Restoration Research Award Program

Final Report Narrative Questions

www.cbtrust.org / 410-974-2941

Complete the final report narrative questions below. After completing your narrative questions, save this document on your computer and then submit the document via your Chesapeake Bay Trust Online System account. You can access your account using this link https://www.GrantRequest.com/SID_1520.

1. **Awardee Information**
   Organization Name: Penn State University (Penn State Harrisburg)
   Project Leader: Shirley Clark
   Award Number: 22064
   Date: July 31, 2026

2. **Project Summary**
   a. Describe the project results achieved. Provide a before and after photo of the project, if applicable.

The project achieved two primary results. First the project developed a combined field and laboratory technique that would allow a user to calculate the parameters to be used in the Horton infiltration equation from a single soil-sensor installation. Currently, to do that calculation, it requires 2 sensors installed vertically in the soil profile. In compacted soil, there may not be enough depth available for a stacked set of sensors and this development moves away from needing the stacked set. Second the project developed a set of curves for compact and noncompact clay and sand that related the water storage depth (as would be input into the SWMM computer program) to the effective Curve Number. Most jurisdictions in the Chesapeake Bay Basin use the CN as a design parameter.

3. **Restoration Research Award Program Narrative Questions**
   a. What was/were your key restoration research question(s)?

The primary research question was to better understand the impact of urban soil compaction, and particularly a nearly-impermeable compaction layer, on the amount of runoff generated from an urban site. The goal was to develop simple field or field-lab procedures that would allow for estimation of modeling parameters that could be used in SWMM or other applications.

   b. What are the results for your research question(s)?

Land development often results in the development of a compaction layer a few inches or less below the soil surface. This is a result of the need for structural soil strengths below buildings and roads and the fact that most older land development graded the land and compacted the soil across the entire site. Many modeling efforts in stormwater management adjust their parameters to account for the reduced porosity in compacted soils, such as by downgrading the Hydrologic Soil Group and increasing the Curve Number. They do not account for the compaction layer, which will prevent water from infiltration below that location. To address this challenge, the project focused on the inputs to the US EPA SWMM computer program. SWMM allows for 3 infiltration models to be used – Horton, Green-Ampt, and Curve Number. Only Horton allows for a maximum water volume to be put into the model, effectively defining a limit on infiltration when the soil is saturated and no water is moving downward due to the compaction layer.

Therefore, the first result was developing a technique and an equation that would take the soil moisture from a single soil sensor and convert it to Horton infiltration parameters. Briefly, the procedure uses a soil cone penetrometer (typically a Dickey-John cone penetrometer). In the field, the cone penetrometer is pushed into the soil until the resistance measures 300 psi. The depth to 300 psi is measured. 300 psi indicates a level of compaction that restricts water movement and inhibits root growth of plants. Therefore, this is considered the depth to the compaction layer. A soil moisture sensor is installed above the compaction layer and data is collected by the user for as many storms as desired. Using the moisture deficit from saturation and the water storage volume at saturation calculated as compaction layer depth multiplied by effective porosity, the Horton parameters can be extracted through nonlinear regression. This is outlined in the file labeled Field Procedures compaction depth to Horton (pptx and pdf).

The second result was to convert from Horton parameters to Curve Number. Most jurisdictions are using CN for stormwater management design. Horton is a time-dependent model while the Curve Number model is a lumped parameter model, which makes direct parameter conversion impossible. The approach was taken to assume a design storm, based on the Maryland (and Pennsylvania) criteria, of a 24-hour design storm. The design storm, based on NOAA 24-hour rainfall distributions A-D that are applicable to use with NOAA Atlas 14, was modeled in SWMM with a 10-acre, fully pervious land watershed. The land slope was 2% and the initial abstraction was 0.05 inches. These seemed reasonable for urban land and the results were not substantially different if slopes up to 3 – 4% or as low as 0.5% were used. The model was run for rainfall depths between 2 and 11 inches, which brackets the rain depths used by Maryland for storms with annual exceedance probabilities between 1% and 50% with the climate adjustments provided by MARISA (as described in the Maryland stormwater guidance manual). Horton parameters were extracted from Dr. Pitt's USEPA 1999 report on compacted urban soils where he found that urban soil could be broken into 4 categories: noncompact sandy, compact sandy, dry compact or saturated clay, or noncompact dry clay). The total runoff and volumetric runoff coefficient Rv were extracted for water storage depths ranging from 0.5 inches to 10 inches. Then using the same watershed and rainfall distribution, the model was run with various CNs to determine which CN matched the Horton model results. To date, the calculations have been completed for compact sandy, compact clay, and noncompact clay soils for all rain distributions and for noncompact sandy soils for rainfall distributions A through C. The results show that the effective curve number is the same for all noncompact soils. They are functions of water storage depth and rainfall but not soil type. They are different for the compact clay and saturated clay as well as compact sand. There are slight differences in the results based on rainfall distribution. To convert the water storage depth to a depth measured by the cone penetrometer, the water storage depth will be multiplied by the effective porosity, which can be estimated from tables. While this was performed for the 24-hour storm event, this could be adjusted based on other rainfall distributions and time periods. This is described in the file labeled Compaction Horton to CN (pptx and pdf).

c. List and describe the regulatory presentations and trainings provided.

Presentations were made (and copies submitted with this report) in the following venues. No regulatory training specifically has been performed although regulators have attended all of the presentations. An example of this was the presentation by Dr. Clark at the MS4Forum in Lancaster County, Pennsylvania. While the results of this project were not the focus of the presentation, this project was mentioned. (Design and Operation of Green and Gray Stormwater).

The following presentations were made based on **Result 1** and the potential application in a highly-developed urban watershed, as an example.

Assessing Low Impact Development Practices Performance Under Various Storms in a Highly-developed Urban Area (LID Presentation_Razavi.pptx; 2026 Low Impact Development Conference, Jacksonville, FL. March 2026).

Modeling strategies for flood mitigation in a highly-developed urban area. (EWRI Congress 2026 Presentation_Razavi.pptx; EWRI 2026 Congress, Mobile, AL. March 2026).

Deriving Horton Infiltration Parameters from Single Soil-Moisture Sensor Data (LID Conference 2026 and EWRI Congress 2026)

Integrating Urban Development Impacts on Infiltration into Hydrologic Modeling. (EWRI Congress 2026).

Result 2 is recent and was only introduced at the 2026 Pooled Monitoring Forum.

The other presentation was presented the Bay Trust Pooled Monitoring Forum in Baltimore, MD. (Bay trust pooled monitoring forum clark 2026.pdf)

Additional presentations are scheduled at the Pennsylvania Stormwater Symposium in mid-October 2026 and at the AWRA National Conference in Philadelphia in early November. These results also will be presented at ASCE 2027 in March 2027.

d. How can the findings be used for the regulatory community, for practitioners, for researchers, and others?

The finding primarily of interest to the regulatory community as the regulations are currently written are the results from the modeling to create Curve Numbers as a function of compaction layer depth. The curves as presented in the files can be used to estimate more appropriate curve numbers for spaces such as lawns and urban parks based on a rapid field investigation using a cone penetrometer and potentially bulk density. Should the jurisdictions update their guidance on modifying curve numbers or otherwise using the volumetric runoff coefficient Rv, charts are provided of Rv as a function of rain depth and compaction layer depth.

As more jurisdictions encourage continuous simulation as part of the design and review process, the first result on how to extract Horton parameters from single-sensor field data will be of more interest. Since the compaction layer is only a few inches below ground, most urban lands are generating more runoff than the models estimate.

e. What future research is needed?

There are two areas of immediate interest. The first that was seen during this project is that the compaction layer is nearly impermeable, but not as impermeable as a landfill liner. Therefore, once it reaches a certain moisture content, it acts as another soil layer allowing deeper infiltration. This was noticed both in the soil moisture sensor data when, after several small storms, a moisture content response was reserved. Understanding the behavior as a function of moisture content will allow for water balance modeling in the subsoils.

As presented in the Pooled Monitoring Forum, field testing post-storm event with the cone penetrometer shows that the depth to 300 psi resistance changes depending on how many days post-event it is. The analogy that has been used to describe the behavior of the compaction layer and its impact on runoff is that of a bowl. If the depth to 300 psi changes based on water content of the soil which depends on how many days the soil has had to dry out, then the question is how to predict it/model it so that it can be used to support an improved water balance evaluation.

f. How and when did you provide the data for this project to the Chesapeake Bay Trust?

The final data sets are being provided with this report.

g. Provide the citation for the scientific paper in the peer-reviewed literature that was submitted.

There are 3 journal papers in preparation. One will be on the field procedures and conversion of the data from a single soil moisture sensor to Horton parameters. The target audience for this is the Journal of Sustainable Water and the Built Environment. The second will on the conversion of Horton parameters and depth of the compaction layer to Curve Numbers. This is targeted for a modeling journal such as the Journal of Urban Water Management Modeling. The third (which should be submitted on or before October 2026) will show the application of these data to a small highly-developed urban watershed.

4. Project Evaluation and Lessons Learned

a. Discuss the project's goal(s) and evaluation(s). Include how the project measured success to meet the goal(s) and to report the outcome(s).

The project's overall goals of understanding the impact of soil compaction on runoff generation were achieved. The goal of creating field procedures that would allow a developer or a regulator to go out into the field and fairly rapidly be able to characterize the depth of compaction on a site and translating that to effective Horton infiltration parameters or Curve Numbers was achieved. The creation of curves that could be used in stormwater guidance to replace the TR-55 curve numbers and provide better guidance on the behavior of urban soils was the primary goal.

Throughout the project, the interim results have been presented at various conferences as well as their application through modeling a highly developed older watershed. This has allowed for feedback from audiences of both researchers and practitioners. It is also considered a success that the results of this project have been selected to present at ASCE 2027, putting these results in front of a large group of land develop engineers from around the US.

b. Discuss the greatest successes.

Soil compaction in urban areas has been addressed as only an issue of changing porosity. This project highlights why the creation of a nearly-impermeable layer of highly compact soil prevents continuous infiltration in urban areas. The issue is a combination of reduced porosity and the depth of the water storage in the soil profile. Therefore, the greatest success is the development of curves of rainfall depth and soil water storage depth related to CN. This should improve both prediction of site behavior in new development and improve recreation of historic events.

As the profession moves towards continuous simulation, the conversion to Horton parameters has the potential to improve modeling.

c. Discuss the greatest challenges, including the lessons learned, and potential roadblocks to future progress.

Two challenges were external to the project and were related to the change in the home university of the project team. The loss of the co-PI who was based in Maryland posed a challenge at the end of the first year. The reorganization of Penn State added a burden to the PI.

From a project standpoint, the biggest challenge was trying to identify sites that were secure and relevant. When working with above-ground equipment that would be visible from the street, site security is a pressing need.

d. Based on the results of the project, how would you refine and improve your project or approach in the future?

The project would have been refined by identifying sites before proposing the project and discussing how the equipment could be secured. The budget did not include fencing or other means of security. The sites that were most secure in the relevant areas were not good sites from a research standpoint. The horizontal movement of water that could be documented and used in a 2-D model is still an unknown.

The project also assumed that the soil texture and porosity were going to provide a larger difference in behavior. This is showing in compacted soils, but the biggest driver of effective Curve Number and Rv is the depth to the compaction layer.

e. What advice would you give someone considering a similar project?

Better preliminary work in terms of identifying the parameters that are important in the modeling. As the projects ends, the modeling with various soil types and porosities is still continuing. Also, field work in a city that is less familiar causes a challenge. Identify sites before submitting the proposal.

That said, these results are likely more useful to the profession now than the original proposal.

5. Final Project Deliverables

a. Provide all final products (e.g., final report, data, scientific paper, fact sheets, presentation, etc.) and any additional deliverables required per the approved award.

Notes to awardees: 1) products may be externally reviewed and this may lead to revisions that should be factored into the budget and timeline and 2) for questions about your final report, contact the Trust program manager at 410-974-2941.

Additional guidance and resources are available online at https://cbtrust.org/forms-policies/.

Directions to submit your final report online:

1. Sign into your account using this link *https://www.GrantRequest.com/SID_1520* and the same username and password as when you applied.
2. Once signed in click on the Requirements tab.
3. If you do not see your requirement, use the dropdown on the right and in the middle of the page to shift between “Show: New” and “Show: In Progress.”
4. You should see below the yellow bar your Final Report link.
5. Click on the Final Report link and follow the instructions.
6. Once complete, click Submit & Review and make sure you have uploaded and entered all of the necessary information.
7. If so, click Submit.

To confirm your requirement was successfully submitted use the dropdown to shift between “Show: In Progress” and “Show: Submitted Requirements.”

Photos: Upload any photos, digital images, newsletter articles, or press clippings to supplement your written description. These supplemental files can be uploaded into your final report submission under “additional attachments,” located on your Chesapeake Bay Trust Online System account.

DISCLAIMER: By submitting photos and videos in your final report, you are acknowledging ownership and copyright of the photos and videos submitted. The copyright will remain with the photographer. However, the Trust reserves the right to publish all items in publications, websites, advertising and promotional materials. You also confirm that you have written consent from all subjects in the photos/video submitted including if any subjects are minors under the age of eighteen.