GEOGRAPHIC INFORMATION SYSTEMS AND WATER RESOURCES III
AWRA SPRING SPECIALTY CONFERENCE
Nashville, Tennessee
May 17-19, 2004

DERIVING MODEL INPUT FOR A LUMPED PARAMETER WATERSHED MODEL

Jason Love and Anthony Donigian, Jr. *

ABSTRACT: A lumped parameter watershed model describes the connectivity of hydrologic and hydraulic elements for analyzing watershed processes and behavior. Each hydrologic element produces a unit response to the external forcing functions based on parameters that describe the hydrologic and water quality characteristics of the element. It is therefore necessary to group regions of the watershed that will: 1) receive the same external forcing functions; 2) have similar hydrologic and/or water quality characteristics that can be described by a set of parameters; and 3) represent elements of interest or concern. The unit response of each hydrologic element is multiplied by an area factor and routed to downstream elements. These downstream elements are typically hydraulic elements that will then transport the flows and/or water quality constituents. The hydraulic elements are defined in a manner to: 1) sufficiently represent the temporal and spatial detail of routing within the watershed; 2) allow a set of hydraulic and water quality parameters to describe the element; and 3) allow model output to be analyzed and data comparisons to be made at desired locations.

Establishing the composition, connectivity, and attributes describing the elements within a watershed is well suited to a GIS environment and is often referred to as 'segmentation' and 'characterization'. The process has become a common and necessary practice in watershed modeling, and the data to support the practice continues to increase in volume and quality. In fact, numerous GIS-based programs and tools exist to assist modelers in performing the segmentation and characterization and provide the required data (e.g., BASINS). However, many of these tools by necessity enforce certain rules and data structures that often inhibit creativity or needed functionality. Often a combination of tools and techniques allow the most representative and predictive model to be developed.

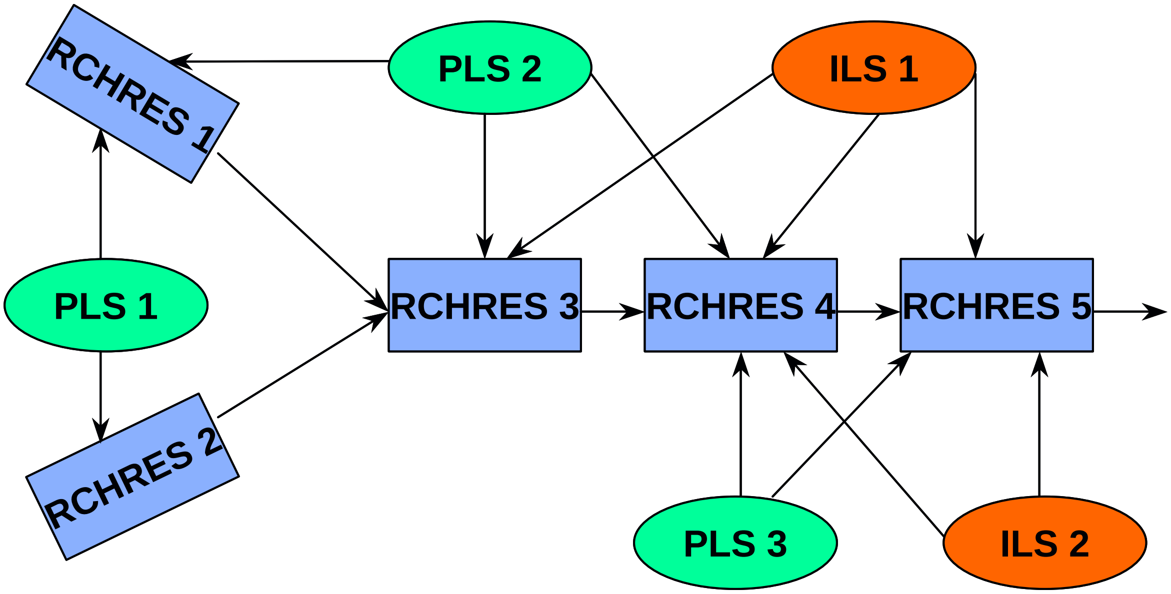
This paper explores GIS techniques, and the rationale behind them, that have been found to be useful based on past experience in developing model input for the U.S. EPA Hydrological Simulation Program – FORTRAN (HSPF), a lumped parameter watershed model for hydrology and water quality. Although the techniques and rationale are presented with HSPF in mind, they are applicable to a wide range of lumped parameter watershed models.

KEY TERMS: GIS, Pre-Processing, Watershed Model, Delineation, Segmentation

INTRODUCTION

A watershed model describes the connectivity of hydrologic and hydraulic elements for analyzing watershed processes and behavior. Each hydrologic element produces a unit response to the external forcing functions based on parameters that describe the hydrologic and water quality characteristics of the element. The unit response of each hydrologic element is then multiplied by an area factor and routed to downstream elements. This is shown schematically in Figure 1. Determining the composition, connectivity, and attributes describing the elements is a critical step in building a useful model. The composition and extent of the element should be chosen in a manner that will allow for parameterization and be consistent with the objective of the model. Ultimately, it is necessary to group regions of the watershed that will: 1) receive the same external forcing functions (e.g., precipitation); 2) have similar hydrologic and/or water quality characteristics that can be described by a set of parameters; and 3) represent elements of interest or concern. The hydraulic elements are defined in a manner to: 1) sufficiently represent the temporal and spatial detail of routing within the watershed; 2) allow a set of hydraulic and water quality parameters to describe the element; and 3) allow model output to be analyzed and data comparisons to be made at desired locations.

Establishing the composition, connectivity, and attributes describing the elements within a watershed is well suited to a GIS environment and is often referred to as 'segmentation' and 'characterization'. The remainder of this paper will discuss the rationale of 'segmentation' and 'characterization' and present examples of developing model input based on past experience with the U.S. EPA Hydrological Simulation Program – FORTRAN (HSPF) (Bicknell et al., 2001).



PLS – pervious land segment; ILS – impervious land segment; RCHRES – channel / water body

Figure 1 – Elements and linkage for a lumped parameter watershed model

SEGMENTATION

Segmentation is the process of delineating the watershed and channel network into discrete elements. The process should account for the variability of the forcing functions and physical characteristics of the watershed and provide locations where model output is required. Table 1 below summarizes some of the considerations to account for during the segmentation process.

Table 1 – Watershed segmentation considerations

	LAND SEGMENTS	CHANNEL SEGMENTS
FORCING FUNCTIONS	o meteorological data (precipitation, evaporation, temperature, etc.) o man-made (irrigation, chemicals)	o point discharges o diversions o reservoir releases
PHYSICAL CHARACTERISTICS	o topography \ drainage o geology (recharge zone) o land use \ vegetation o soils o aspect	o slope o roughness o morphology obstructions o bed sediment characteristics o channel junctions
MODEL OUTPUT	o alternative land use management scenarios o cropping practice	o gage \ data locations o management alternatives

The first step in segmentation typically involves defining outlets, or pour points, along the channel and then delineating the incremental drainage area to each channel segment. The pour points are chosen with consideration of the items presented in Table 1 and should result in a drainage network with sufficient detail to represent the channel routing. If water quality is a concern, then additional detail is required to define reach segments that have relatively similar water quality characteristics for the constituent(s) of concern (e.g., for sediment simulations it would be necessary to pay attention to the channel bed characteristics). Figure 2 shows an example of selecting pour points for a generic watershed configuration; the locations of the points were based on:

1. Forcing functions
   - below the sewage treatment plant (STP)
2. Physical Characteristics
   - at tributary junctions
   - above and below the reservoir
   - at the detention basin
3. Model output
   - at the three stream gages located within the watershed
   - below the agricultural and urban dominated catchments

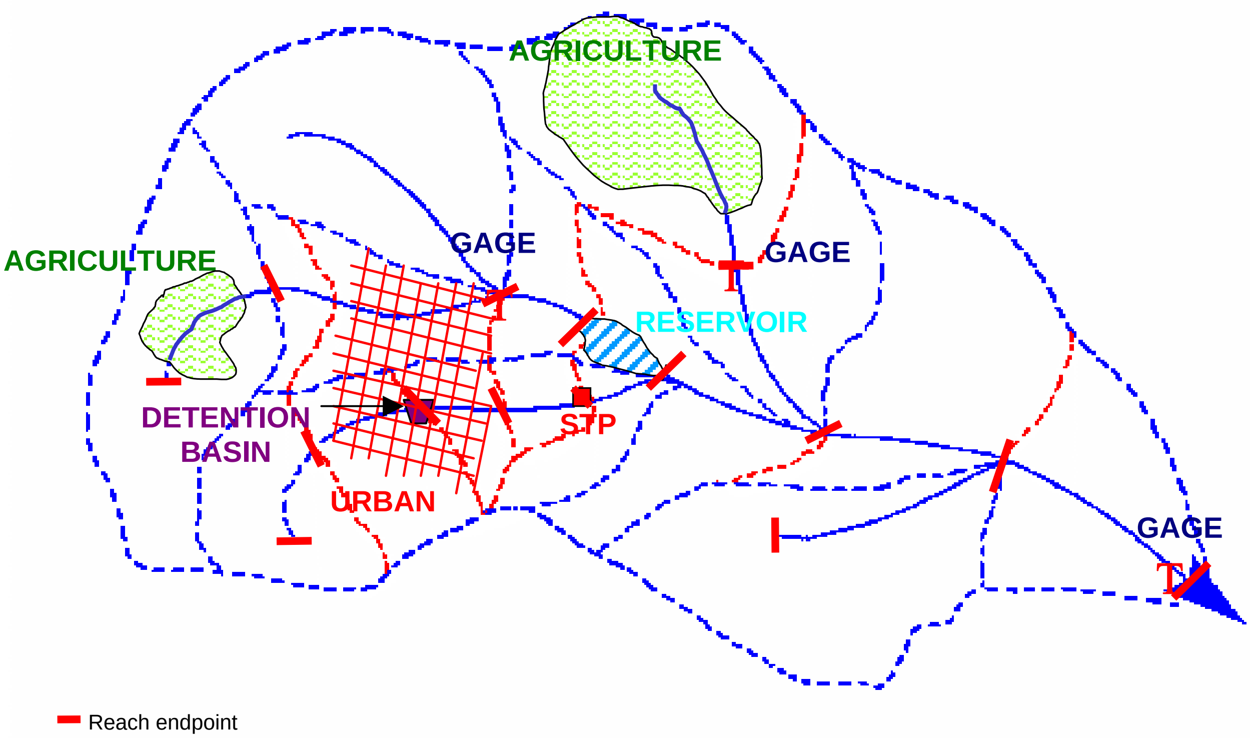


Figure 2 – Defining reach boundaries and tributary areas

Once the reach segmentation has been defined, additional segmentation is performed for the land segments with consideration of the items presented in Table 1. Precipitation is the primary driving force in any watershed model application; therefore, one of the primary segmentation considerations is delineating and assigning precipitation gages to segments in a manner that accurately represents the historical rainfall across the watershed. This usually is accomplished using a Thiessen network and/or an isohyetal map. Isohyetal maps may be available from local or state/federal agencies and they can be produced for the conterminous United States using the 'Parameter-elevation Regressions on Independent Slopes Model' (PRISM). PRISM is an expert system that uses point data (i.e., gage long-term average annual totals) and a digital elevation model (DEM) to generate gridded estimates of climate parameters, including precipitation. PRISM incorporates a conceptual framework that allows the spatial scale and pattern of orographic precipitation to be quantified and generalized (PRISM website http://www.ocs.orst.edu/prism/). The remaining 'other' meteorological timeseries are typically less variable, both temporally and spatially, than precipitation and usually do not require a finer segmentation scheme than that required for precipitation. Additional boundaries may however be required to define regions with significantly different physical characteristics that affect the hydrologic or water quality response (e.g., upland vs. lowland soil, contributing vs. recharge zone). The segmentation should also isolate areas where model output will be required. This might include regions where alternative land use management scenarios will be evaluated. Figure 3 shows an example of segmenting the generic watershed based on soil characteristics and using a Thiessen network to delineate and assign precipitation stations. In this case, the soils divide roughly corresponds to the eastern precipitation station boundary. The boundary of the Thiessen network is not absolute, and it will therefore make sense to combine the boundaries to reduce model complexity.

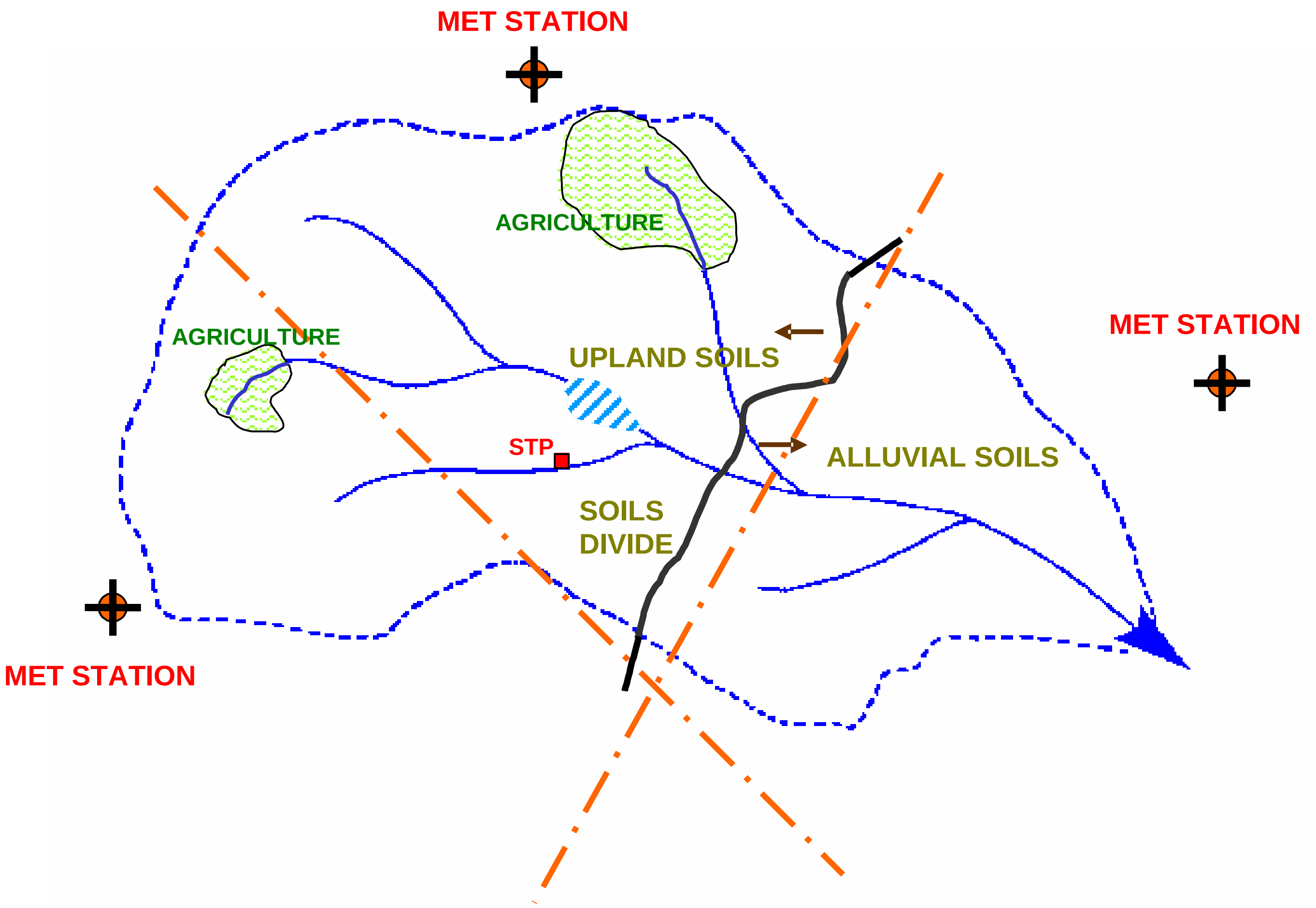


Figure 3 – Defining boundaries of meteorological regions within a watershed

Ultimately, the reach and land segmentation schemes are intersected, additional boundaries are adjusted where appropriate to further reduce complexity, and a logical numbering scheme is developed for the reaches. The final segmentation scheme for the generic watershed is shown in Figure 4. The figure displays the final 18 reach segments and the three meteorological segments adjusted to reach drainage divides. At this point, the segmentation has determined the following:

- there will be 18 reaches included in the model
- there will be 3 meteorological segments (e.g., reaches 1,2,8, and 9 and areas draining to these reaches will receive precipitation from the 'segment 1' gage)
- segments 1 and 2 will have characteristics of upland soils and segment 3 will have characteristics of alluvial soils

Numerous tools have been developed and are freely distributed to assist in the segmentation process. The tool of choice should provide functionality to preprocess a DEM, provide a stream 'burn-in' option to more accurately represent the drainage network in flat areas or areas where a high-resolution DEM is not available, provide the ability to import and interactively select/delete pour points, and automatically delineate the areas upstream of the specified pour points. Most tools also provide functionality to assist in manually delineating boundaries where the flow paths are not explained by the DEM. Table 2 lists some useful tools used by the author that are freely available to extend ESRI's ArcView (ESRI, 1996) capabilities. Refer to the documentation available at links provided in Table 2 for information on delineation techniques specific to the respective tools. Additional information on delineation and segmentation techniques, primarily related to HSPF and BASINS, are available on CD-ROM (AQUA TERRA Consultants, 2000).

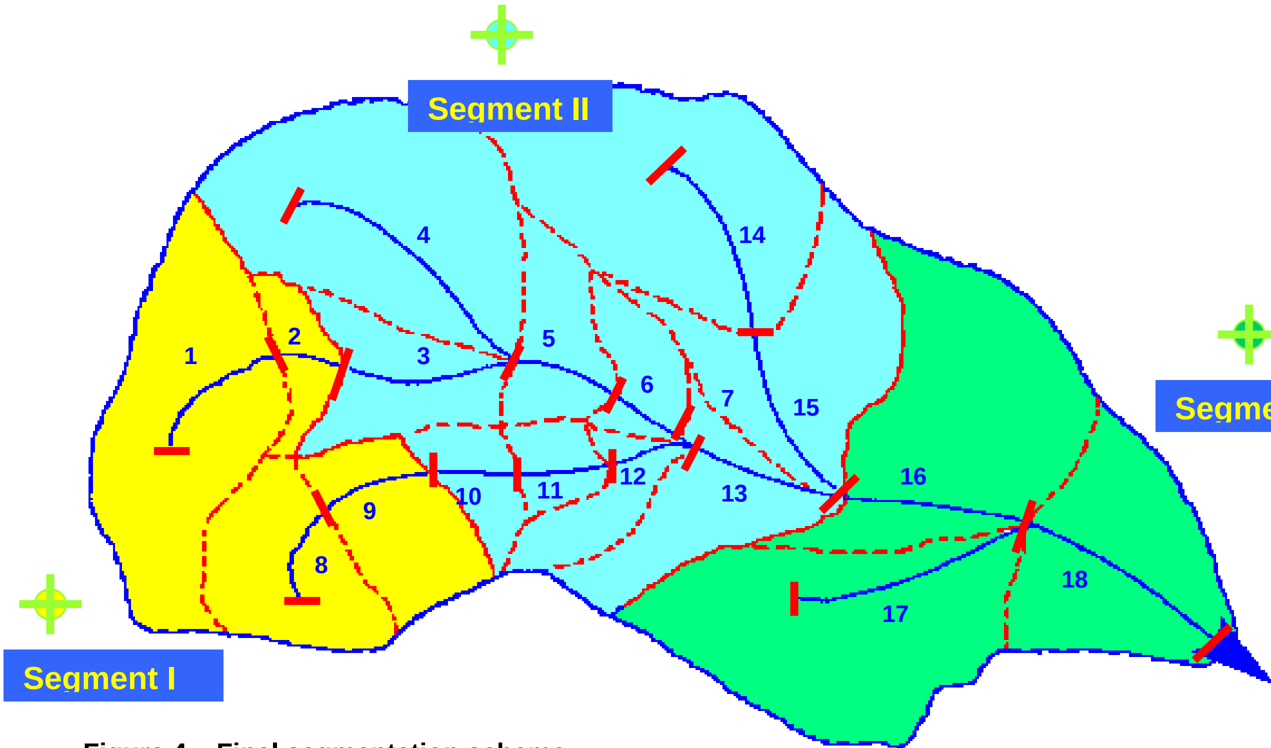


Figure 4 – Final segmentation scheme

Table 2 – Watershed segmentation tools

TOOL	REQUIREMENTS	AVAILABLE FROM
CRWR-Prepro (ArcView 3.x) PrePro2002 (ArcView 8.x)	ArcView 3.x or 8.x and Spatial Analyst	http://www.ce.utexas.edu/prof/olivera/prepro/prepro.htm http://ceprofs.tamu.edu/folivera/GISTools/PrePro2002/register_PrePro.htm
AvSwat2000	ArcView 3.1,3.2, or 3.3 and Spatial Analyst	http://www.brc.tamus.edu/swat/avswat/
BASINS Delineation Tools	ArcView 3.1,3.2, or 3.3 and Spatial Analyst for automatic delineation	http://www.epa.gov/waterscience/basins/

CHARACTERIZATION

At this point, only the connectivity of the reach network and the overall land area draining to each reach has been established for our generic watershed. Additional work is required to define the composition and the connectivity of the hydrologic elements that drain to each reach and establish the hydraulic properties of the reaches. This process is referred to as 'characterization'.

The reach characterization depends highly on the model used and its purpose. A watershed model such as HSPF requires at a minimum information describing the length and elevation drop between reach endpoints, a representative cross-section, and channel / floodplain characteristics (Manning's n) for each element. Most delineation tools will develop a reach coverage along with the individual reach lengths as part of the delineation process. Within ArcView's Map Calculator, the reach lengths can be easily calculated if necessary by opening the reach coverage's attribute table, adding a new field to hold the length values, and using the command 'Shape.ReturnLength'. The elevation drop across the reaches can be determined using the DEM and reach endpoints. In ArcView, this can be accomplished using either the 'Identify' tool or 'ZonalStats' command with the points as the zone and the DEM's elevation as the value to summarize (ESRI, 1996). Digital elevation models, vegetation, and land use coverages are readily available for most watersheds to sufficiently describe the topography and roughness of the reach floodplains; however, additional data are typically collected to develop site specific coverages to describe the channel itself.

The land characterization is a function of the hydro-geologic properties and land use characteristics of the watershed as they relate to the intent of the model application. Referring back to our generic watershed, we have already accounted for variations in the external forcing functions by assigning three meteorological segments. This means that a minimum of three hydrologic elements must exist to provide a unit response, or local drainage, to the 18 reaches. Since the variation in soils could be approximately isolated within the meteorological segments, no additional elements are needed to uniquely parameterize the elements with different soil properties. However, numerous other physical and anthropogenic characteristics might exist in the watershed that require additional elements to be defined. For example, it might be necessary to develop elements that describe the unit response of different combinations of vegetation and slope that occur in our watershed in order to make informed management decisions. Using the DEM and a vegetation coverage, the following steps could be used to develop the required hydrologic element categories and determine the respective areas draining to the 18 reaches.

1. Create a slope coverage from the DEM
2. Reclassify the slope grid into an integer grid with steep, moderate, and low slope categories (represented as values 1, 2, and 3, respectively) based on user specified ranges
3. If the vegetation coverage is a polygon coverage, convert to an integer grid with the same resolution as the reclassified slope grid
4. Reclassify the vegetation grid into groups with similar properties that can be parameterized with a common set of parameters (e.g., group deciduous trees, coniferous trees, brush, and grass into 4 groups represented as values 1-4)
5. Multiply the reclassified slope grid by 10 and add it to the reclassified vegetation grid

This process will result in a grid with 12 unique values being possible, representing the combinations of slope and vegetation that might exist in our watershed (see Figure 5). Using the hydrologic element grid and the previously developed

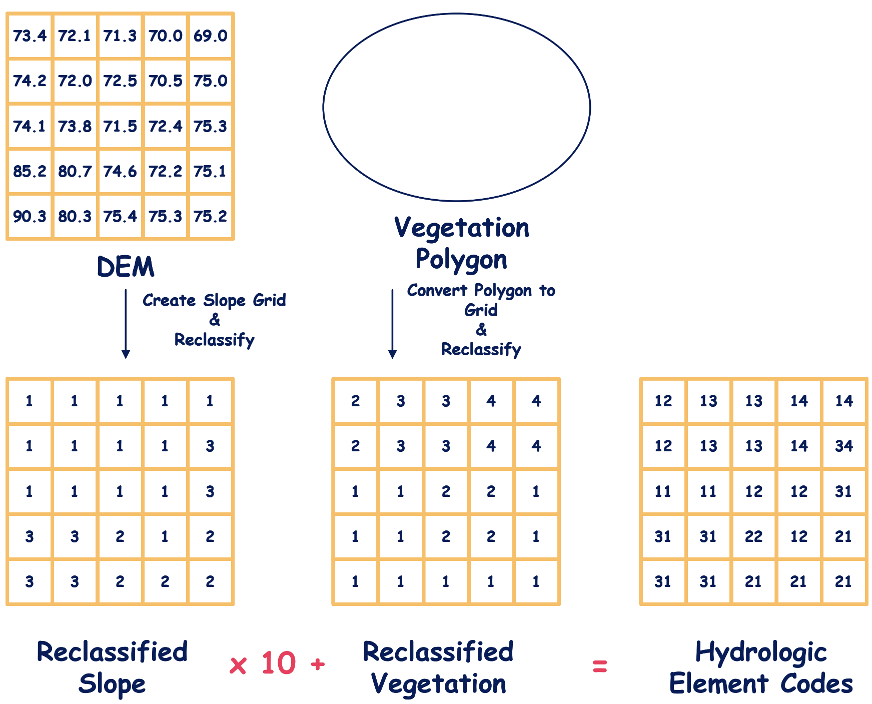


Figure 5 – Creating the hydrologic elements

reach drainage coverage, the area of each of the possible 12 hydrologic elements can be tabulated on a reach-by-reach basis. In ArcView, this is easily accomplished using the ‘Tabulate Area’ command with the reach drainage polygon coverage specified as the ‘zone’ and the slope-vegetation grid as the ‘value’ to tabulate. Since three meteorological segment boundaries exist (i.e., three sets of forcing functions), there are actually 36 possible hydrologic elements providing a unit response and draining to the 18 reach elements. When simulating water quality constituents, it would also be necessary for the elements to represent the variability of land use within the watershed, as groups with the same vegetation, soil, and slopes can have a different water quality response based on the land use type and therefore require different parameterization.

In contrast to reclassifying or grouping categories to reduce model complexity, it is often necessary to increase the number of categories by splitting existing ones. For example, detailed watershed models are required to represent the hydrologic processes occurring within pervious and effectively impervious areas (EIA), yet most coverages used in watershed modeling do not directly contain this type of information. This requires modelers to first develop the hydrologic element categories within a GIS, tabulate the area of each category draining to a reach on a reach-by reach basis, develop estimates of the fraction of EIA within each hydrologic category, and finally revise the GIS areas to create the additional elements based on the assumed fractions. This type of work can be effectively accomplished within a database via a ‘look-up table’ or using matrix algebra. Figure 6 provides an example of using matrix algebra to convert the areas of two types of hydrologic categories represented within the GIS (i.e., GIS codes 11 & 12), which drain to four reaches, into areas of three hydrologic categories that will be used in the watershed model (one of which is EIA) based on assumed fractions. The ‘Fractions’ matrix is first transposed so the column dimension of ‘GIS Areas’ equals the row dimension of ‘Fractions’ (requirement for matrix multiplication) and then the matrices are multiplied. In this particular example, the areas from the GIS codes are also split between multiple pervious categories. In order not to create or destroy area, the fractions must sum to 1.0 for each GIS code.

GIS Areas

	GIS Codes		Total
Reach	**11**	**12**	
1	20	5	25
2	0	5	5
3	5	0	5
4	4	0	4
Total	29	10	39

Fractions

	GIS Codes	
Hydrologic Element	**11**	**12**
Evergreen Forest	0.45	0.05
Pasture\Grass	0.50	0.80
Effectively Imperv.	0.05	0.15
Total	1	1

Model Input Areas

	Hydrologic Element			
Reach	Evergreen Forest	Pasture\Grass	Effectively Imperv.	Total
1	9.25	14.00	1.75	25.00
2	0.25	4.00	0.75	5.00
3	2.25	2.50	0.25	5.00
4	1.80	2.00	0.20	4.00
Total	13.55	22.50	2.95	39.00

GIS Areas **X** transpose(Fractions) **=** Model Input Areas

Figure 6 – Postprocessing GIS tabulated areas

Ultimately, the composition of the elements depends solely on: 1) the objective of the model; 2) the available data and associated accuracy; 3) the ability of the user to parameterize the element; and 4) the model’s ability to represent the intended response of the element. These four points provide the framework for building a useful model that is not overly complex and does not overstate its predictive power.

CONCLUSION

Establishing the composition, connectivity, and attributes describing the elements within a watershed is well suited to a GIS environment and is often referred to as ‘segmentation’ and ‘characterization’. The process has become a common and necessary practice in watershed modeling and the data to support the practice continues to increase in volume and quality. Many of the tools currently available to assist in the process by necessity enforce certain rules and data structures that often inhibit creativity or needed functionality and do little to assist the user in the rationale behind the process. Often a combination of tools and techniques allow the most representative and predictive model to be developed.

This paper has tried to enhance the readers understanding of the rationale behind ‘segmentation’ and ‘characterization’ and some of the tools and methods available to develop model input for a lumped parameter watershed model.

REFERENCES

AQUA TERRA Consultants. 2000. BASINS Workshop Lecture 13 – Segmentation, CD-ROM Developed for EPA.

Bicknell, B.R., J.C. Imhoff, J.L. Kittle Jr., A.S. Donigian, Jr., T.H. Jobes, and R.C. Johanson. 2001. Hydrological Simulation Program - FORTRAN, User's Manual for Version 12. U.S. EPA, National Exposure Research Laboratory, Athens, GA.

Environmental Systems Research Institute (ESRI). 1996. ArcView GIS: Using ArcView GIS, Environmental Systems Research Institute, Inc., Redlands, CA.