MPC-619
February 18, 2020

Project Title

Evaluating Nonlinear Methods for Flood Hydrograph Generation to Evaluate Bridge Scour

University

Colorado State University

Principal Investigators

Jeffrey D. Niemann
Faoro Professor of Water Resources
Colorado State University
Phone: (970) 491-3517
Email: jeffrey.niemann@colostate.edu
ORCID: 0000-0002-2988-0879

Research Needs

Sustainable construction and maintenance of roadways requires reliable hydraulic design. A critical element of hydraulic design is ensuring that bridge abutments and piers can withstand scour of the surrounding bed material. In fact, the most common cause of bridge failures is erosion around bridge foundations (Arneson et al. 2012). Scour occurs when the streamflow produces enough shear stress or stream power to mobilize the bed material. For non-cohesive bed material, scour can occur rapidly, and maximum scour depths can be reached during a single flood event. For cohesive bed material, scour often occurs much slower, so the cumulative contribution of multiple storm events must be considered (Arneson et al. 2012). Erosion of bed material depends nonlinearly on the streamflow rate, so using the average flow rate in calculations would not produce the same results as using the actual record of streamflow (Tucker and Bras 2000). Thus, proper calculation of scour rates requires accurate representation of streamflow variability both within and between flood events.

Most bridges are built at locations without stream gauges. Consequently, historical streamflow data are rarely available, and streamflow values must be inferred from nearby stream gages and/or the physical characteristics of the associated watershed. In some cases, stream flows are obtained by developing a storm with a prescribed return period, converting the storm's rainfall into excess rainfall (or runoff), and then determining the resulting flood hydrograph. In such cases, the Colorado Department of Transportation recommends the use of unit hydrograph (UH) theory (Mommandi et al. 2004). UH theory assumes that a linear relationship exists between the excess rainfall that occurs in the watershed and the resulting streamflow at the watershed outlet (Sherman 1932). Under this assumption, any pulse of excess rainfall can be transformed into a time-series of streamflow at the outlet using the basin's UH. The UH is typically synthesized from the characteristics of the watershed. Several methods are available to estimate the UH including the Soil Conservation Service method (SCS 1972; NRCS 2007), the Snyder method

(Snyder 1938; Aron and White 1982), and the Clark method (Clark 1945; Kull and Feldman 1998).

However, the linearity assumption that underlies UH theory is increasingly recognized by hydrologists as invalid. Amorocho (1963) conducted tests with a laboratory catchment and found that the observed hydrographs do not match those that would be generated from the linearity assumption. Specifically, later pulses generated more discharge than earlier pulses of the same size, which contradicts the assumption. Porporato and Ridolfi (2003) used nonlinear time series analysis with streamflow data from northern Italy. They found noticeable evidence of nonlinearity at high discharges, while linear dynamics dominated at low discharges. Woolridge (2019) examined the response of mountain basins in Colorado to large historical storm events (mainly the floods of 1976 and 2013). He found that the time of concentration decreased with increasing rainfall intensity in contrast to linear UH theory. In particular, the intense rainfall of the 1976 storm produced much quicker basin responses than the less intense rainfall of the 2013 storm.

Several sources of nonlinearity have been identified. One source is the occurrence of thresholds in streamflow generation mechanisms. For example, Tromp-van Meerveld and McDonnell (2006a) found that subsurface stormflow in an experimental watershed greatly increases when storm precipitation exceeds a threshold. This threshold occurs due to depressions in the bedrock surface that must be filled before subsurface stormflow can reach the stream (Tromp-van Meerveld and McDonnell 2006b). Another source of nonlinearity is temporal variability of flow speeds in the watershed. For larger events, flow depths throughout a watershed are greater, so a smaller portion of the flow is exposed to the frictional effects of the hillslope surface or channel bed. In addition, large floods can strip vegetation from floodplains, which reduces the surface roughness and associated friction of those surfaces (Arcement and Schneider 1989). Thus, average flow speeds are higher for larger events (Lee and Yen 1997). Furthermore, the drainage density (i.e. extent of channels in the watershed) has been shown to increase with storm size (Gregory and Walling 1968). Consequently, for larger events, a greater portion of the flow path to the outlet is channelized, and flow speeds are much greater in channels than on hillslopes (van der Tak and Bras 1990).

The nonlinear behavior of watersheds has important implications for bridge scour and other hydraulic evaluations of infrastructure. If nonlinearity is neglected, a watershed's response to small events cannot be used to infer its behavior for large events. For this reason, the Federal Energy Regulatory Commission cautions that small floods should not be used to determine the UH for the probable maximum flood (FERC, 2001). Assuming linearity can also result in underestimation of the peak flows for large flood events. For example, as flow speeds increase throughout a watershed, the base time of the flood hydrograph decreases, which results in higher peak flows (Lee and Yen 1997). This behavior is not captured by linear UH theory.

Two general approaches have been proposed to overcome the linearity assumption of UH theory. One approach replaces the UH with a functional series or other nonlinear estimation technique. In this approach, the response to a given excess rainfall pulse can depend on every preceding excess rainfall pulse (Amorocho, 1963; Liu and Brutsaert, 1978; Muftuoglu 1984; Muftuoglu, 1991; Kashani et al. 2014). The second approach replaces the UH with a kernel function that varies in time (often called a time-varying UH). Ding (1974) generalized the traditional

Muskingum routing method to derive a UH that depends on the excess rainfall intensity and thus varies in time. A higher intensity results in a UH with a shorter base time and higher peak. Chen and Singh (1986) used a similar approach, and the resulting instantaneous UH (or IUH) is the weighted sum of Ding's (1974) nonlinear and Nash's (1957) linear IUH. Rodriguez-Iturbe et al. (1982) combined an IUH that describes the basin structure using Horton's (1945) ratios with climatic effects, and the resulting IUH depends on the excess rainfall properties. Gironás et al. (2009) replaced the Horton Ratio approach with a channel network inferred from a digital elevation model (DEM) (following Muzik 1996) and calculated the travel times using a kinematic wave approach (following Lee and Yen 1997). The resulting IUH depends on the excess rainfall rate and thus varies in time. Time-varying UHs have received more attention than functional series in the scientific literature because they are simpler and more directly linked with the physical characteristics of the watershed. However, they have not been commonly used in engineering practice because available modeling software has not included this capability until very recently.

In 2018, the Hydrologic Engineering Center (HEC) included a time-varying UH method in its Hydrologic Modeling System (HMS) Version 4.3 (HEC 2018). This approach is a generalization of Clark's (1945) UH method. That traditional method includes two components. The first component is a UH that describes the translation of runoff to the watershed outlet (and relies on the linearity assumption). The second component is a linear reservoir that represents the effects of storage in the watershed. To apply the traditional method, the user needs to specify a time of concentration T_c, which is used to determine the UH, and a time constant R, which controls the linear reservoir. In the new HEC-HMS method, the user can specify functions that describe how T_c and R vary with excess rainfall intensity. This methodology is qualitatively similar to the time-varying UH methods in the literature (e.g., Gironás et al. 2009), but it is much more flexible. Little technical guidance is provided by HEC regarding this method (see HEC 2018 and references therein). Thus, three key questions must be resolved before the method can be used in practice. First, how should the T_c and R functions be specified? Second, does the HEC-HMS model successfully reproduce the observed nonlinearity in basin response? Third, how different are the nonlinear and linear UH results for conditions that are relevant to scour calculations and other hydraulic design applications?

Research Objectives

The overall goal of this project is to develop guidelines for using the HEC-HMS nonlinear UH framework in hydraulic design applications including evaluations of bridge scour. This overall goal includes the following specific objectives:

1. Develop recommendations for specifying the time of concentration and reservoir time constant functions.
2. Evaluate the performance of the nonlinear UH approach in reproducing observed hydrographs for large flood events (i.e. events that are relevant for hydraulic design).
3. Assess the importance of including nonlinearity when using UH methods for infrastructure evaluations including bridge scour.

Research Methods

The general approach to meet these objectives will begin by deriving theoretical equations that determine T_c and R as a function of the excess rainfall rate. These functions will be developed based on kinematic wave theory. Kinematic wave is an approximation of the Saint-Venant flow equations that neglects local and advective accelerations as well as the effects of pressure forces (Chow et al. 1988). The kinematic wave approximation has been shown to be reliable for many practical circumstances (not very flat and/or deep channels) (Chow et al. 1988). An expression is already available that determines T_c as a function of the excess rainfall for a channel with constant width and slope and flow entering from upstream (Wong 2001; Gironás et al. 2009), and a similar expression is available for a hillslope with constant width and slope and flow entering from upslope (Wong 1995; Gironás et al. 2009). A watershed includes both hillslopes and channels. In addition, the channel width and slope vary with upstream area in the watershed. An overall expression for T_c of the watershed will be derived by describing the longest flow path in the watershed as a series of hillslope and channel segments, using the two existing expressions for the appropriate segments, and applying empirical relationships that estimate the channel width (Livers and Wohl 2015) and slope (Tarboton et al. 1989) as a function of the upstream area. A similar relationship between R and excess rainfall rate will be developed using research that has shown that the $T_c/(T_c + R)$ remains relatively constant within a region and regression results that describe the dependence of this ratio on watershed characteristics (Sabol 2008; Wilkerson and Merwade 2010).

The derived T_c and R functions will then be applied to four watersheds in the Colorado Front Range: Cheyenne Creek above Colorado Springs (56 km^2), Big Thompson River above Lake Estes (357 km^2), North Fork of the Big Thompson River above Drake (220 km^2), and South Boulder Creek above Eldorado Springs (278 km^2). These watersheds were selected because they have shown indications of nonlinear response in previous research (Woolridge 2019), they are located within United States Department of Transportation (USDOT) Region 8, and they are of interest to the Colorado Water Conservation Board (CWCB), who will provide most of the cost-share for the proposed project. For each basin, the T_c and R values from the derived relationships will be compared to T_c and R values from an explicit calculation of travel times from a DEM for bank-full conditions (Woolridge 2019). They will also be compared to T_c and R values that are calibrated to reproduce the observed hydrographs for large historical floods. Based on data availability, the 1976 flood (McCain et al. 1979) will be considered for the North Fork of the Big Thompson River, and the 2013 flood (Gochis et al. 2015) will be considered for the remaining basins.

The importance of considering nonlinearity in the UH method will be evaluated by comparing two versions of the HEC-HMS model for each basin: (1) using the derived T_c and R functions (nonlinear method) and (2) using constant T_c and R values that are estimated from explicit consideration of travel times (linear method) (Woolridge 2019). These two approaches will be compared for the historical storms. The difference in their ability to reproduce the observed hydrographs will give one measure of the importance of considering nonlinearity. The two approaches will also be compared for annual exceedance probability and probable maximum precipitation design storms. The difference in the estimated peak flows will provide another measure of the importance of considering nonlinearity. Finally, the predicted flow rates from the two approaches will be used in the HEC River Analysis System (HEC-RAS) for a series of hypothetical scenarios to determine circumstances where nonlinearity significantly affects bridge scour evaluations.

Expected Outcomes

The key products from this project will be: (1) a set of guidelines for application of the HEC-HMS nonlinear UH method, (2) empirical testing that demonstrates the validity of the guidelines, and (3) identification of conditions where nonlinearity plays an important role in bridge scour applications. These products are expected to help overcome key limitations that result from using linear UH methodologies. They will help practitioners better predict the response of a basin to a large event based on its responses to smaller events. Such understanding could improve data availability by increasing the number of relevant historical storm events. In addition, these products will improve estimates of streamflow distributions that infrastructure components might encounter during their design life. These products could eventually be incorporated into future hydrologic guidelines for evaluating transportation infrastructure or even dam safety.

Relevance to Strategic Goals

This project has strong relevance to the USDOT goal of a "state of good repair," and it also has relevance to the goal of "safety." The project aims to improve the hydrologic analysis and design of surface transportation projects, particularly bridge scour, by improving the estimation of flood hydrographs. 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 properly managing scour). 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 helps 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 to MPC will be used to support a master's student. The funding will provide stipend, fringe benefits, and tuition for about one year of study (it is expected that support for the student's other year of study will be provided by a graduate teaching assistantship). 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.

Technology Transfer

The models and data developed in this project will be made available according to the MPC data management plan. They will also be provided to CWCB and Colorado Dam Safety (who is a collaborator on the CWCB project) for potential use by consultants in spillway design and other dam safety applications. The results of the research will be presented at a professional conference and published in a peer-reviewed journal article. The supported student will also summarize the results in a master's thesis, and a final report will be provided to MPC, CWCB, and Colorado Dam Safety.

Work Plan

The project work plan includes the following major tasks:

1. Develop robust HEC-HMS models for the Cheyenne Creek, Big Thompson River, North Fork of the Big Thompson River, and South Boulder Creek watersheds.
2. Derive expressions to determine T_c and R as a function of excess rainfall rate.
3. Implement the T_c and R expressions for the modeled basins and compare to independent estimates for bank-full conditions and calibrated values for historical storms.
4. Compare the nonlinear and linear UH method results for the historical storms as well as annual exceedance probability and probable maximum precipitation design storms.
5. Evaluate the implications of nonlinearity for bridge scour applications in HEC-RAS.
6. Document the results in a conference presentation, peer-reviewed journal article, thesis, and final report.

Task 1 will be performed under the CWCB project that is providing most of the cost-share. Preliminary versions of the HEC-HMS models currently exist, but the model structures and parameterizations need to be finalized for use in the proposed project. Task 1 will be completed 12 months after the project start date. In Task 2, the required expressions will be derived by the PI in collaboration with the graduate student who will be supported by the MPC project. The involvement of the PI will be supported by the academic year salary that is part of the cost-share. This task will be completed about 14 months after the project start. Task 3 will be performed by the MPC-supported graduate student and will be completed about 16 months after the project start. Task 4 will be performed by the same graduate student under the PI's guidance and will be completed in about 18 months. Task 5 will be performed by the graduate student under the PI's guidance and will be completed in about 20 months. Task 6 will be completed 24 months after the project start.

Project Cost

Total Project Costs:	$118,900
MPC Funds Requested:	$ 60,900
Matching Funds:	$ 58,000
Source of Matching Funds:	Colorado Water Conservation Board, $40,000
	Colorado State University, $18,000

References

Amorocho, J. (1963) Measures of Linearity of Hydrologic Systems. *Journal of Geophysical Research*, 68(8), 2237-2249.

Arcement, G.J., Jr. and Schneider, V.R. (1989) Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains. United States Geological Survey Water-Supply Paper 2339.

Arneson, L.A., Zevenbergen, L.W., Lagasse, P.F., and Clopper, P.E. (2012) Evaluating Scour at Bridges, Fifth Edition, Hydraulic Engineering Circular No. 18, Federal Highway Administration, U.S. Department of Transportation.

Aron, G. and White, E.L. (1982) Fitting a Gamma Distribution over a Synthetic Unit Hydrograph. *Water Resources Bulletin*, 18(1), 95-98.

Chen, S.J., and Singh, V.P. (1986) Derivation of a New Variable Instantaneous Unit Hydrograph. *Journal of Hydrology*, 88, 25-42.

Chow, V.T., Maidment, D.R., and Mays, L.W. (1988) Applied Hydrology, McGraw Hill, New York.

Clark, C.O. (1945) Storage and the Unit Hydrograph. *Proceedings of the American Society of Civil Engineers*, 69, 1333–1360.

FERC (2001) Chapter VIII Determination of the Probable Maximum Flood, Engineering Guidelines for the Evaluation of Hydropower Projects, Federal Energy Regulatory Commission.

Gironás, J., Niemann, J.D., Roesner, L.A., Rodriguez, F., and Andrieu, H. (2009) A Morpho-Climatic Instantaneous Unit Hydrograph Model for Urban Catchments Calculated from Digital Elevation Models. *Journal of Hydrology*, 377, 317-334, doi: 10.1016/j.jhydrol.2009.08.030.

Gochis, D., Schumacher, R., Friedrich, K., Doesken, N., Kelsch, M., Sun, J., Ikeda, K., Lindsey, D., Wood, A., Dolan, B., Matrosov, S., Newman, A., Mahoney, K., Rutledge, S., Johnson, R., Kucera, P., Kennedy, P., Sempere-Torres, D., Steiner, M., Roberts, R., Wilson, J., Yu, W., Chandrasekar, V., Rasmussen, R., Anderson, A., and Brown, B. (2015) The Great Colorado Flood of September 2013. *Bulletin of the American Meteorological Society*, 96(9), 1461–1487.

Gregory, K.J., and Walling, D.E. (1968) The Variation of Drainage Density Within a Catchment. *Bulletin of the International Association of Scientific Hydrology*, 13(2), 61-68.

HEC (2018) Hydrologic Modeling System HEC-HMS Release Notes Version 4.3, Hydrologic Engineering Center, U.S. Army Corps of Engineers.

Horton, R.E. (1945) Erosional Development of Streams and Their Drainage Basins: Hydrophysical Approach to Quantitative Morphology. *Geological Society of America Bulletin*, 56, 275-370.

Kashani, M.H., Ghorbani, M.A., Dinpashoh, Y. (2014) Comparison of Volterra Model and Artificial Neural Networks for Rainfall-Runoff Simulation. *Natural Resources Research*, 23(3), 341-354. doi:10.1007/s11053-014-9235-y

Kull, D.W., and Feldman, A.D. (1998) Evolution of Clark's Unit Graph Method to Spatially Distributed Runoff. *Journal of Hydrologic Engineering*, 3, 9–19. doi:10.1061/(ASCE)1084-0699(1998)3:1(9)

Lee, K.T., Yen, B.C. (1997) Geomorphology and Kinematic-Wave-Based Hydrograph Derivation. *Journal of Hydraulic Engineering*, 123, 73–80. doi:10.1061/(Asce)0733-9429(1997)123:1(73)

Liu, C. C.-K., and Brutsaert, W. (1978) A Nonlinear Analysis of the Relationship Between Rainfall and Runoff for Extreme Floods. *Water Resources Research*, 14(1), 75-83.

Livers, B., and Wohl, E. (2015) An Evaluation of Stream Characteristics in Glacial Versus Fluvial Process Domains in the Colorado Front Range. *Geomorphology*, 231, 72–82.

McCain, J.F., Hoxit, L.R., Maddox, R.A., Chappell, C.F., and Caracena, F. (1979) Storm and Flood of July 31-August 1, 1976 in the Big Thompson River and Cache la Poudre River Basins, Larimer and Weld Counties, Colorado, Part A. Meteorology and Hydrology in Big Thompson River and Cache la Poudre River Basins, U.S. Geological Survey Professional Paper 1115.

Mommandi, A., Yanagihara, S., and Molinas, A. (2004) Chapter 7 Hydrology, Drainage Design Manual, Colorado Department of Transportation.

Muftuoglu, R.F. (1984) New Models for Nonlinear Catchment Analysis. *Journal of Hydrology*, 73, 335-357.

Muftuoglu, R.F. (1991) Monthly Runoff Generation by Non-Linear Methods. *Journal of Hydrology*, 125, 277-291.

Muzik, I. (1996) Flood Modelling with GIS-Derived Distributed Unit Hydrographs. *Hydrologic Processes*, 10, 1401–1409. doi:10.1002/(SICI)1099-1085(199610)10:10<1401::AID-HYP469>3.0.CO;2-3

Nash, J.E. (1957). The Form of the Instantaneous Unit Hydrograph. *International Association of Scientific Hydrology Publication*, 45(3), 114-121.

NRCS (2007) Hydrographs, National Engineering Handbook, U.S. Department of Agriculture, Washington, D.C.

Porporato, A., and Ridolfi, L. (2003) Detecting Determinism and Nonlinearity in River-Flow Time Series. *Hydrologic Sciences*, 48(5), 763-779.

Sabol, G.V. (2008) Hydrologic Basin Response Parameter Estimation Guidelines. Dam Safety Branch, Office of the State Engineer, State of Colorado.

SCS (1972) SCS National Engineering Handbook. Section 4, Hydrology, National Engineering Handbook.

Sherman, L.K. (1932) Streamflow from Rainfall by Unit-Graph Method. *Engineering News Record*, 108, 501-505.

Snyder, F.F. (1938) Synthetic Unit-Graphs. *Transactions American Geophysical Union*, 19, 447–454. doi:10.1029/TR019i001p00447

Tarboton, D.G., Bras, R.L., Rodriguez-Iturbe, I. (1989) Scaling and Elevation in River Networks. *Water Resources Research*, 25, 2037–2051. doi:10.1029/WR025i009p02037

Tromp-van Meerveld, H.J., and McDonnell, J.J. (2006a) Threshold Relations in Subsurface Stormflow: 1. A 147-Storm Analysis of the Panola Hillslope. *Water Resources Research*, 42, W02410. doi:10.1029/2004WR003778

Tromp-van Meerveld, H.J., and McDonnell, J.J. (2006a) Threshold Relations in Subsurface Stormflow: 2. The Fill and Spill Hypothesis. *Water Resources Research*, 42, W02411. doi:10.1029/2004WR003800, 2006

Tucker, G.E., and Bras, R.L. (2000) A Stochastic Approach to Modeling the Role of Rainfall Variability in Drainage Basin Evolution. *Water Resources Research,* 36(7), 1953-1964.

van der Tak, L., and Bras, R.L. (1990) Incorporating Hillslope Effects into the Geomorphologic Instantaneous Unit Hydrograph. *Water Resources Research*, 26(10), 2393-2400.

Wilkerson, J., and Merwade, V. (2010) Incorporating Surface Storage and Slope to Estimate Clark Unit Hydrographs for Ungauged Indian Watersheds. *Journal of Hydrologic Engineering*, 15(11), 918-930.

Wong, T.S.W. (1995) Time of Concentration Formulae for Planes with Upstream Inflow. *Hydrologic Sciences Journal*, 40, 663–666. doi:10.1080/02626669509491451

Wong, T.S.W. (2001) Formulas for Time of Travel in Channel with Upstream Inflow. *Journal of Hydrologic Engineering*, 6, 416–422.

Woolridge, D.D. (2019) An Assessment of Streamflow Production Mechanisms for Dam Safety Applications in the Colorado Front Range. Master of Science Thesis, Colorado State University, Fort Collins, Colorado.