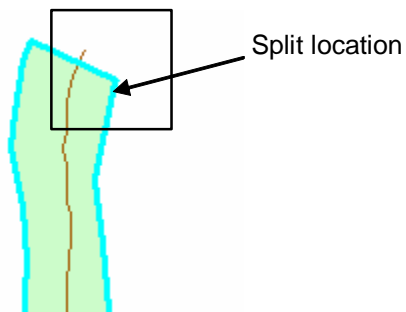
Choose ChannelBoundary for Polygon Layer and BoundarySegments for Line Layer as shown below:




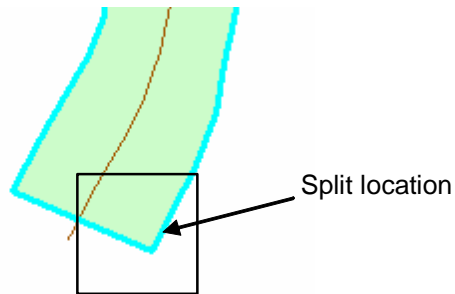
Click *OK*, and the process takes less than two seconds to complete. Click *OK* on the process completion window.



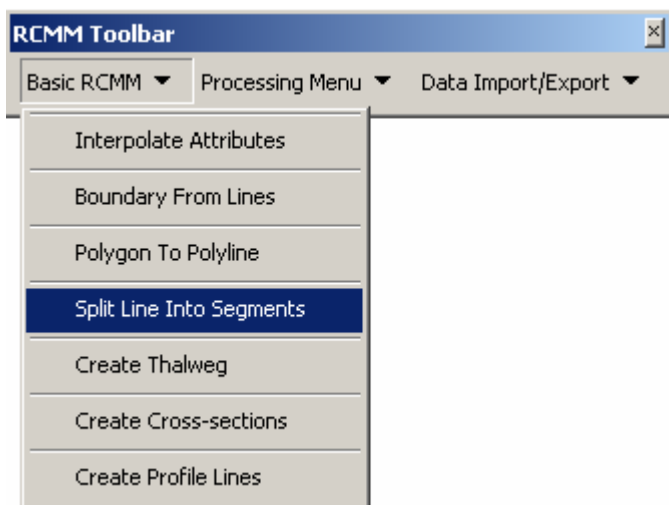
Open the attribute table for BoundarySegments and notice a new feature was added to the feature class. The next step is to extract only the left bank from this boundary polyline. This task can be accomplished by using the split tool available with the ArcMap editor toolbar. Start an edit session with BoundarySegments as the target layer. Zoom in to the upstream left corner of the channel boundary, and select the newly created feature in the BoundarySegments feature class. The Brazos River flows from Richmond to Rosharon, so the upstream left corner is the corner near the Richmond gaging station as shown below:



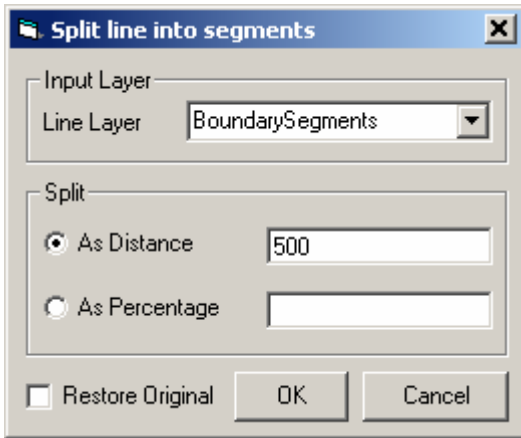
Using the Split button  on the editor toolbar, and split the boundary segment at the upstream left corner (shown above). Save the edits. Similarly, zoom in to the downstream left corner, and select the boundary segment feature that contains the left bank, and split the polyline at the downstream left corner as shown below.



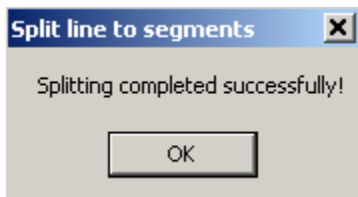
The split produces three features in the BoundarySegments feature class. Retain only the left bank, and delete all other features from the BoundarySegments feature class. Save the edits and stop the edit session. The final step in processing the left bank is splitting it into boundary segments so that cross-sections can be created for each segment. Select the left bank from the BoundarySegments feature class, and click *Basic RCMM*→*Split Line Into Segments* as shown below:



Choose BoundarySegments as input to the Line Layer. There are two options to split the left boundary. The “as distance” option will split the polyline into equal parts of specified length. The “as percentage” option will split the polyline into equal parts of specified percentages of the total length. Choose the “as distance” option, and enter 500 in the corresponding text box. Restore original will restore the original line along with the new split segments, uncheck the restore original check box as shown below:

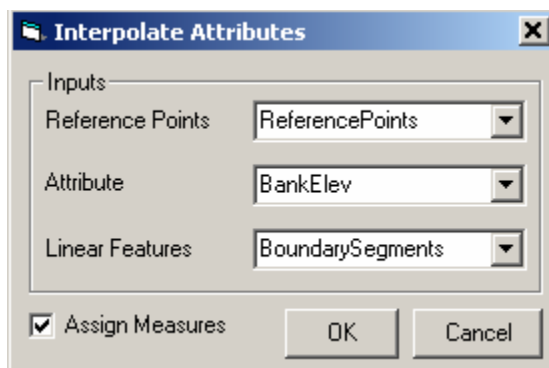


Click *OK*, and the process should finish within two seconds giving the following message box:

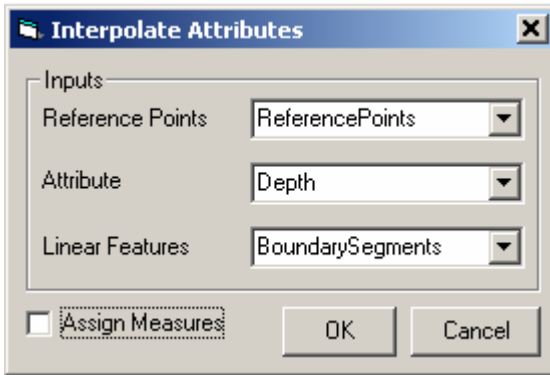


Click *OK*, and open the attribute table for *BoundarySegments* to see that a single left bank polyline is replaced by several features, each approximately 500m long. Depending on where the boundary polygon was split, the *BoundarySegments* feature class should have 131 or 132 features in it.

After the left bank is split into segments, interpolate the *BankElev* and *Depth* attributes from *ReferencePoints* onto *BoundarySegments*. These attributes are necessary for creating thalweg from boundary segments. Click on *Basic RCMM* → *Interpolate Attributes*, and choose inputs as shown below:



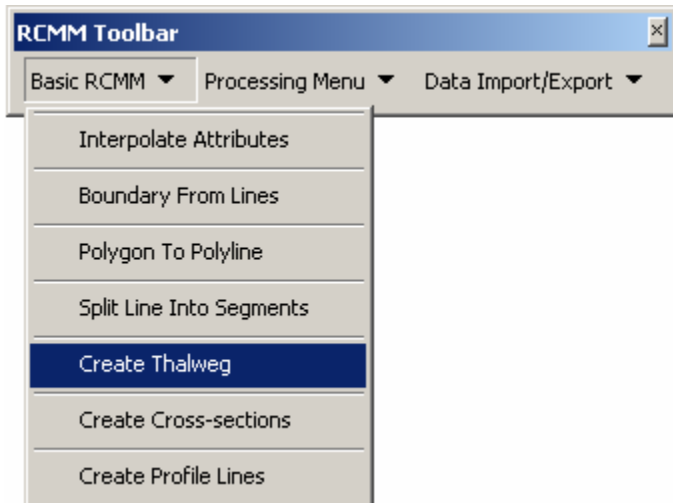
Let the *Assign Measures* option checked. Click *OK*. Interpolate the *Depth* attribute in the same way. The *Assign Measures* option can be unchecked at the second time as shown below:



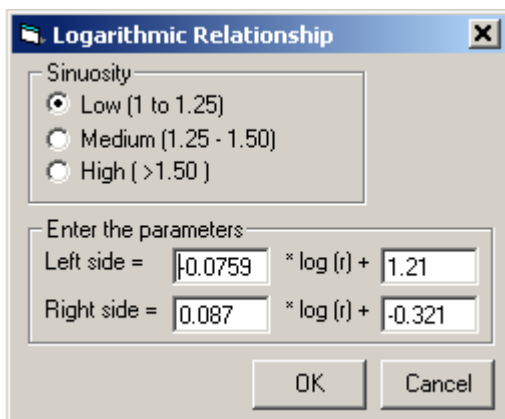
Click OK to assign the depth attributes. Open the attribute table for BoundarySegments to see the new fields and attributes. The feature class should have Depth, Measure, and BankElev fields, all populated. Close the attribute table.

OBJECTID ^a	SHAPE ^a	SHAPE_Len	Depth	Measure	BankElev
6	Polyline M	499.999071	7.3	249.9995	18.6
7	Polyline M	500.000601	7.3	749.9994	18.6
8	Polyline M	499.999904	7.3	1249.9996	18.6
9	Polyline M	500.000561	7.3	1749.9999	18.6
10	Polyline M	500.000242	7.3067	2250.0003	18.5884
11	Polyline M	499.998587	7.3373	2749.9997	18.5356
12	Polyline M	500.001850	7.3678	3249.9999	18.4827
13	Polyline M	500.000011	7.3984	3750.0008	18.4299
14	Polyline M	499.998268	7.4289	4250	18.377

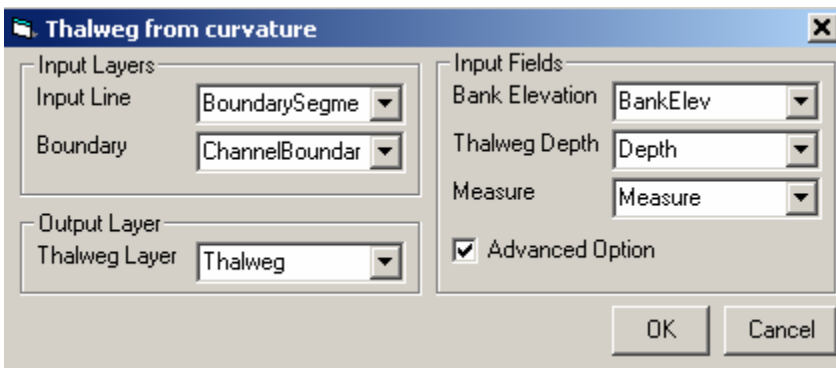
This completes all the pre-processing for creating the thalweg. Add the Thalweg feature class from Brazos_RCMM.mdb to the map document. Start the edit session. Click on *Basic RCMM* → *Create Thalweg* as shown below:



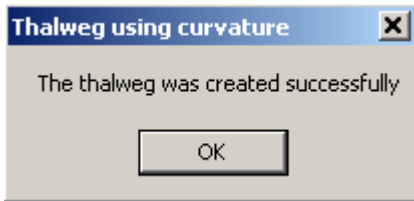
The creation of thalweg is based on a logarithmic relationship between the shape of the channel (radius of curvature of the left bank) and the distance of the thalweg from the left bank (Merwade, 2004). For this study dataset, choose the low sinuosity option, accept the default parameters, and click OK.



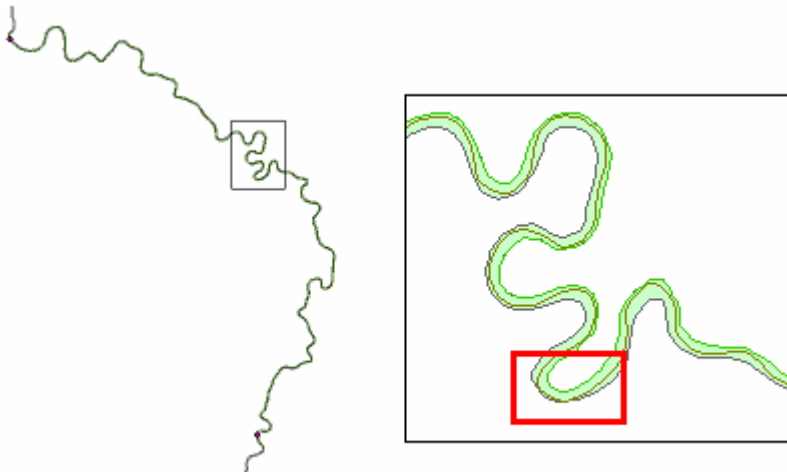
Choose BoundarySegments for Input Line, ChannelBoundary for Boundary, Thalweg for Thalweg layer, BankElev for Bank Elevation, Depth for Thalweg Depth, and Measure for Measure field. Check the Advanced Option (explained later) as shown below:



Click *OK*. The form will show the progress at the bottom-left corner, and the creation of thalweg takes about 15-20 seconds. Click *OK* on the final process completion message.




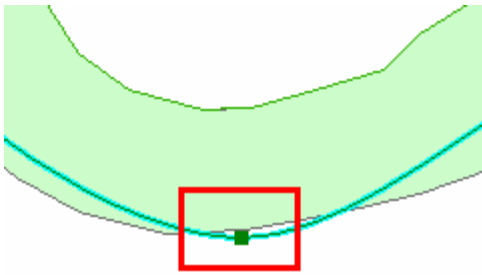
The thalweg creation tool creates one thalweg point per boundary segment, and the advanced option interpolates these points to create three thalweg points per boundary segment. The thalweg is also converted to a Bezier Curve, which sometimes (very rarely) causes the thalweg to go outside the channel boundary, especially at sharp bends. It is recommended to zoom in and look at areas with sharp bends to make sure that the thalweg lies inside the channel. For example, at one location (shown below), the thalweg goes outside the channel banks.




Right now, no automated tools exist for handling this situation. Zoom in to the area shown in the above figure. Select the thalweg, change the editor task to Modify feature, and set the editor target to Thalweg as shown below:



With the Modify Feature option, and the thalweg feature selected, the thalweg should show the location of its vertices. Using the edit tool on the editor toolbar , move the vertex of the thalweg that lies outside the channel to bring it inside the channel as shown below:



While in modify feature mode, click on sketch properties button  on the editor toolbar to see the edit sketch properties of the thalweg as shown below (Note: The Z attribute should show decimal values. If not, change the Z domain properties to reflect a precision of at least 10. The Z attribute without decimal values will cause an error during the cross-sections creation process):

Part	X	Y	Z	M
0	232965.765	3277837.865	11.300	250.000
1	232956.311	3277568.920	11.300	250.000
2	232986.165	3277318.951	11.300	250.000
3	233027.111	3277066.423	11.300	750.000
4	233095.707	3276829.387	11.300	750.000
5	233106.004	3276592.122	11.300	1250.000
6	233018.321	3276381.791	11.300	1250.000
7	232847.997	3276223.976	11.300	1750.000
8	232735.457	3275916.446	11.300	1750.000
9	232898.181	3275680.560	11.282	2250.000
10	233057.448	3275499.090	11.282	2250.000

Finish Sketch

The thalweg is a PolylineZM feature, and it has two extra attributes, z and m , besides (x,y) attributes. Both z and m attributes are extracted from the boundary segment features ($z = \text{BankElev-Depth}$, and $m = \text{Measure}$). Close the edit sketch properties window by clicking Finish Sketch button, and save the edits.

Open the attribute table for BoundarySegments and look at the new attributes added to these features by the thalweg creation tool.

IsRight	rCurvature	ThaLocation	FromLine	ToLine	Upstream	Downstream
0	2386.971863	0.619666	273	275	0.619666	0.635488
0	1573.203006	0.651310	274	276	0.635488	0.681123
0	717.156861	0.710935	275	277	0.681123	0.700662
0	940.104238	0.690389	276	278	0.700662	0.689367
0	965.780754	0.688344	277	279	0.689367	0.507637
-1	1715.509554	0.326929	278	280	0.507637	0.283892
-1	637.845317	0.240854	279	281	0.283892	0.238321
-1	601.765613	0.235789	280	282	0.238321	0.240442
-1	669.710765	0.245096	281	283	0.240442	0.305497

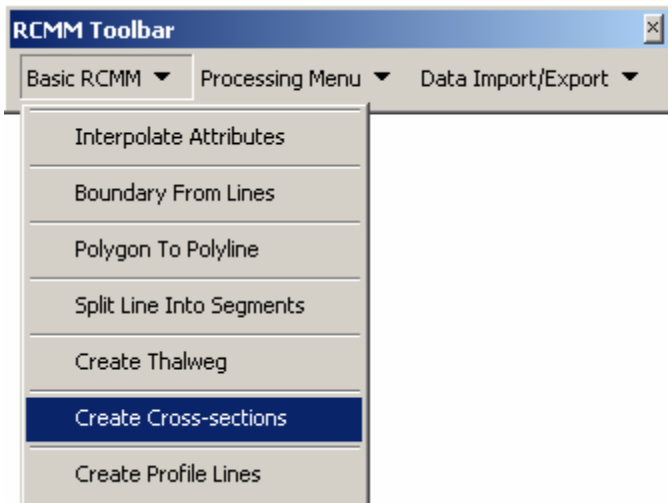
Record: 3 Show: All Selected Records (0 out of 127 Selected.)

IsRight indicates the direction of meander (0 is a right meander and -1 is a left meander). ThaLocation indicates the location of the thalweg point from the mid-point of the boundary segment. The ThaLocation value is stored as percentage of the total width, and should be multiplied by Width to get the real distance. The FromLine attribute is the OBJECTID of the upstream boundary segment, and ToLine is the OBJECTID of the downstream boundary segment. Upstream is the thalweg location from the starting point of the boundary segment, and Downstream is the thalweg location from the end point of the boundary segment. The ThaLocation, FromLine and ToLine attributes are used to compute Upstream and Downstream.

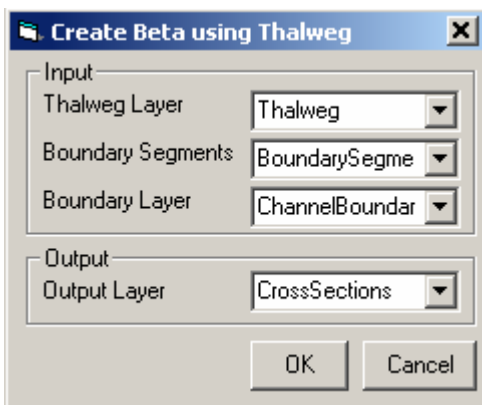
After the thalweg is created, the next step is creating cross-sections.

Creating Cross-sections

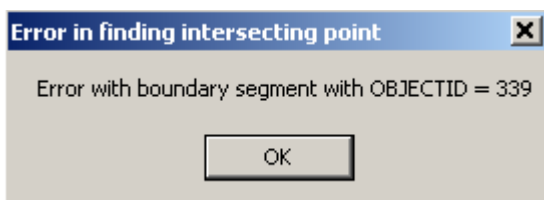
Add the CrossSections feature class from Brazos_RCMM to the map document. The CrossSections feature class is empty, and will be populated in this section. Before creating cross-sections, copy BetaParameters.mdb from the tutorial folder to c:\temp. Storing BetaParameters.mdb in "c:\temp" is necessary for creating cross-sections. BetaParameters.mdb contains parameters for creating beta distributions that are used to describe the cross-sections in RCMM. Click on *Basic RCMM* → *Create Cross-sections* as shown below:



Choose Thalweg for the Thalweg Layer, BoundarySegments for Boundary Segments and CrossSections for the Output Layer.



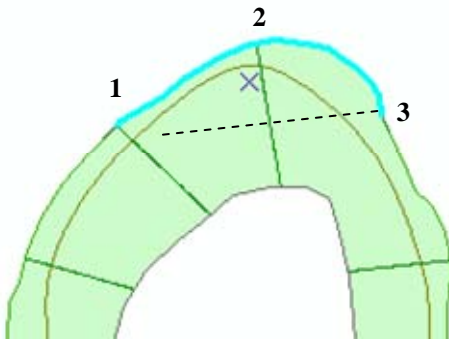
Click *OK*. The process of creating cross-sections is relatively long compared to other processes in RCMM. It takes about a minute or two to create cross-sections for the study dataset. Depending on the shape of the boundary segments, the program sometimes faces problems in locating the channel banks and gives an error message similar to the one shown below:



If such an error occurs, just note down the OBJECTID of the boundary segment and click *OK*.



Click *OK* after all the cross-sections are completed successfully. Save the edits. Select the boundary segment which produced an error during the cross-section generation process, and study why this error occurred. A close-up of the location where an error occurred while creating cross-sections is shown below:



RCMM creates cross-sections perpendicular to three points along a boundary segment: from (start) point, mid-point, and to (end) point. The start and mid-point worked fine for the selected segment, but when a perpendicular (dashed line) is drawn at the end-point of the above segment, it crosses another cross-section before hitting the channel boundary thus producing an error. This problem can be fixed by modifying the geometry of this particular segment manually. In addition, errors also occur if a boundary segment does not overlap exactly with the channel boundary polygon. An error message during the program execution means no cross-section is created at that particular location. If a cross-section is desired at error causing locations, the boundary segments at those locations need to be modified by doing a simple edit tasks. Regardless of error messages, check for overlapping cross-sections and delete those manually (Note: most errors associated with creating cross-sections arise from boundary segments. The next version of the program which will use the centerline as a reference instead of boundary segments will take care of these errors).

Open the attribute table for cross-sections, and look at the new attributes added by the cross-section tool.

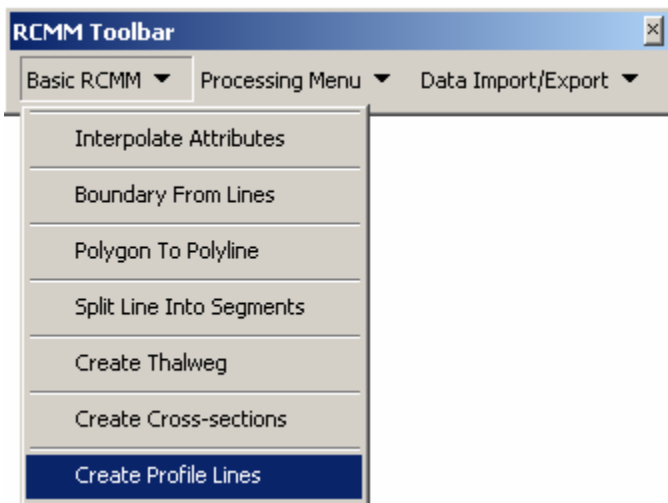
OBJECTID*	SHAPE*	SHAPE_Len	ALPHA1	BETA1	ALPHA2	BETA2	FACTOR	Measure
1054	Polyline ZM	144.333467	5.196610	3.602543	1.799152	1.799152	0.248034	260.1453
1055	Polyline ZM	146.435871	5.263622	3.552283	1.815906	1.815906	0.247364	531.5497
1056	Polyline ZM	142.140842	5.513083	3.365188	1.878271	1.878271	0.244869	797.8361
1057	Polyline ZM	157.257772	5.156518	3.632611	1.789130	1.789130	0.248435	1046.8288
1058	Polyline ZM	123.655108	6.163928	2.918036	2.027321	2.027321	0.238361	1332.1809
1059	Polyline ZM	137.430860	5.304234	3.521824	1.826059	1.826059	0.246958	1602.275
1060	Polyline ZM	158.792106	5.903916	3.072063	1.975979	1.975979	0.240961	1858.6212
1061	Polyline ZM	137.466245	7.444536	2.277732	2.240756	2.240756	0.225555	2147.7471
1062	Polyline ZM	150.075613	5.883394	3.087454	1.970849	1.970849	0.241166	2438.3361

Record: 0 Show: All Selected Records (0 out of 253 Selected.) Options

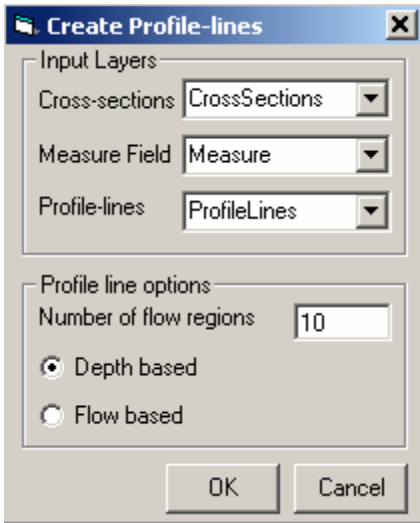
Most of the new parameters for cross-sections are related to beta distributions that are used to describe them. Each cross-section is a combination of two beta distributions. Therefore, ALPHA1, BETA1 and ALPHA2, BETA2 are the beta distribution parameters and FACTOR is a multiplying factor for these distributions. Measure gives the distance of the cross-sections along the thalweg.

Creating profile-lines from cross-sections

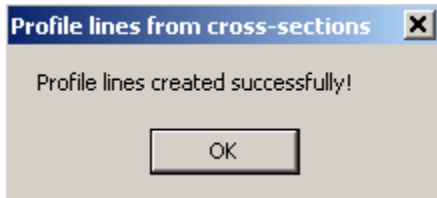
Add the ProfileLines feature class from Brazos_RCMM.mdb to the map document. Click on *Basic RCMM* → *Create Profile Lines* as shown below:



Choose CrossSections for Cross-section, Measure for Measure Field, ProfileLines for Profile-lines, and the Depth based option. Do not choose the flow-based option, it is really slow. Leave the default number of flow regions (10) unchanged. Click *OK*.



The process takes about 2-3 seconds to finish. Click OK at the final message.



Save the edits. Open the attribute table for ProfileLines to look at the new attributes (Note: the values in the attribute table may be little different depending on where the left bank was split).

OBJECTID*	SHAPE*	SHAPE_Length	ProfileID
1	Polyline ZM	62771.829686	0
2	Polyline ZM	63043.176217	1
3	Polyline ZM	63395.808175	2
4	Polyline ZM	63817.159569	3
5	Polyline ZM	64264.026092	4
6	Polyline ZM	64651.741497	5
7	Polyline ZM	64923.709900	6

Only one new attribute is added to the ProfileLines feature class, which is ProfileID. ProfileID indexes the profile lines from left bank (ProfileID = 0) to right bank (ProfileID = 2*number of flow regions).

Stop editing, and save the ArcMap document. Generation of thalweg, cross-sections and profile-lines complete the basic operations in the RCMM toolset for creating the three-dimensional morphology of river channels. The following sections briefly describe how

the three-dimensional channel representation can be used to create input files for HEC-RAS.

Using RCMM output (cross-sections) for creating HEC-RAS input files

HEC-RAS is a hydraulic model used for simulating one-dimensional steady and unsteady flows in river channels. The following sections describe how the RCMM output can be used to create the files necessary for running HEC-RAS simulations. A brief description of HEC-RAS input files is given below. HEC-RAS requires the following four files as input:

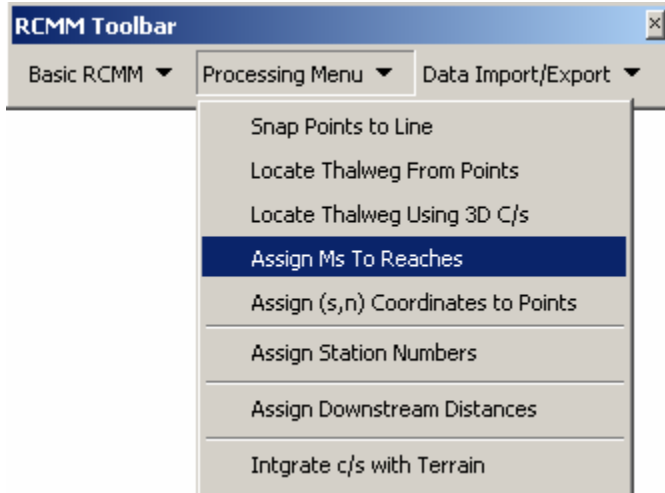
1. **Geometry File:** A HEC-RAS geometry file contains all of the geometric data for the river system being analyzed. The geometric data mainly consist of cross section information along with information on hydraulic structures (e.g., bridges and culverts) and roughness coefficients. Geometry files have extension from g01 to g99. The "g" indicates a geometry file, while the number corresponds to the order in which they were saved for that particular project.
2. **Flow file:** A HEC-RAS flow file contains boundary conditions (upstream and downstream) for hydraulic simulations. Flow files for steady flow simulations have extension .f01 to .f99. The "f" indicates a steady flow data file, while the number corresponds to the order in which they were saved for that particular project. Unsteady flow files have "u" instead of "f" in the file extension.
3. **Plan file:** A HEC-RAS plan file contains the list of files that are associated with the plan (e.g., geometry file and steady/unsteady flow file), and a description of all the simulation options that were set for the plan. Plan files have the extension .p01 to .p99. The "p" indicates a plan file, while the number represents the plan number.
4. **Project file:** A HEC-RAS project file contains the title of the project, the units system, and a list of all the files that are associated with the project. Project file has a .prj extension.

All files associated with a HEC-RAS project must be saved in the same folder. HEC-GeoRAS which is a GIS interface for HEC-RAS actually creates the HEC-RAS geometry file. The following sections describe how RCMM output can be converted to a HEC-RAS geometry file.

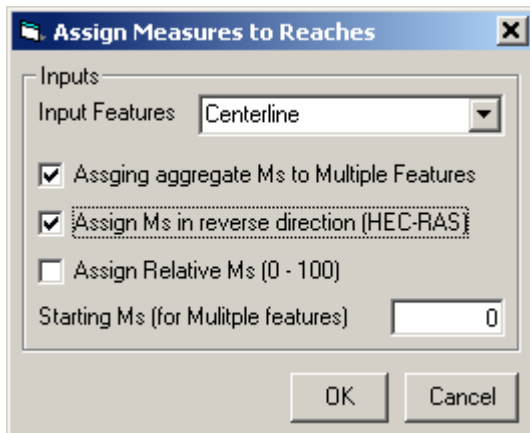
Pre-processing of RCMM for generating HEC-RAS geometry file

The pre-processing for HEC-RAS requires only the Centerline and CrossSections feature classes. Turn-off or remove the other layers. The goal is to create a HEC-RAS model for the Brazos River between Richmond and Rosharon gaging stations. The centerline features can be used to create the HEC-RAS reach. The HEC-RAS reach must have the measures assigned to it from downstream to upstream. In addition, all the features in the centerline feature class form a single reach. Therefore, measures must be assigned to the

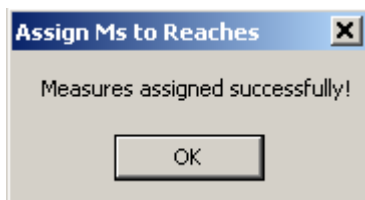
centerline features collectively, and not individually, which means the measure value at the end of one line is the starting value for the next line, and so on. Select all the features in the centerline feature class, click on *Processing Menu*→*Assign Ms to Reaches* as shown below:



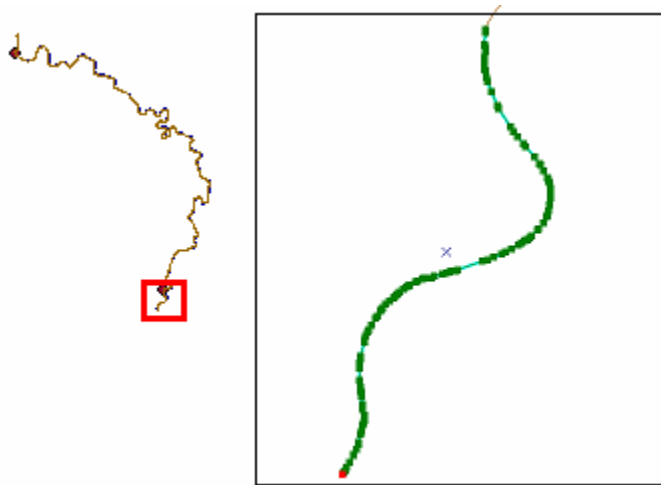
Choose CenterLine for Input Features, check Assign aggregate Ms to Multiple Features and Assign Ms in reverse direction (HEC-RAS) options. Assign Relative Ms is not advised if the measures are to be assigned for creating a HEC-RAS model because Relative Ms assigns measures as percentages and not as distances. Let the Starting Ms be zero.




Click *OK*. The process takes about 2-4 seconds to finish.



Click *OK* for the process completion message. Start an edit session with the Modify Feature task, and CenterLine as the target. Zoom in on the most downstream feature in the centerline feature class as shown below:



Using the select tool, select the downstream feature, and click on sketch properties button  on the editor toolbar to see the edit sketch properties.

Part	X	Y	Z	M
0	249254.597	3249579.015	0.000	3299.000
1	249254.549	3249577.339	0.000	3298.000
2	249253.167	3249561.398	0.000	3282.000
3	249249.827	3249493.447	0.000	3214.000
4	249250.070	3249485.450	0.000	3206.000
5	249251.633	3249473.547	0.000	3194.000
6	249251.957	3249453.540	0.000	3174.000
7	249249.530	3249417.614	0.000	3138.000
8	249249.497	3249393.605	0.000	3114.000

Finish Sketch

Note that the starting point of the selected line has a measure equal to the length of the line (3299.285), and the end point has a measure equal to the zero (reverse measures). Check the edit sketch properties of other features to see continuity and how the measures are assigned.

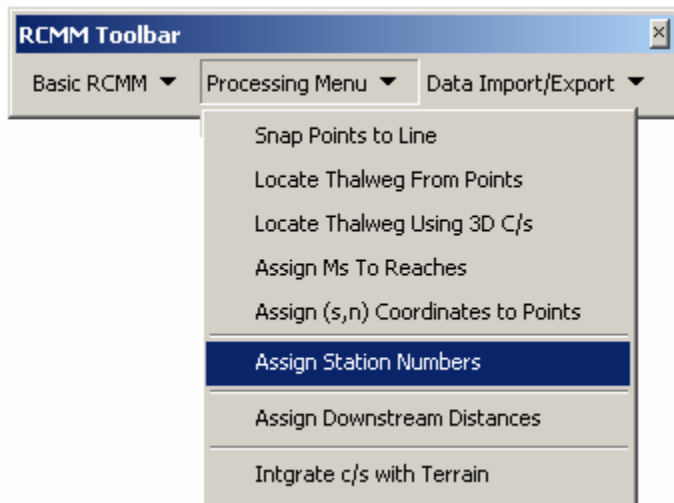
Close the edit sketch properties window by clicking Finish Sketch button, and stop the edit session. After the measures are assigned to the reach, the next step is to assign station numbers to cross-sections.

Assigning Station Numbers to CrossSections

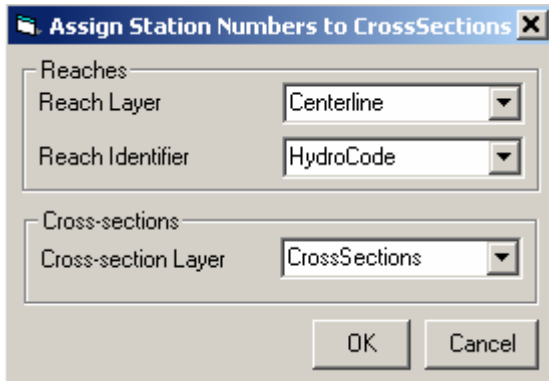
A station number gives the location of each cross-section along the reach. The measures assigned to the reach are used to assign station numbers to cross-sections. To assign a

station number to a particular cross-section, a point is created at the intersection of that cross-section and the reach, and the measure associated with the reach at that intersection point is assigned to the cross-section as its station number. It is therefore necessary to make sure that all cross-sections intersect with the reach (centerline). When an error occurs while creating cross-sections, ArcGIS creates a row in the CrossSections feature class with no shape (shape_length is approximately zero for such a feature). Make sure to delete such rows from the CrossSections feature class. The easiest way to check the intersection of cross-sections with the reach is to make a spatial selection (on the ArcGIS menu, click Selection→Select By Location...) of cross-sections based on intersection with the reach. If all cross-sections are selected, there is no problem. If some cross-sections are not selected, they should be either deleted or edited to intersect with the reach.

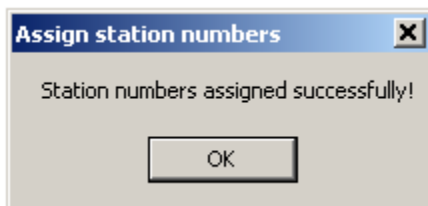
After examining the cross-sections, click on *Processing Menu*→*Assign Station Numbers* as shown below:



Choose CenterLine for Reach Layer, HydroCode for Reach Identifier, and CrossSections for Cross-section Layer. In this exercise, the goal is to model the reach between the Richmond and Rosharon gaging stations, and ideally the centerline layer should one feature per reach. Since the measures are assigned by aggregating all the reaches, having multiple features in the centerline feature class does not present a problem.



Click *OK*. The process takes about 5-10 seconds to assign station numbers to cross-sections.



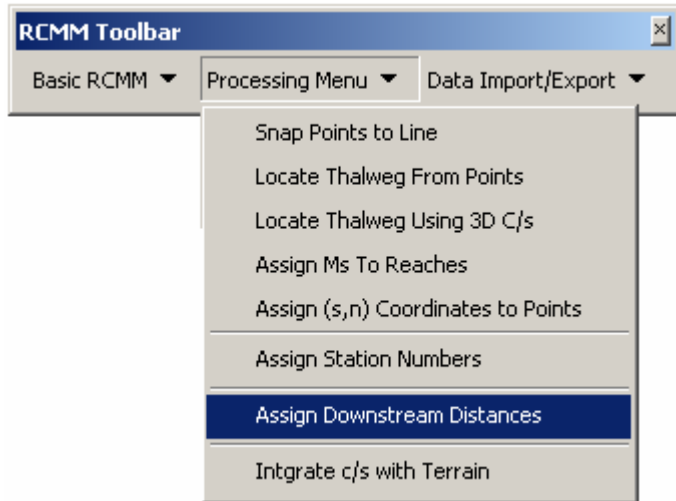
Click *OK* on the process completion message box. Open the attribute table for cross-sections to look at the new attributes (Note: the attribute values may be different depending on how the boundary segments are split).

	BETA1	ALPHA2	BETA2	FACTOR	Measure	HydroCode	StationNo
▶	3.75	1.704404	1.704404	0.254560	260.1453	95937797	63285.3182
	3.602543	1.799152	1.799152	0.248034	260.1453	95937797	63027.6619
	3.552283	1.815906	1.815906	0.247364	531.5497	95937797	62762.0261
	3.365188	1.878271	1.878271	0.244869	797.8361	95937797	62499.2135
	3.632611	1.789130	1.789130	0.248435	1046.8288	95937797	62249.8153
	2.918036	2.027321	2.027321	0.238361	1332.1809	95937797	61976.001
	3.521824	1.826059	1.826059	0.246958	1602.275	95937797	61710.3235

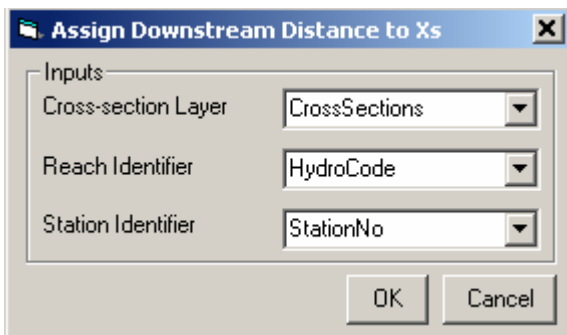
Two new fields are added, HydroCode and StationNo. HydroCode is the cross-section identifier that links the cross-section to reaches. For any cross-section that lies on a particular reach, its HydroCode is equal to the HydroCode of the reach. StationNo is the measure along the reach. HydroCode identifies which reach the cross-section belongs to, and StationNo identifies the exact location on the reach.

Assigning downstream distances to cross-sections

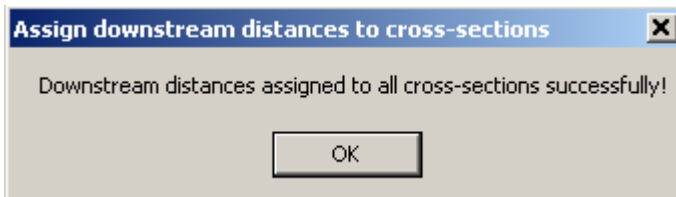
One last attribute necessary for creating a HEC-RAS geometry file is the distance between adjacent cross-sections. This can be accomplished by using the Assign Downstream Distances tool. Click on *Processing Menu*→*Assign Downstream Distances* as shown below:



Choose CrossSections for Cross-sections Layer, HydroCode for Reach Identifier and StationNo for Station Identifier. Click *OK*.



The process should take about 15-20 seconds to finish. Click OK on the final completion message.



Open the attribute table for CrossSections to see the new attribute, DistanceDS. DistanceDS stores the reach length between adjacent cross-sections on a reach. The last cross-section on a reach will have a DistanceDS = 0.

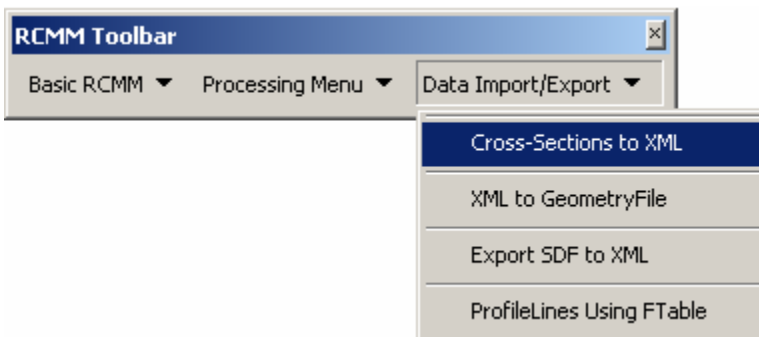
ALPHA2	BETA2	FACTOR	Measure	StationNo	DistanceDS	HydroCode
1.799152	1.799152	0.248034	260.1453	63027.6619	265.635800	95937797
1.815906	1.815906	0.247364	531.5497	62762.0261	262.812600	95937797
1.878271	1.878271	0.244869	797.8361	62499.2135	249.398200	95937797
1.789130	1.789130	0.248435	1046.8288	62249.8153	273.814300	95937797
2.027321	2.027321	0.238361	1332.1809	61976.001	265.677500	95937797
1.826059	1.826059	0.246958	1602.275	61710.3235	254.897700	95937797
1.975979	1.975979	0.240961	1858.6212	61455.4258	276.9859	95937797
2.240756	2.240756	0.225555	2147.7471	61178.4399	277.622900	95937797
1.970849	1.970849	0.241166	2438.3361	60900.817	265.822200	95937797
1.540988	1.540988	0.270901	2707.7302	60634.9948	255.3773	95937797
1.932674	1.932674	0.242693	2962.5681	60379.6175	0	95937797

Record: 1 Show: All Selected Records (0 out of 253 Selected.) Opti

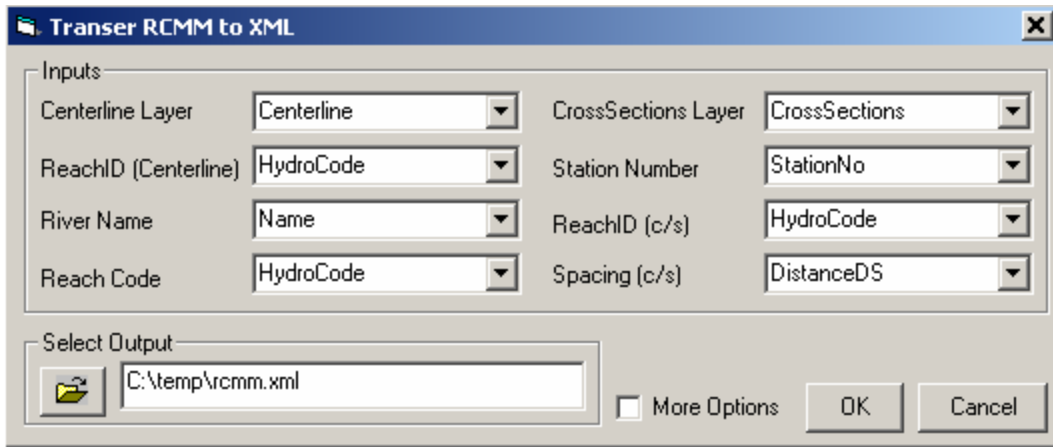
Close the attribute table for CrossSections. The RCMM cross-sections are now ready for export to a HEC-RAS geometry file via XML format. The XML format is adopted because it is generic, and can be used as input to other models. The data are, therefore, first converted to XML format, and then the XML file is used to create the geometry file for HEC-RAS.

Creating HEC-RAS files from RCMM

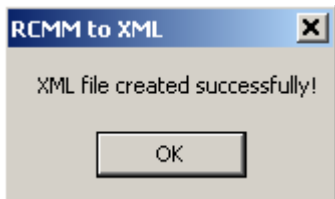
Click on Data *Import/Export* → *Cross-sections to XML* as shown below:



Choose Centerline for Centerline Layer, CrossSections for CrossSections Layer, HydroCode for ReachID (both Centerline and c/s), HydroCode for Reach Code, Name for River Name, StationNo for Station Number and DistanceDS for Spacing (c/s). Save the output XML file as rcm.xml as shown below (Note: The More Options check box at the bottom is intended to provide additional parameters such as Manning's N, expansion/contraction ratio, etc for the HEC-RAS geometry file, but this part of the interface is still under development, and will not be used in this tutorial):



The process takes about a minute or so to finish. Click *OK* at the final message.



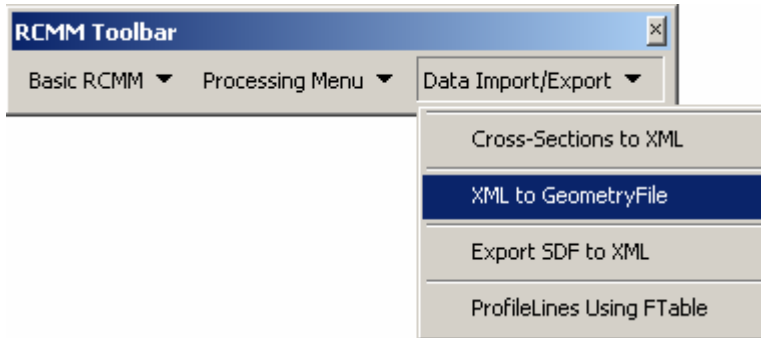
Open the xml file in internet explorer from windows explorer to see the structure of the file (depending on what browser is used to open the xml file, the view may be little different compared to the view shown below).

```
<?xml version="1.0" ?>
- <ChannelGeometry>
  - <Header>
    - <Extent>
      <NECornerXY X="254341.748653282" Y="3277899.73146947" />
      <SWCornerXY X="232747.507609171" Y="3247031.70200072" />
    </Extent>
  </Header>
  - <Reaches>
    - <Reach>
      <ReachID ID="95937623" />
      <RiverName Name="Brazos River" />
      <ReachCode Code="95937623" />
      <ReachPoint X="233000.513433407" Y="3277899.73146947" Z="0" />
      <ReachPoint X="232995.248025401" Y="3277888.94874946" Z="0" />
      <ReachPoint X="232988.985241396" Y="3277874.22567745" Z="0" />
      <ReachPoint X="232986.175385393" Y="3277866.72590144" Z="0" />
      <ReachPoint X="232983.900057391" Y="3277859.06023743" Z="0" />
      <ReachPoint X="232979.267481387" Y="3277839.60218941" Z="0" />
      <ReachPoint X="232975.943577384" Y="3277815.83105339" Z="0" />
      <ReachPoint X="232975.914905384" Y="3277807.82951738" Z="0" />
      <ReachPoint X="232974.028697382" Y="3277779.89889336" Z="0" />
      <ReachPoint X="232971.53832938" Y="3277764.09447734" Z="0" />
      <ReachPoint X="232969.744281378" Y="3277756.29774134" Z="0" />
    </Reach>
  </Reaches>
</ChannelGeometry>
```

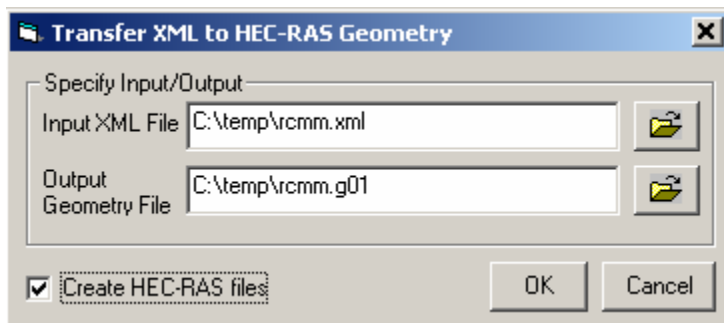
The data are organized on a reach-by-reach basis. First, the reach data are stored as x,y,z points, and for each reach, the cross-sections are stored, also as x,y,z points.

After the XML file is created, the final step in preparing the data for HEC-RAS is creating the geometry file. In addition to the geometry file, other files for HEC-RAS (project, plan, and flow files) can also be created by using RCMM. However, other files (.prj, .p01 and .f01) will not have all the required information for running a hydraulic simulation. For example, the flow file will not have the boundary conditions specified, or the plan file will not have simulation options (subcritical/supercritical) etc. The idea is to create the files with basic information so the project can be loaded in HEC-RAS.

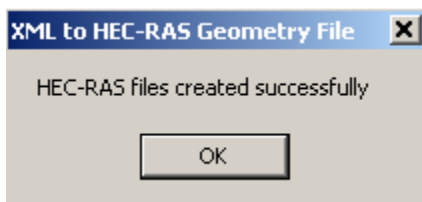
Click on *Data Import/Export* → *XML to GeometryFile* as shown below:



Browse to rcmm.xml file for input, and name the output geometry file as rcmm.g01 (specifying the extension is optional). Check the Create HEC-RAS files option to ensure the project file, flow file, and plan file are also created for running HEC-RAS. The name specified for the geometry file is used to create other HEC-RAS files with appropriate extensions, and all files are stored in the same folder as the geometry file.

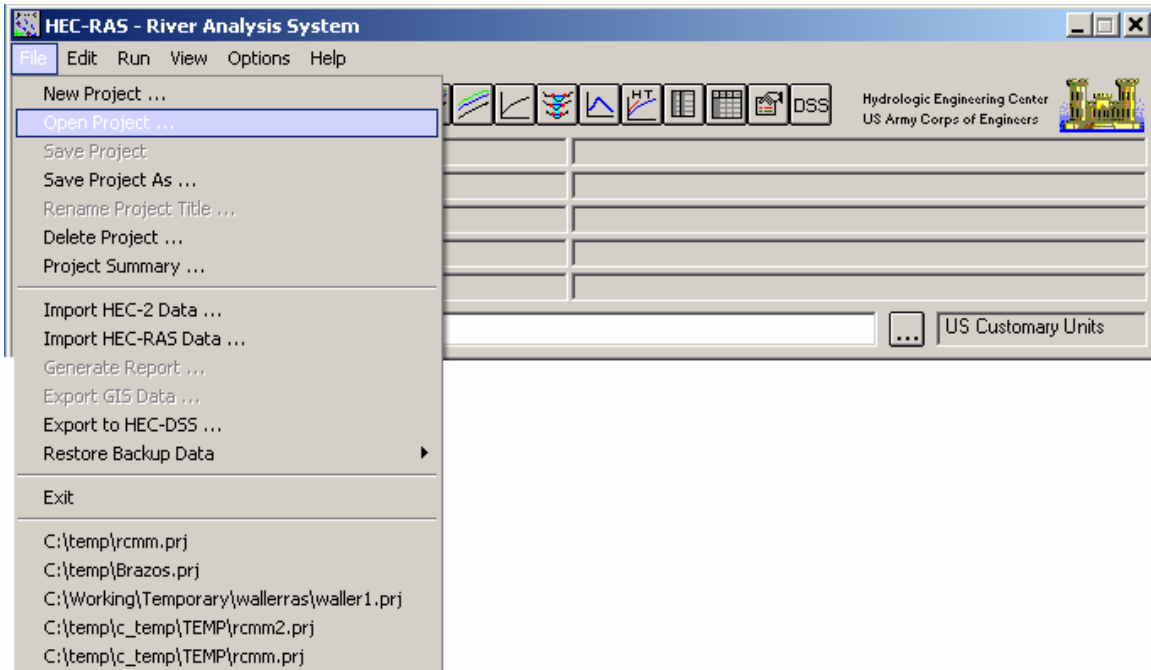


Click *OK*, and the file creation process should finish in about 5-10 seconds. Click *OK* on the process completion window as shown below.

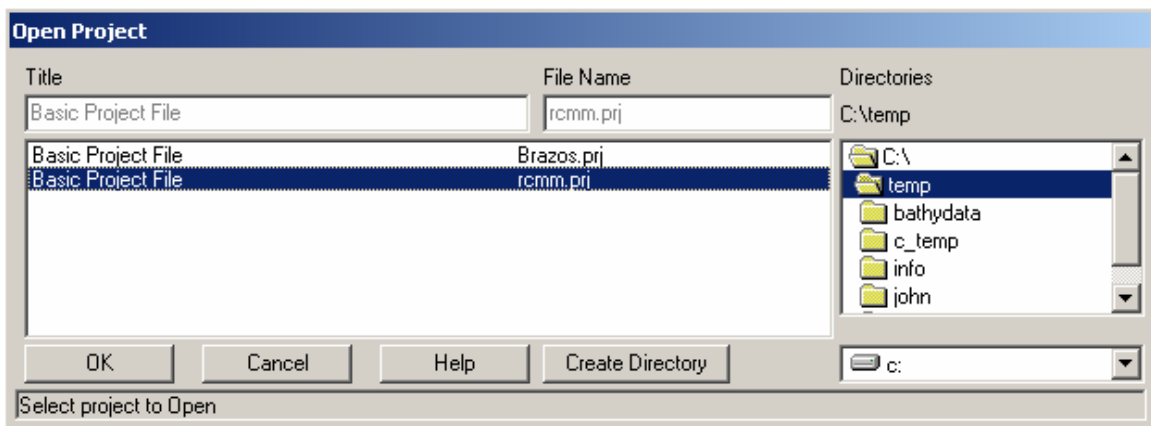


Opening RCMM in HEC-RAS

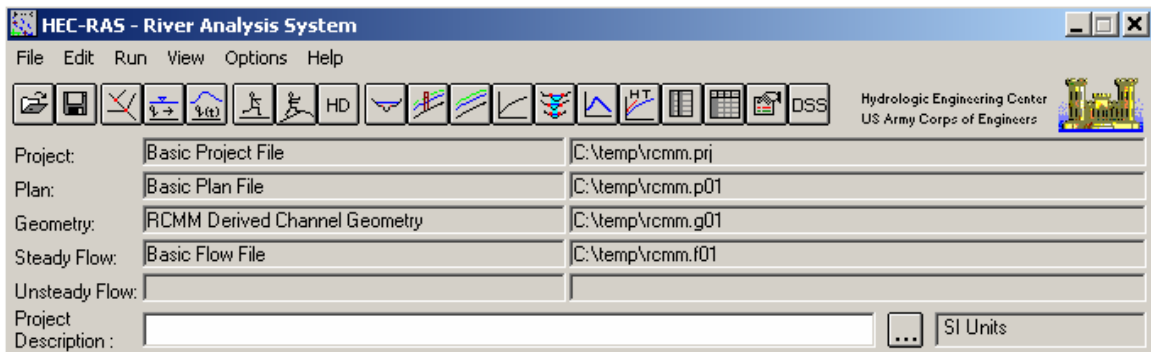
Open HEC-RAS, and click on *File* → *Open Project..* as shown below:




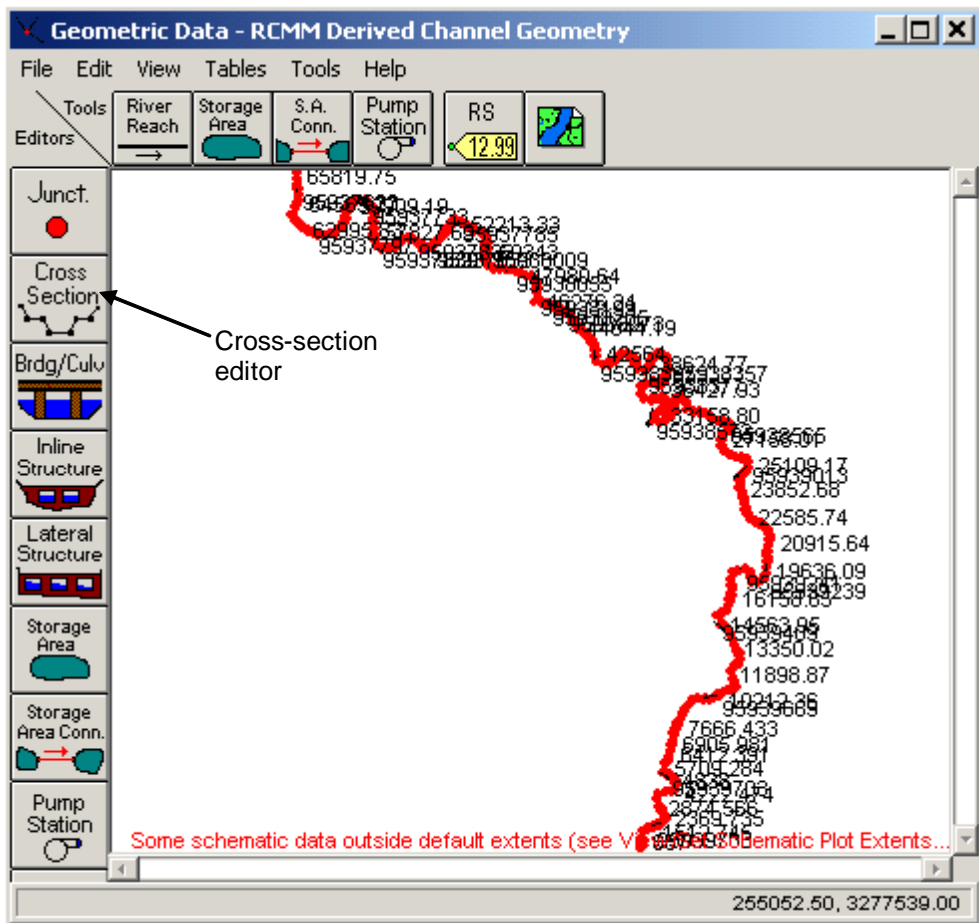
Browse to rcmm.prj and click *OK*.



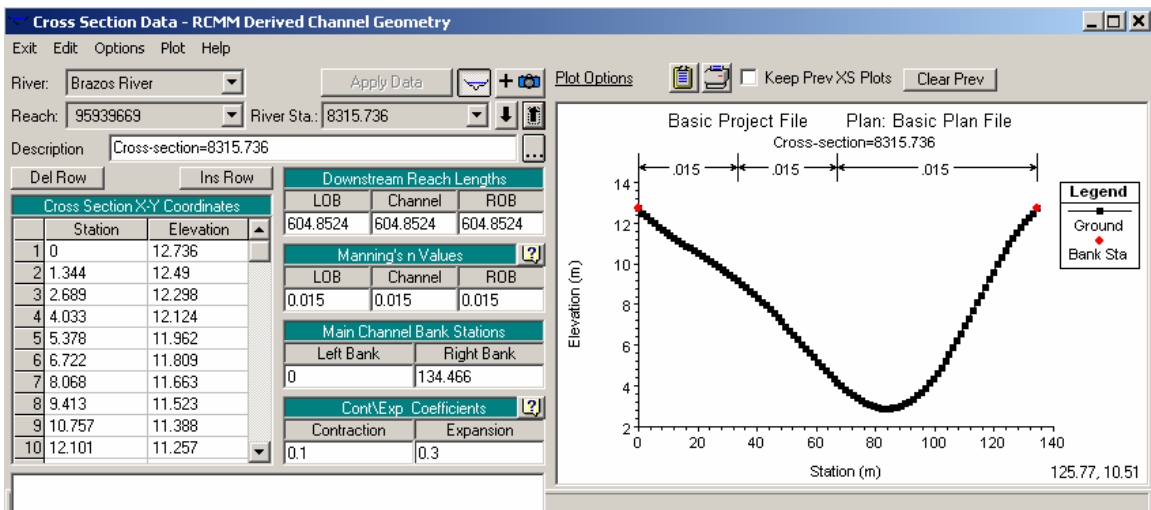
With the rcmm.prj file, other files will be automatically added to HEC-RAS as shown below (depending on where the files are created, the file locations will be different compared to the view shown below):



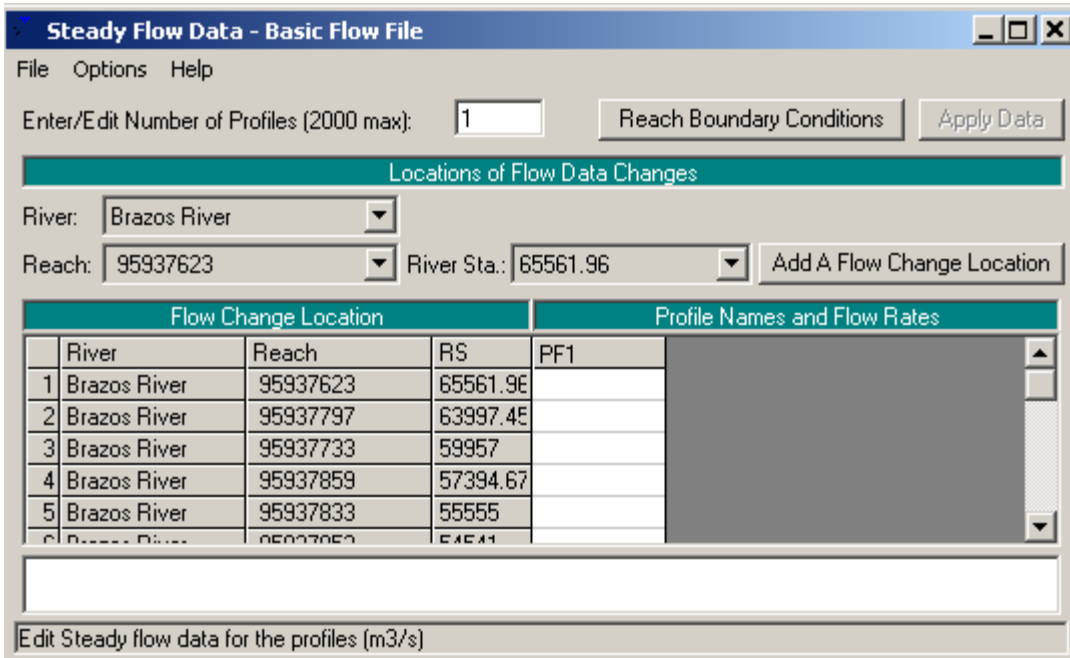
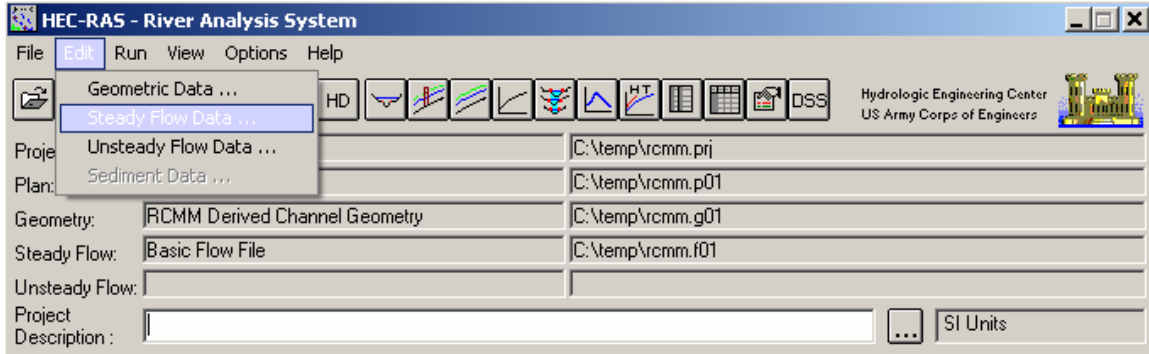
Click on the geometric data editor  to look at the cross-sections as shown below:



Click on the cross-section editor to view RCMC cross-sections (depending on the station numbers, the cross-section view will be different than the view shown below).



Close the geometric data editor. On the main project interface, click on Edit→Steady Flow Data to see the flow data.



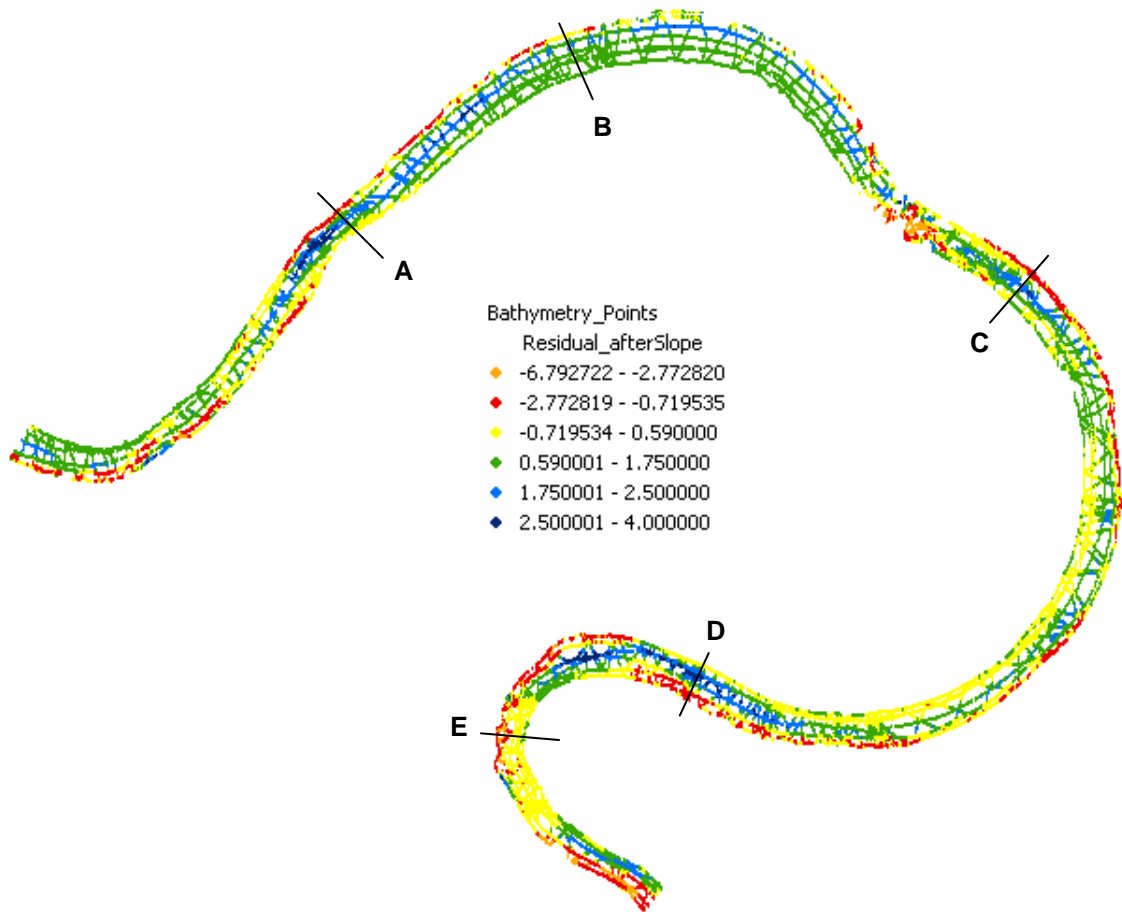
RCMM creates only a basic flow file for HEC-RAS, and does not include any flow data or boundary conditions. The user is expected to enter the flow and boundary conditions data to run HEC-RAS.

Manipulating boundary conditions and running HEC-RAS is not included in this tutorial.

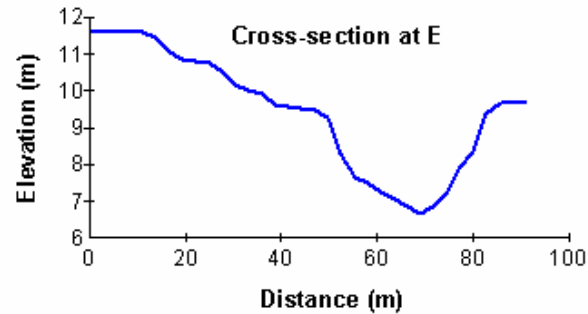
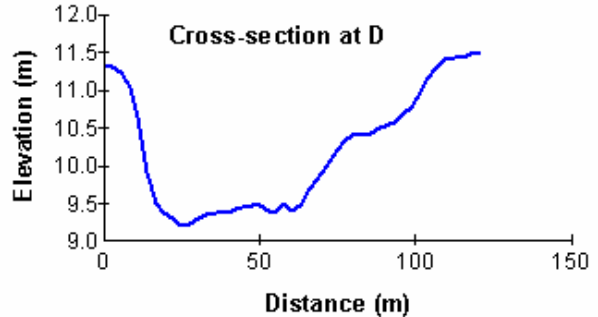
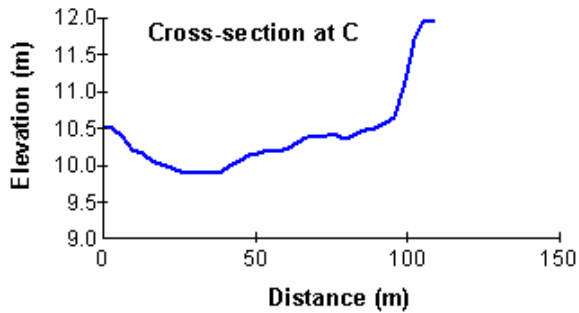
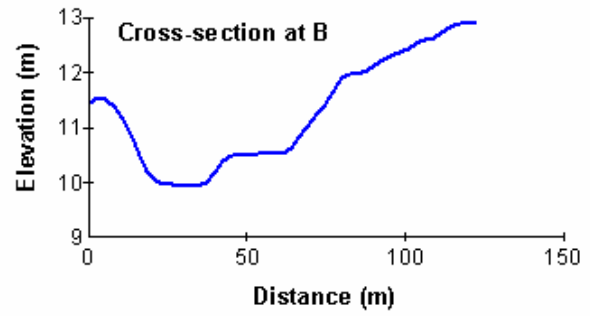
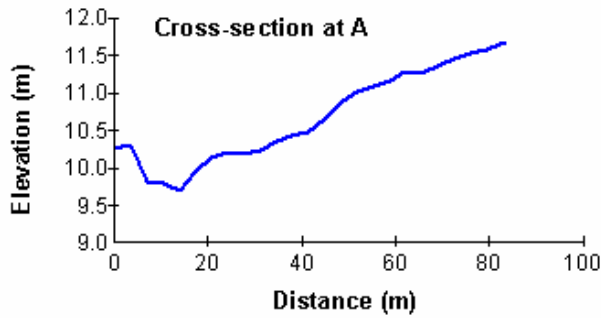
Section 3 - Analysis of Residuals from RCMM

RCMM defines only an average surface (deterministic trend) for the channel bed, and to describe the structure of the channel bed completely, the stochastic trends (local-scale variations) must also be incorporated. The classical approach to identify the local variations is to filter the observed data from the RCMM cross-sections, which means subtracting the analytical cross-sections from the observed bathymetry points. Negative residuals will signal a deep pool and positive residuals will signal a shallow riffle. This is the simplest approach one can use to identify the riffle-pool sequence (Knighton, 1998). In this section, the results of application of RCMM to the site 1 on the Brazos River are subtracted from the observed bathymetry to study the residuals. For details on application of RCMM to site 1 on the Brazos River, the reader is referred to chapter 5 of Merwade and Maidment (2004) provided with the CD-ROM.

Before correlating the residuals with the pool-riffle sequence, it is important to make sure that RCMM is capturing all the trends. There are two types of trends in the data: longitudinal (along the flow) and lateral (across the flow). For river channels, the lateral trend is more pronounced compared to the longitudinal trend. Although, RCMM does not have a procedure to incorporate the longitudinal trend (slope), the thalweg estimated by RCMM can be modified (by changing its z attribute) to account for the slope in the channel. A slope of 1:3334 (estimated from the observed data) is applied to the RCMM output before calculating the residuals. A plot of residuals at Site 1 on the Brazos River is shown below:

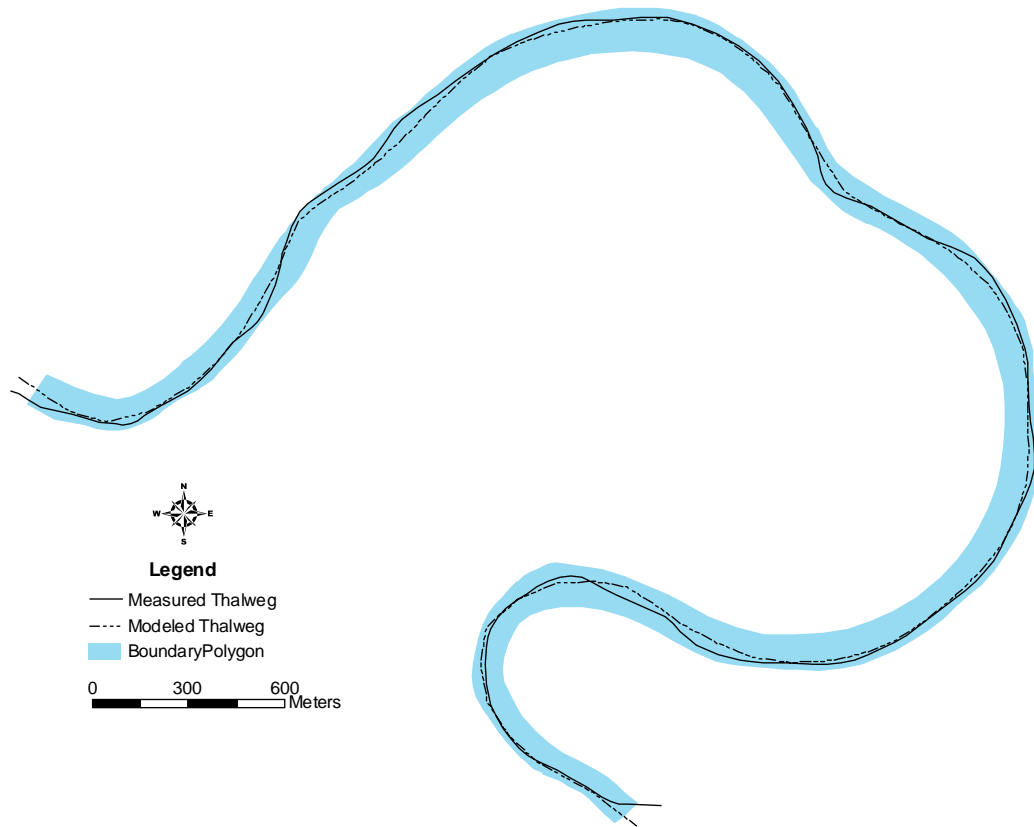


From the above figure, it is not immediately apparent whether a positive/negative residual area signals a riffle/pool, or the residuals are resulting from some other factors. To further analyze the residuals from the above plot, cross-sections are plotted by using the observed data at locations A, B, C, D and E. The observed cross-sections are plotted starting from the left bank (looking downstream) with distance along the cross-section on the x-axis, and the corresponding elevation on the y-axis as shown below.



The residuals are a result of one or a combination of the following factors:

- The observed data have incomplete information about the left bank (plots A and C) at some locations resulting in negative residuals along the edges.
- RCMM results are produced by using a constant bank elevation of 12.25m, which is close to the observed bank elevation at most locations, except in the area surrounding location B, where the bank elevation is 13m or higher (plot B). This produces positive residuals along the right bank in the area surrounding location B.
- Since the location of thalweg dictates the shape of the cross-sections produced by RCMM, inaccurate estimation of thalweg results in residuals that may be misleading in identifying pools/riffles. The following figure shows the measured thalweg and the RCMM output. Residuals surrounding location D result from inaccurate prediction of thalweg.

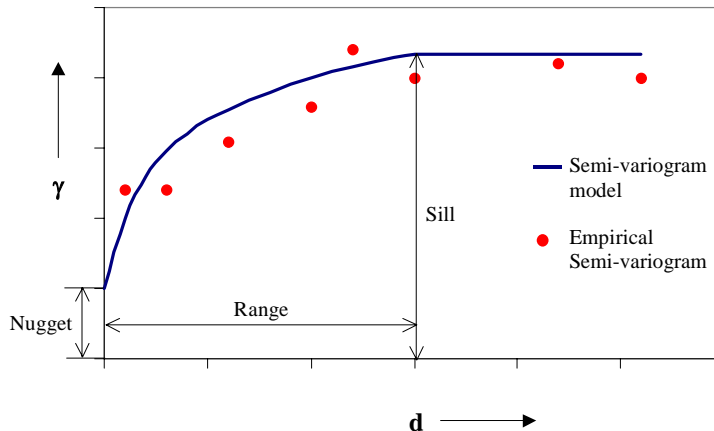


- At location E there is an abrupt drop in the thalweg elevation (5m) compared to the thalweg just upstream at location D (2m). This produces negative residuals at that particular location.

Locations like E are the target areas for identifying local scale variations in the channel bathymetry, but factors such as the quality of the observed data, and the inability of RCMM to capture some important details in the data (for example, the thalweg at some locations) produce residuals that are misleading. It is, therefore, necessary to first modify RCMM to describe the channel morphology better by incorporating additional factors such as geology, terrain, etc. before studying the residuals in detail. The following section discusses a possible approach for quantifying local scale variations by using RCMM residuals.

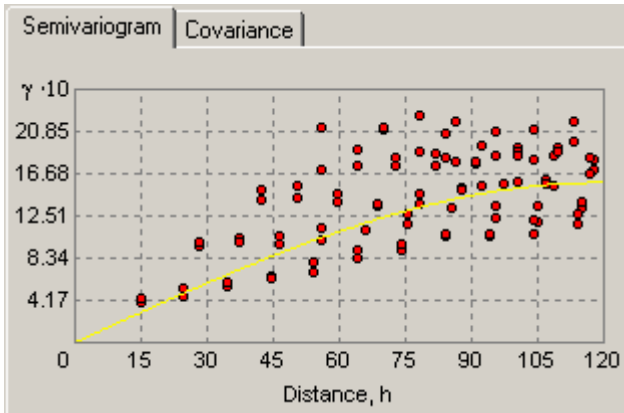
If RCMM is able to describe the mean surface of the channel bathymetry accurately, the residuals should have no spatial correlation (white noise). However, it is usual to observe some small spatial correlation even after removing the lateral (cross-sectional shape) and longitudinal trends (slope) in the data (Kanevski et. al, 2002). The first task, therefore, is to study the spatial correlation of the residuals. The geostatistical analyst extension in ArcGIS is used to fit the semivariograms for studying the spatial correlation of the residuals. Semivariogram modeling is similar to fitting a least-squares line in regression analysis. Any type of function that can serve as a reasonable model can be used to fit the

semivariogram. For example, a spherical type that rises at first and then levels off for larger distances beyond a certain range is commonly used. The figure below shows a hypothetical semivariogram, which is a plot of semivariance (γ) versus the distance (d) with semivariance as the ordinate (Figure below):

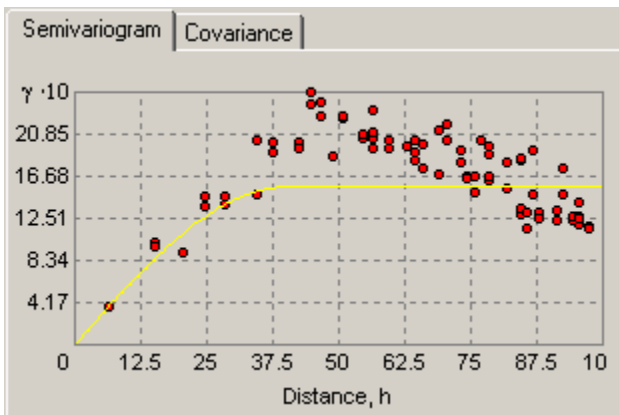


Three terms are important in semivariogram modeling: the range, sill, and nugget. The distance from the origin to a point where the semivariogram first flattens out is called as the range. All the locations that are separated by distances shorter than the range are spatially correlated, whereas the locations further apart are not (spatially independent). On a semivariogram plot, the range is measured along the horizontal (x) axis. When a semivariogram model attains the range, the corresponding value on the y -axis is called as the sill. The value along the y -axis at a point where the semivariogram intercepts with the y -axis is called as the nugget. At zero separation distance ($d_{ij} = 0$), the semi-variance is zero. However, measurements tend to vary at infinitesimal separation distances. The nugget also referred to as nugget effect, can be attributed to measurement errors or to spatial variations at micro-scales smaller than the sampling distances. The sill minus the nugget is referred to as the partial sill. Since the semivariogram computes semivariance versus distance for each pair of points in the dataset, the numbers of pairs to be computed multiply with the size of the dataset. Therefore, a procedure known as binning is used, where average values of semivariance and distance are computed for all the pairs in a bin. The average values for each bin are then used in the semivariogram plot. The semivariogram plots presented in this report are produced by using the binning procedure, and therefore, the number of data points on the plots is much smaller than the number of points in the original dataset

To get a better sense of the residuals, the data are analyzed in (s,n,z) coordinate system so that semivariograms can be fitted in both n - (across the flow) and s - (along the flow) directions (Merwade et al, 2005). The semivariogram plot for residuals along the Site 1 of the Brazos River in s -direction (flow direction) is shown below:



Similarly, the semivariogram for residuals in n-direction is shown below:



In the semi-variogram plots shown above, the red dots are obtained from the residuals, and the yellow lines are theoretical models (Spherical type) fitted to red dots. Details on what equations are used to fit a spherical type semivariogram model, and how these semivariograms can be used to make a prediction at unknown locations can be found in Section 4.5.4 of Merwade and Maidment (2004) provided with the CD-ROM.

The following table summarizes the parameters of semivariograms for residuals along s- and n-directions.

Parameters	Brazos River at Site 1	
	n-direction	s-direction
Range	40	118
Partial Sill	1.58	1.58
Nugget	0	0

The range and partial sill in both s and n direction suggest that the residuals do have a spatial correlation. The range across the flow (n direction) is almost 1/3rd of the range along the flow (s direction). The partial sill, however, is the same.

The stochastic small-scale spatial variations exhibited by the residuals can be handled in several ways: spectral methods, moving average processes, geostatistical methods, etc. Christakos (1992) provides a good overview of these different methods. Geostatistical methods would be the best way to deal with residuals in a GIS environment. The current version of geostatistical analyst in ArcGIS does not offer any functions to simulate random fields. However, external libraries such as GSLIB (Deutch and Journel, 1992) and GSTAT (Pebesma and Wesseling, 1998) offer a technique called Sequential Gaussian Simulation (SGS), which can be used to simulate random fields. A SGS model requires two inputs: semivariogram and the extent of area to be simulated. In the absence of any pre-defined condition or data, SGS starts with a single cell (data point) at any random location in the area of interest, and employs the input semivariogram to predict a value at that point using the kriging technique. This first point is then used to condition the prediction value at the second point, the first two points are then used to condition the prediction value at the third point, and this process continues until all the points are visited only once. A single prediction for each point constitutes a single realization of the procedure. Multiple realizations are performed to get a distribution at each point, and a value is picked for each cell.

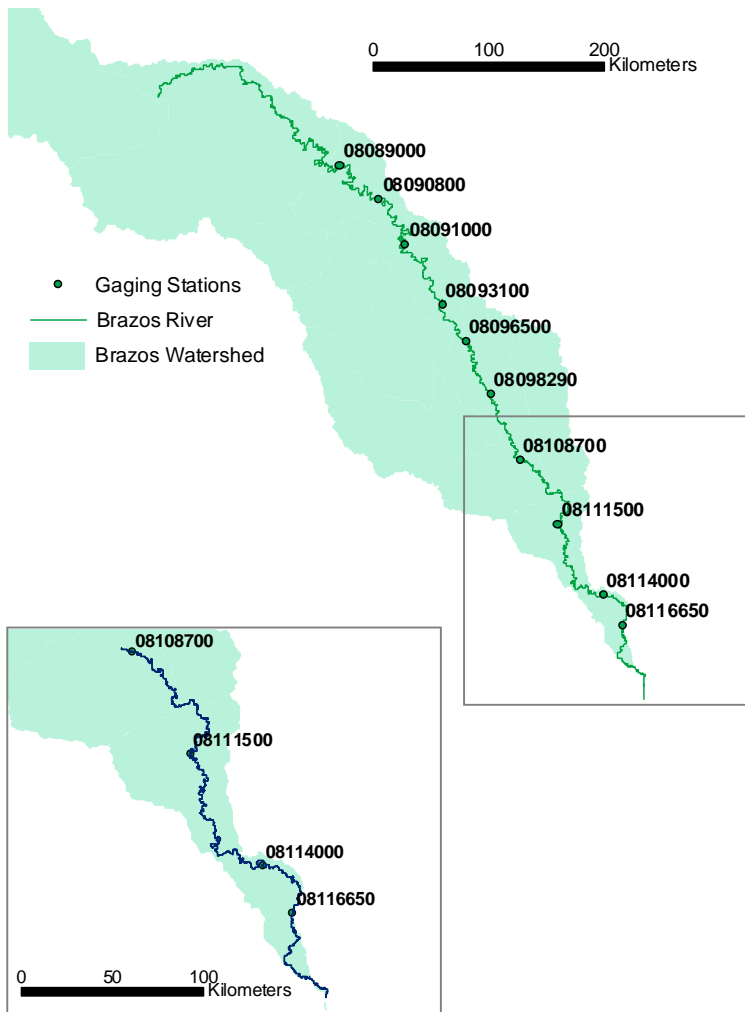
The output from the SGS process can be added to the mean surface obtained from RCMM to get the final result, which will then have both the deterministic and a realization of the stochastic component of the channel bathymetry. As mentioned earlier, the SGS process is not available with ArcGIS, and considerable effort would be required to employ libraries such as GSLIB or GSTAT to perform SGS in ArcGIS. This topic is, therefore, not addressed in the current scope of work, and will be revisited in the future.

Section 4 - Application of RCMM to the Lower Brazos Priority Segment

In this section, the applicability of RCMM to the lower Brazos priority segment (regional scale) is presented. The following two questions associated with the applicability of RCMM at regional scale:

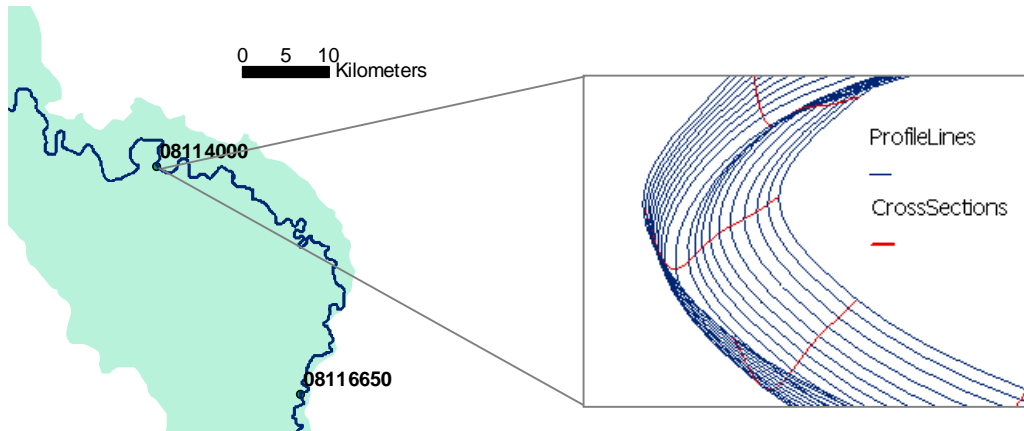
- 1) Can RCMM produce cross-sections for river reaches that are several hundred kilometers long?
- 2) If the answer to Question 1 is yes, how good is the RCMM output?

To answer the first question, RCMM is applied to the lower Brazos segment (Approximately 470 Km) starting from Brazos River at SH 21 near Bryan, Texas as shown in the figure below:



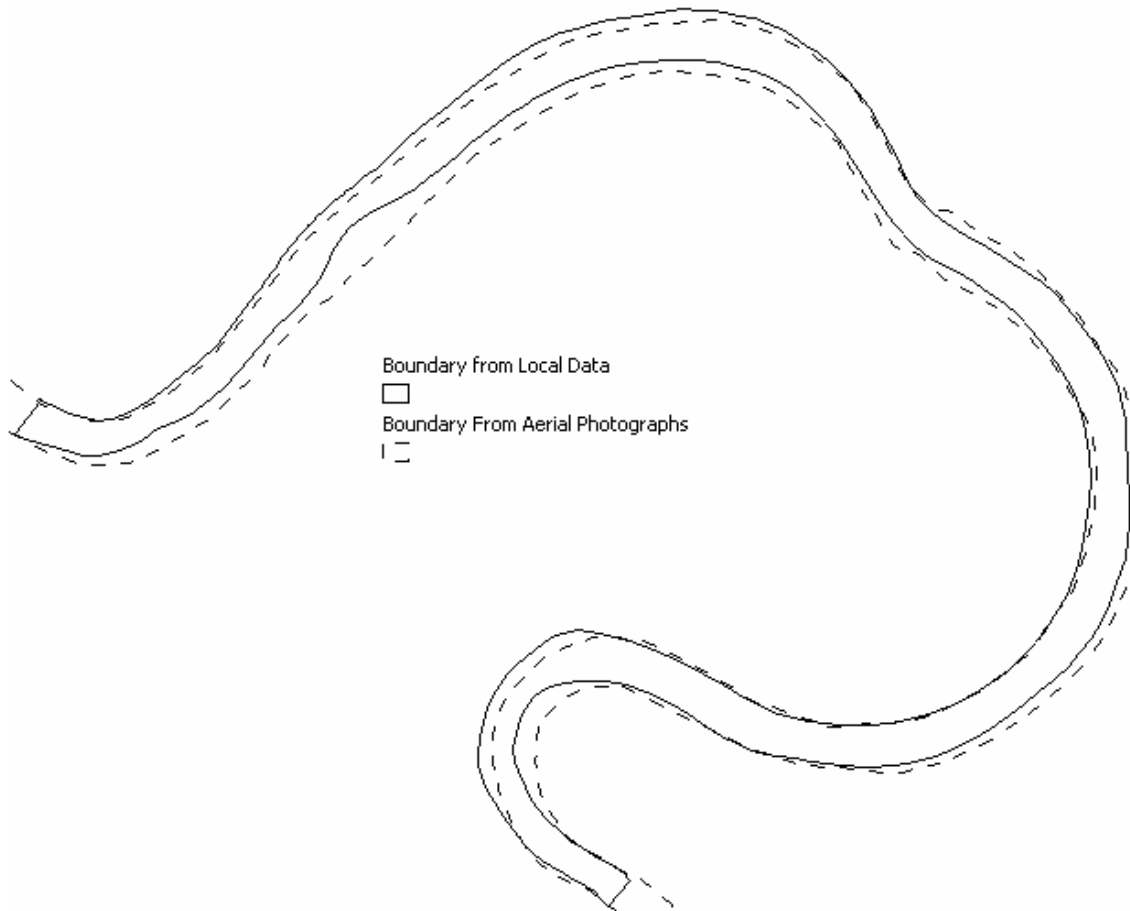
Hydraulic geometry relationships developed for the gaging stations are presented in Table 5.4 of CRWR_04-08.pdf provided with the CD-ROM. Using the hydraulic geometry relationships, depth and bank elevation at each gaging station are calculated for

average flows, which area available from the USGS. Flow statistics such as minimum, maximum, average etc. for each station can be obtained from the USGS website by using the recent daily flow data link. The width is obtained by digitizing the channel boundary using aerial photographs. By using RCMM, a three-dimensional representation for the lower Brazos segment is produced. The following figure shows the output for a cross-section near Richmond gaging station.



With an affirmative answer to the first question (Can RCMM produce cross-sections for river reaches that are several hundred miles long?), the accuracy of the RCMM output must be analyzed. .

The answer to the second question (How good is the RCMM output?) depends on the input to RCMM. There are three parameters that are critical in describing the general shape of any cross-section: width, depth and bank elevation. In addition there are scaling issues involved. To develop a channel representation at regional scale, regional scale data are used which, very often, do not match with data collected at local scales. The results from regional application of RCMM are evaluated by comparing RCMM output with the locally collected data at Site 1 along the Brazos River. The following figure shows the channel boundaries at Site 1 obtained using aerial photographs and locally collected data.



The lateral shift in the channel boundary delineated from aerial photograph range anywhere from 5m to 35m. This discrepancy in the channel boundary definition affects the thalweg prediction which in turn affects the cross-sections produced by RCMM.

Other important parameters that affect RCMM output are depth and bank elevation, which are obtained from USGS gaging stations data. The upstream and downstream gaging stations from Site1 at Brazos River are Hempstead and Richmond, respectively. The hydraulic geometry relationships at these two locations, presented in Merwade and Maidment (2004), are used to calculate the average depth and bank elevation at Site 1. The average depth at Site 1 for an average flow of $276 \text{ m}^3/\text{s}$ is estimated to be 4.5m, which matches with the average depth of the observed bathymetry data. The bank elevation, however, does not match with the observed data. The bank elevations at average flows for Hempstead and Richmond station are 37.12m and 13.2m, respectively. A linear interpolation of these values gives a bank elevation of 21m at Site1, which is about 9m higher than locally surveyed data (12.25m). This causes a shift of 9m in the vertical datum making the RCMM output unrealistic for any kind of analysis. Such a discrepancy in the vertical datum suggests that the USGS data must be supplemented by local elevation data to make the RCMM output realistic.

Section 5 – Summary and Future Work

Summary

A toolset (RCMM) is developed for analyzing and extrapolating river channel bathymetry. The three-dimensional representation of river channels described by RCMM can be used to run HEC-RAS model. Although RCMM has tools for creating HEC-RAS files only, the XML output from RCMM can be used to create geometry files for other hydraulic models as well. The current version RCMM provides only the mean surface for the channel, and the capability to add local-scale variations to this mean surface still needs to be added. The approach of subtracting RCMM from observed data and plotting the residuals to study the patterns in local-scale variations does not provide a clear picture of these small-scale variations in the bathymetry. A better approach would be to model these variations using geostatistical methods such as sequential gaussian simulation. When applying RCMM at regional scale using the USGS flow and elevation data, it is recommended to supplement the elevation data with local measurements to get meaningful output from RCMM.

Future Work

Future work involves modification to RCMM code, conceptual enhancement of RCMM, and a method for incorporating local scale variations to RCMM output. Some of the tasks that are envisaged for the future work are listed below:

- The current version of RCMM uses the left bank of the channel as a reference for locating the thalweg and creating cross-sections, which produce errors during program execution. These errors arise mainly from discrepancy between the channel boundary and the boundary segments. In addition, intermediate steps such as converting polygon to polyline, interpolating attributes for the boundary segments, etc. could be eliminated if the left boundary is replaced by the channel centerline (NHD) as a reference.
- The current version of RCMM looks for parameters for creating beta distribution on a local drive (“c:\temp”). In addition, other parameters such as Manning’s N, expansion/contraction ratio, etc. for use in HEC-RAS are hard coded in the program. These issues need to be addressed for a more user-friendly experience with RCMM.
- Since RCMM can be exported to a XML file, this structure could be exploited to use RCMM output for other hydrodynamic models that are used by Texas Water Development Board (eg. SMS mesh for RMA2).
- Modification of RCMM to account for local-scale variations by using the concept of sequential gaussian simulation.
- Incorporation of factors such as slope, geology, land use etc. into RCMM.
- Extending RCMM to include channel confluences and other channel types (eg. braided channels).

References:

- Christakos, George, 1992. *Random field models in earth sciences*. Academic Press, San Diego, CA, 474 p.
- Deutch, C., V., and Journel, A., G., 1992. *GSLIB: geostatistical software library and user's guide*. Oxford University Press New York, 340 p.
- Kanevski, M., R. Parkin, A. Pozdnukhov, V. Timonin, M. Maignan, B. Yatsalo, and S. Canu (2002). Environmental Data Mining and Modelling Based on Machine Learning Algorithms and Geostatistics. *Proceedings of the First Biennial Meeting of the International Modelling and Software Society, IEMSS'2002*, June 2002, Lugano, Switzerland. A. E. Rizzoli & A. J. Jakeman (Eds), Vol. 3., pp. 414-419.
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