MPC-537
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Project Title:
Quantifying Mountain Basin Runoff Mechanisms for Better Hydrologic Design of Bridges and Culverts

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Research Needs:
Sustainable construction and maintenance of surface transportation systems requires accurate hydrologic design. A critical element of hydrologic design is the estimation of flood discharges that bridges and culverts must convey and their abutments must withstand. Such flows are produced by the combination of rainfall with a prescribed frequency of occurrence and the conversion of the rainfall into runoff and, ultimately, streamflow. In some cases, the streamflow can be estimated using statistical methods, but for many ungauged basins, the flows are estimated by rainfall-runoff modeling. An important and long-standing problem for the Rocky Mountain Region is that traditional rainfall-runoff modeling methods appear to significantly overestimate major floods based on comparisons to paleoflood evidence and regional peak streamflow statistics. The Colorado Water Conservation Board (CWCB), Colorado Division of Water Resources (DWR), and State of New Mexico are currently conducting a $1.5 million study to develop improved estimates of extreme rainfall for the two state region. DWR has also been working to improve flood hydrology methods for the Rocky Mountain region. Solving this problem will align with these ongoing efforts and allow higher confidence in bridge and culvert design, more efficient allocation of transportation repair and replacement funds, and the possibility of streamlined design guidelines.

Traditional flood hydrology methods utilize low infiltration rates to model flood runoff solely by an infiltration-excess mechanism. By this mechanism, runoff occurs when the rainfall intensity exceeds the infiltration capacity of the soil. However, forested basins typically have soils with high infiltration capacities that produce little infiltration-excess runoff (Dunne and Leopold, 1978; MacDonald and Stednick, 2003). Furthermore, the bedrock geology of many mountain basins leads to coarse soils with high infiltration rates. Recent advances by DWR indicate that flood runoff in mountain basins might be controlled by a saturation-excess mechanism (DWR, 2014 and 2015). Saturation-excess runoff can occur when a relatively shallow soil is underlain by a layer with much lower permeability (usually bedrock), which is a relatively common situation in Rocky Mountain basins. Rainfall rates that are less than the infiltration capacity can still produce runoff if the storm continues long enough to saturate the thin soil layer. Such low-intensity events are expected to be more important at higher elevations where strong convective storms are less common (Grimm et al., 1995). A recent but preliminary examination of the Gross Reservoir basin (South Boulder Creek) that was performed by Colorado Dam Safety suggests that saturation-excess runoff might be important for extreme precipitation events (Perry and Franz, 2017). For the September 2013 storm that produced widespread flooding along the Colorado Front Range, the rainfall rate in the Gross Reservoir basin never exceeded 1.2 in/hr, but the storm continued for about 6 days. During that period, two peaks in rainfall intensity occurred approximately one day apart. Although the first peak had a higher rainfall intensity, the second peak produced much more runoff (Fig. 1). This behavior is not consistent with infiltration-excess runoff, which would produce higher runoff rates for higher rainfall rates, but it is consistent with saturation-excess runoff, which depends more on the accumulated depth of rainfall.

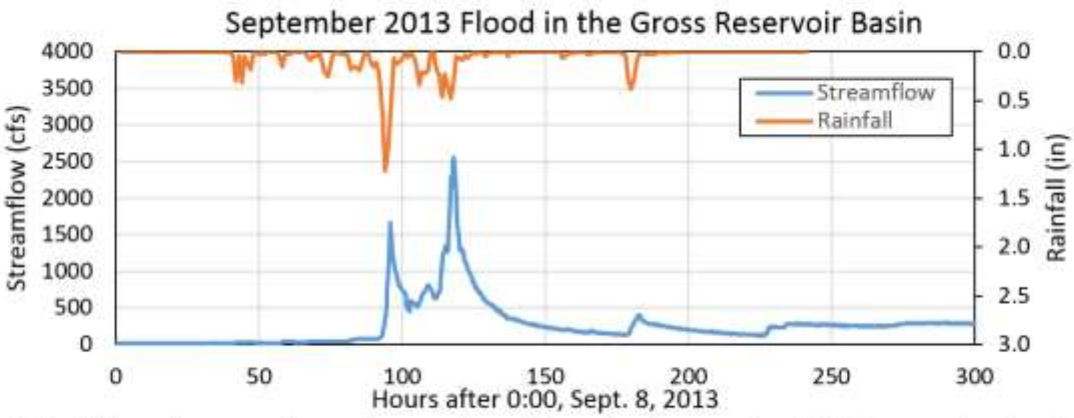

Figure 1. Rainfall and streamflow observations from the September 2013 storm in the Gross Reservoir basin (South Boulder Creek).

Similarly, a study sponsored by the Colorado Department of Transportation (CDOT) calibrated a rainfall-runoff model to 10-day September 2013 flows in the upper Big Thompson River basin and then used frequency rainfall estimates in the model to estimate frequency flows for bridge and culvert design. Their calibration efforts indicate high rainfall losses and almost no runoff until 5 days into the 10-day period, followed by a sudden change to minimal losses and high runoff (Jacobs, Inc., 2014). Although a physical explanation was not provided, these results are consistent with saturation-excess runoff.

Finally, both the Colorado Dam Safety and CDOT studies had difficulty reproducing the observed hydrograph recessions for historic long-duration events in mountain basins. This problem appears to be associated with lateral subsurface flow (i.e. interflow) and may be consistent with a saturation-excess model where high volumes of water are temporarily stored in relatively coarse-grained shallow soils.

Research Objectives:

1. To determine the importance of saturation-excess runoff production for large storms that affect the design and performance of key surface transportation infrastructure

2. To develop a generalized model for runoff production in mountainous basins that can be used by consultants to perform hydrologic analysis of transportation infrastructure

The objectives of this MPC research project are: (1) to determine the importance of saturation-excess runoff production for large storms that affect the design and performance of key surface transportation infrastructure and (2) to develop a generalized model for runoff production in mountainous basins that can be used by consultants to perform hydrologic analysis of transportation infrastructure. This project would allow expansion of a one-year research project that was recently awarded by CWCB to the PI and collaborators in Colorado Dam Safety into a two-year effort.

To achieve the project goals, a physically-based model that allows production of both infiltration-excess and saturation-excess runoff will be implemented and used to examine the mechanisms that have been active for three large historical rainfall events that occurred in the Colorado Front Range. Future phases of this research will consider mountain basins outside of the Front Range. The model used in this study must fulfill several key requirements. First, it must be physically-based to maximize the reliability of its results. Second, it must simulate both infiltration-excess and saturation-excess runoff so the appropriate runoff production mechanism(s) can be identified and simulated. Third, the model must not require calibration because most basins above bridges and culverts are ungauged. Fourth, it must be implemented in a simple and low-cost framework and utilize existing Natural Resources Conservation Services (NRCS) or United States Forest Service (USFS) soil survey data to allow possible future adoption by consultants who perform hydrologic analysis of transportation infrastructure.

Research Methods:
Widely-available hydrologic models such as the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) do not include an infiltration model that meets the project requirements. Thus, we anticipate implementing a Green and Ampt (GA) infiltration method in a spreadsheet environment that includes an impervious bedrock layer at a specified depth. The GA model is an approximation of Richard's Equation in which the wetting front in the soil is assumed to be abrupt. The GA method was first proposed by Green and Ampt (1911) and subsequently modified by Mein and Larson (1973). It was then extended to apply to temporally varying rainfall rates by Chu (1978). More recently, Liu et al. (2011) recommended several modifications to allow application of the GA model to soils that are underlain by an impermeable layer.

The GA model will be applied to three large historical storms that occurred at three basins in the Colorado Front Range. The selected basins will be at higher elevations where longer and lower intensity storms are more important. They will be located along the Front Range in part to make use of the data available from the September 2013 floods. By focusing on this region, the basins are also expected to have relatively similar bedrock geology (e.g., granite and granodiorite). The selected storms will have produced significant flooding and impacts to transportation infrastructure. Among the events and basins with adequate available data, the following are likely candidates for selection: the September 2013 storm for the Gross Reservoir basin, the May 1969 storm for the Little Thompson River basin, and the July 1976 storm for the North Fork of the Big Thompson River basin. For each case, the model will be applied in a semi-distributed fashion where the number of sub-basins is determined by the heterogeneity of the basin and storm characteristics. The GA model will also be coupled with flow accumulation and baseflow methods that allow the overall model to simulate the entire flood hydrograph. These modeling methods will also be chosen so they can be applied to ungauged basins. Specifically, the model inputs will be physical characteristics that can be estimated from available datasets and do not require calibration.

To evaluate the new GA approach, its runoff production will be compared to that of a full Richard's Equation model for a series of hypothetical storm events. Then, to determine whether saturation-excess runoff is occurring, the GA approach will be applied with and without the impermeable bedrock layer to the three historical events. When this layer is excluded, any runoff production must be produced by infiltration excess, which is consistent with the present practice. When the bedrock layer is included, runoff production can be produced by both infiltration-excess and saturation-excess runoff. The appropriate mechanism will be determined in part by comparing against the observed responses of the three basins. During the project, we will also interact with the U.S. Army Corps of Engineers to discuss a long-term plan for improving the infiltration models in HEC-HMS. The goal of this interaction is to provide a suitable infiltration model that can be easily used by consultants with existing datasets for hydrologic analysis of transportation projects.

Expected Outcomes:
A key product is the spreadsheet model that will implement the physically-based GA infiltration model and allow generation of both infiltration-excess and saturation-excess runoff. This model will also implement appropriate flow accumulation and baseflow methods to allow simulation of the entire flood hydrograph (including the recession limb). The model will be user friendly and readily applicable to a variety of basins. For example, Visual Basic macros and user-forms will be implemented to facilitate future modeling. Another key outcome is the documentation of the model and experimental results. The accuracy of this model will be documented by comparing its results to Richard's Equation for a diverse range of hypothetical conditions. The relative importance of infiltration-excess and saturation-excess runoff production will also be documented for the events considered. Finally, recommendations will be provided regarding: follow-up investigations to generalize the results, a plan for incorporating the improved model into HEC-HMS, and a strategy for possible automated acquisition of soil characteristics from existing NRCS and USFS soil surveys.

Relevance to Strategic Goals:

- State of Good Repair
- Safety

This project is most relevant to the United States Department of Transportation goal of a "state of good repair," and it also has relevance to the goals of "safety," "economic competitiveness," and "environmental sustainability." The project aims to improve the hydrologic analysis and design of surface transportation projects in mountainous regions by better quantifying the runoff production from storms. Maintaining transportation systems in a state of good repair requires proper hydrologic design of project components, and improved hydrologic design will help avoid early replacement if a project fails to meet its intended objectives. A state of good repair also requires efficient allocation of limited maintenance funds. Project prioritization relies on accurate assessments of whether projects are meeting their objectives (including protecting the public by safely conducting storm flows). Finally, maintaining a state of good repair requires transportation systems that are robust and resilient to natural disasters. Accurate hydrologic design and analysis helps protect surface transportation systems and avoid repeated and costly interruptions and repairs. The hydrologic methods developed in this project might also enhance flood warning capabilities, leading to improved safety.

Educational Benefits:
Nearly all direct costs for this project will be used to support a master's student. The funding will provide stipend, fringe benefits, and tuition for one year of study (support for the student's other year of study will be provided by matching funds from CWCB). The student will perform all the modeling described in this proposal under the supervision of the PI, and this project will provide the central thrust for the student's thesis. The project will also help prepare the student for future participation in the transportation workforce.

Tech Transfer:
The model developed in this project will be made available according to the MPC data management plan. It will also be provided to DWR for potential use by consultants in spillway design and other dam safety applications. In the long term, similar modeling approaches could be added to HEC-HMS, which would facilitate even broader use (the PI supervised development of a snowpack model that is currently being added to HEC-HMS). The results of the research will be presented at a professional conference and published in a high-quality peer-reviewed journal article. The supported student will also summarize the results in a master's thesis. A final report will also be provided to MPC, CWCB, and DWR.

Work Plan:
1. Model Construction
2. Model Evaluation
3. Data Compilation and Model Application
4. Evaluation of Runoff Production Mechanisms
5. Document Results

The primary tasks and expected timeline for the proposed project are as follows:

Task 1 – Model Construction. The spreadsheet model will be constructed to allow simulation of both infiltration-excess and saturation-excess runoff and simulation of complete hydrographs. The model will be readily applicable to a variety of basins and storms. (Months 1-5)

Task 2 – Model Evaluation. The model will be evaluated by comparing its infiltration results to those from Hydrus-1D or another model that uses Richard's Equation. (Months 5-10)

Task 3 – Data Compilation and Model Application. The required model inputs will be collected for the selected basins and storms, and the model will be applied to describe the runoff production and hydrograph generation for the storms. (Months 10-17)

Task 4 – Evaluation of Runoff Production Mechanisms. For each basin/storm, the model will be implemented when neglecting and including the bedrock layer. Comparison of these two cases to the observed discharges will allow assessment of the importance of saturation-excess runoff production. (Months 17-21)

Task 5 – Document Results. Present the results at a professional conference and write journal publication, thesis, and final report. (Months 21-24)

Project Cost:
Total Project Costs: $100,000
MPC Funds Requested: $50,000
Matching Funds: $50,000
Source of Matching Funds: "Mountain Basin Hydrologic Response Study," Colorado Water Conservation Board (CWCB), State of Colorado, $50,000. Project was approved at the 3/22/2017 CWCB meeting. Project duration is July 1, 2017 to June 30, 2018.

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