MPC-481
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Project Title:
Incorporating River Network Structure for Improved Hydrologic Design of Transportation Infrastructure

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Colorado State University

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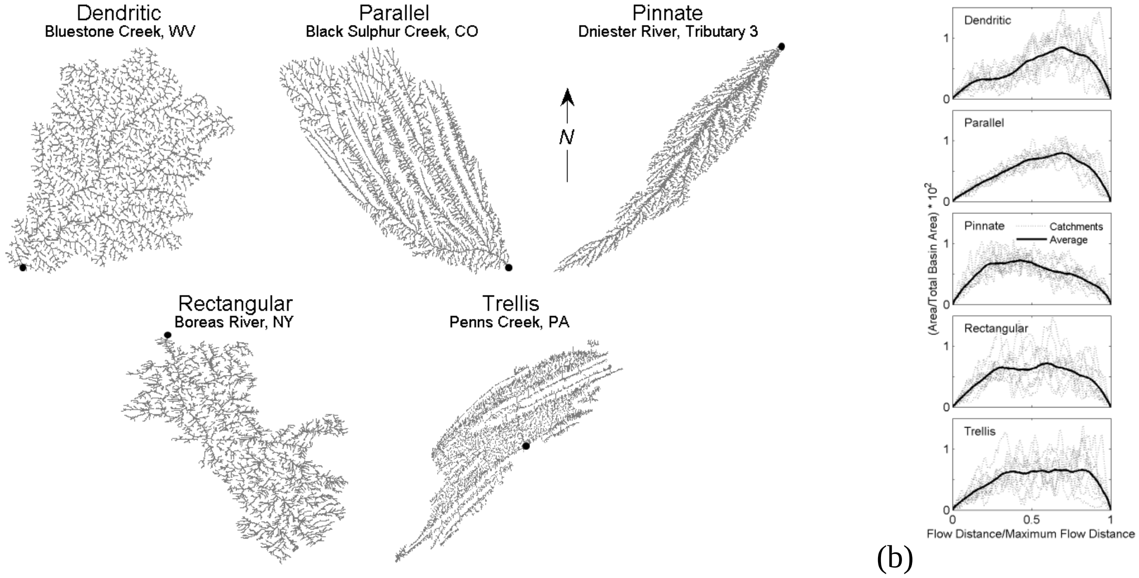
Research Needs:

Sustainable construction and maintenance of transportation infrastructure requires accurate hydrologic design. A critical element of the hydrologic design is the estimation of the flow rates that bridges and culverts must convey and their abutments must withstand. It is difficult to determine reliable design flows because most channels are ungauged. Furthermore, urbanization and climate change are altering basins and introducing additional uncertainty.

For ungauged basins, storm flows are most commonly estimated using synthetic unit hydrograph (UH) methods. Synthetic UHs are closely related to the travel time distribution for runoff that is produced throughout the basin to the outlet, and they are commonly estimated from the physical characteristics of the basin. Using an assumption that the storm flows are linearly related to the excess rainfall amounts, the synthetic UH can be used to determine the flow rates that are produced by any selected storm.

Several methods are available in software such as HEC-HMS to estimate synthetic UHs. For example, the Soil Conservation Service (SCS) method in HEC-HMS is based on a single dimensionless UH that is assumed to apply in all cases. To develop the synthetic UH for a given basin, the dimensionless UH is simply rescaled using values for the time to peak and the peak UH value. Those two values can be calculated from the basin area, length, slope, and curve number. Similarly, the Clark method in HEC-HMS is based on a single time-area curve that describes the distribution of travel times to the outlet. The time coordinates are multiplied by the time of concentration, which is estimated in a similar manner as the time to peak in the SCS method. The resulting UH is then routed through a linear reservoir to determine the final synthetic UH.

The use of synthetic UHs has two recognized limitations. First, the approach assumes linearity between the excess rainfall amounts and storm flows at the basin outlet. However, it is well-known that higher volumes of flow tend to move faster. That behavior violates linearity and can increase the magnitude of the peak flow and potentially affect the suitability of a bridge or culvert design. Second, these synthetic UHs do not account for differences in the channel network structure. Channel networks are known to exhibit distinct structures (such as dendritic, parallel, pinnate, rectangular, or trellis) depending on the conditions under which they developed (Figure 1a). Such diverse networks are abundant in the mountains-plains region, and they convey flow to their outlets using very different flow-path distributions (Figure 1b).



(a) (b)

Figure 1. *(a) Examples of five different channel network types (dots indicate basin outlets), and (b) the distributions of flow-path lengths for the same channel network types.*

Some synthetic UH methods have been proposed to allow consideration of basin shape. For example, the modified Clark method (Kull and Feldman, 1998) replaces the standardized time-area curve with one that is derived for the basin of interest. The geomorphic instantaneous unit hydrograph (Rodríguez-Iturbe and Valdés, 1979) describes the channel network using locally-derived Horton's ratios. Although these methods include the actual basin shape, they still rely on the linearity assumption. Other methods have been proposed to relax the linearity assumption, but they do not consider the channel network type.

Research Objectives:

This project has three primary goals:

1. Implement an alternative to the synthetic UH approach that allows nonlinearity and considers different network structures,
2. Identify conditions where nonlinearity affects the peaks flows,
3. Determine whether the network type provides sufficient information to determine the distribution of travel times.

Research Methods:

The proposed approach is based on flood-wave travel times that are derived from kinematic wave theory (Wong, 2003). A digital elevation model (DEM) will be used to determine the basin topography and channel network. Each grid cell will be identified as either a hillslope or channel cell based on its drainage area and topographic curvature. The total travel time from each grid cell to the outlet will be calculated by summing the travel times in each cell along the path to the outlet. The travel time in each cell will be determined from Wong (2003). Because the travel time expressions depend on the excess rainfall, the calculated UH will vary in time and higher flow rates will have faster travel times. The storm flow hydrograph will be determined by convolving the time-varying UHs with their associated excess rainfall amounts. This spatially distributed travel time (SDTT) method has already been implemented for urban basins and provides reliable results (Gironás et al., 2009). It is comparable to the Modified Clark method, but it includes nonlinearity.

In this project, the SDTT method will be modified to produce a statistical travel time (STT) method. All spatially-variable basin properties will be inferred using models that do not require a gridded representation of the basin in the hydrologic model. For example, the slope in a grid cell will be estimated from its drainage area using the well-known slope-area relationship. After these substitutions, the travel time at time *i* from cell *j* to the outlet ($T_{i,j}$) can be written as:

$$T_{i,\mathrm{j}} = E_i^{-0.4}\left[m_h A_{sh,j} + m_c A_{sc,j}\right]$$

where E_i is the excess rainfall at time *i*, m_h and m_c are constants that collect the specified hillslope and channel characteristics, respectively, and A_{sh} and A_{sc} are functions that depend only on the drainage network structure. In the STT method, A_{sh} and A_{sc} will be treated as random variables and their distributions will be determined. Once those distributions are known, then the distribution of travel times can be found. This model is comparable to the Clark method, but it includes nonlinearity and differences in network type (through the distributions of A_{sh} and A_{sc}).

The SDTT and STT methods will be evaluated using an available dataset that includes ten basins from each of the five network classifications. The classifications have been previously determined using an objective method (Mejía and Niemann, 2008) and the hillslope and channel cells have already been identified.

Expected Outcomes:

This project will produce a new method to estimate flow rates for the hydrologic design of transportation and other infrastructure that overcomes two key limitations of existing methods. The STT method is simple enough to be implemented in a spreadsheet by practicing engineers and could be implemented in modeling software such as HEC-HMS because it does not require hydrologic computations on a grid. The results of this project will be submitted for publication in a high-quality, peer-reviewed journal.

Relevance to Strategic Goals:

This project is highly relevant to the goal of a "state of good repair." Well-maintained infrastructure requires that the infrastructure was appropriately designed before it was constructed. In addition, replacement of obsolete infrastructure requires identification of structures that no longer meet their intended objectives. Accurate hydrologic design and analysis plays a key role in such tasks. The proposed project is a vital step toward improving hydrologic design by better accounting for landscape characteristics, and it is particular relevant due to the diversity of landscapes that occur in the mountains-plains region.

Educational Benefits:

All requested funding will be used to support (stipend and tuition) a masters-level student who will work on the project. The project will provide the central thrust for the student's thesis.

Work Plan:

This project will support the second year of a two year effort (year 1 is presently supported by USAID). The primary tasks for the proposed project are as follows:

- Task 1: Implement the STT method with the A_{sh} and A_{sc} distributions from individual basins and compare to the SDTT method. This comparison will evaluate the assumptions used to derive the STT method.
- Task 2: Implement the STT method using the average distributions of A_{sh} and A_{sc} for each channel network type and compare to the SDTT method.
- Task 3: Implement the STT method using average distributions of A_{sh} and A_{sc} that neglect the channel network type and compare to the SDTT method. Together with Task 2, this comparison will evaluate the value of using the network classification to infer the distribution of travel times.
- Task 4: Compare the SDTT method to the Modified Clark method. This comparison will evaluate the importance of including nonlinearity when estimating the storm flows.
- Task 5: Write a journal publication to document results.

The expected schedule is given below:

	Months								
Task	1	2	3	4	5	6	7	8	9
1	■	■	■	■					
2			■	■	■				
3			■	■	■	■			
4					■	■	■	■	
5							■	■	■

Project Cost:
Total Project Costs: $59,160
MPC Funds Requested: $29,000
Matching Funds: $30,160

Source of Matching Funds:

- Colorado State University: Salary support for principal investigator plus fringe and indirect costs ($30,160)

TRB Keywords:
Bridges, culverts, hydrology, hydrographs, prediction, flow rates, modeling, basins

References:

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