Climate Change and the Rainfall Energy R in RUSLE

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Highlights

- By the mid-2000s, calculated R values in Pennsylvania were 25 – 100% greater than predicted by RUSLE.
- Through 2023, R is steadily increasing as more high-intensity, short-duration storms occur.
- Increases in R are directly proportional to the soil loss during construction and captured in a sediment pond.

Introduction

Knowing the soil loss on a construction site drives the size of the sediment pond and its maintenance frequency, and it may affect the ability of vegetation to establish prior to soil washout. In addition, excess erosion potentially adds to the cost of regrading and cleaning out of storm-water pipes to the construction project. Therefore, controlling erosion at the source through the proper selection of control practices is both legally required and good economic practice.

Soil loss is often calculated using the Revised Universal Soil Loss Equation (RUSLE). The equation states:

Soil Loss = (Rainfall Energy, R)(Length-Slope Factor)(Soil Erosivity)(Protection Practices – Construction and Agricultural)

With the exception of R, the remaining factors are either properties of the soil or the human interaction with the soil. The parameter most affected by climate change is the Rainfall Energy R.

Methodology

Initial Work (Clark, et al. 2009)

The initial phase of this work began in the mid-2000s through the work of a graduate student Aigul Allison. The rainfall records from twenty-seven locations throughout the state of Pennsylvania were extracted from NCDC Hourly Rainfall Precipitation Database using the rain module in WinSLAMM. Depending on the station, the length of rainfall records available ranged between 23 and 55 years. Years with only partial rainfall records were excluded. The hourly precipitation database was purchased from Earth Info and included rainfall records through December 2005. For the purposes of this study, a 6 h interevent period was chosen as the delineation time between separate storm events and all storms greater than or equal to 0.25 mm (0.01 in) were extracted. For each location, the individual storm R values were summed to calculate the annual R values.

Current Work

The rainfall data from 1990 through 2023 were extracted from the Pennsylvania State Climatologist website using the FAA Hourly Link. This is the same NCDC Hourly Rainfall Data set used in Clark et al. 2009. The analysis, with the exception of using WinSLAMM due to differences in how the rain records are organized making WinSLAMM difficult, is identical to the prior work. There is a 6-hour interevent period to differentiate between rain events.

Key Findings

An example of the data analysis conducted in this 1990-2023 is Figure 1 from Allentown. As expected the data is variable from year to year. Broadly, however, there is an increase in the median annual R value if the years 1990 – 1993 are compared to 2017-2023. Analyzing the intermediate years is ongoing, as is the analysis for an additional 20 locations across Pennsylvania.

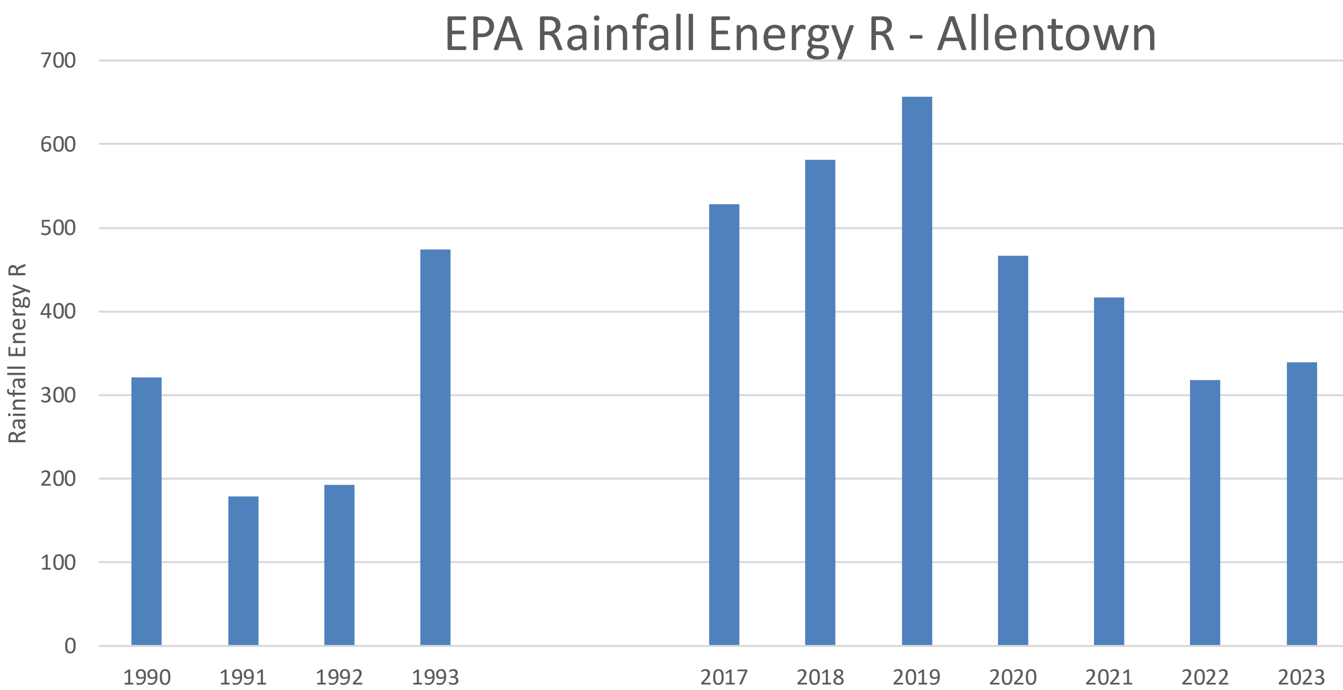

Figure 1. Annual R value for Allentown by year, as calculated by USEPA (1973).

The implications of increases in annual R values are twofold. For Pennsylvania, the greatest impact will be an unexpected increase in the soil loss on a construction site. This loss of soil, if the system is designed properly, will increase the amount of sediment trapped by the sediment pond. Increasing sediment loads either require larger ponds or more frequent maintenance. These are costs imposed on development by climate change. It is unknown in the literature as to whether increasing R values also make other erosion controls, such as silt fences, more likely to fail. The US EPA also has issued a construction erosion control waiver for areas and projects where R < 5. These calculations show that the mapped R from the 1960s likely underpredicts R by 50% or more. In practical terms, this means that fewer sites would qualify for the waiver if the R values used by the USEPA reflects climate change.

Recommendations

A proposed modified map of R values in Pennsylvania will be included in an updated ASCE Standard (Standard 66). Use of map values from this study will allow a contractor to adequately design a sediment pond at the desired maintenance interval.

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Stormwater Management Facilities in Coastal Areas with Respect to Climate Change

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Highlights

- Adapting stormwater management design to climate change is challenging due to related hydrologic processes
- Modeling is an important tool for predicting and informing future management needs
- New tools in integrated surface-subsurface modeling can be instrumental in stormwater management designs

Introduction

Stormwater and stormwater management systems are important infrastructures for safeguarding human and ecosystem health because they are conduits for the safe transportation and stormwater treatment before disposal into receiving bodies. However, unprecedented changes in rainfall patterns, projected sea level rise (SLR), rising shallow groundwater levels, and saltwater intrusion in coastal environments pose threats such as weakening of vertical gradients, corrosion of pipes, disruption of treatment system integrity and water infrastructure to these infrastructures (Cao et al., 2020; Flood & Cahoon, 2011; Hummel et al., 2018; Nicholls et al., 2007). In response to these emerging challenges, it becomes imperative to thoroughly assess the existing stormwater management systems and then develop future-proof design strategies that accommodate the anticipated impacts of climate change. This paper aims to draw connections between modeling conducted by the research team at the University of Delaware and practical engineering solutions implemented by Straughan. In both settings, we present examples of how to incorporate the latest projections for SLR and changes in rainfall patterns into the design process while also considering the effects of groundwater dynamics on these designs.

Methodology

Groundwater Flow and Stormwater Management Modelling

For our study, we address climate change impacts on stormwater and groundwater systems in Bowers Beach, Delaware, by coupling EPA's Stormwater Management Model (SWMM) and USGS MODFLOW, a groundwater flow model. SWMM is used to simulate surface runoff and the hydraulic performance of stormwater infrastructure under varying rainfall conditions, particularly the engineered components like storm drains, pipes, green infrastructure, and sanitary sewers. Despite SWMM's capabilities, its limited functionality for groundwater level analysis and particularly 3-D, variable density groundwater flow (i.e., from saltwater intrusion) is why we are also integrating MODFLOW, renowned for its detailed groundwater dynamics simulations especially relating to SLR. This coupling enhances our ability to examine the complex interactions between SLR-induced groundwater rise, rainfall-induced runoff and the existing stormwater infrastructure, highlighting potential risks of capacity exceedance due to multiple interacting factors. By leveraging SWMM for runoff and infiltration analysis and MODFLOW for groundwater level simulations, our approach offers a nuanced understanding of how climate change variables—specifically SLR and varying rainfall patterns—can impact stormwater management strategies. This integrated model framework provides critical insights for developing resilient infrastructure designs capable of mitigating the effects of climate change.

Risk Assessment Factors

When designing stormwater management infrastructure in coastal communities, the design teams assess the effects of rising coastal water levels and intensifying rainwater. Rising coastal water levels lead to higher groundwater tables, weakening of vertical gradients and saltwater intrusion in groundwater, which results in shallow, more saline groundwater. Intensifying rainfall leads to increased stormwater runoff, which can lead to stormwater and stormwater management infrastructure failure. To properly design resilient stormwater infrastructure, design teams have assessed these risks separately using modeling. The eventual design is therefore supported by numerous background calculations and considerations regarding climate change which creates improved resilience.

Key Findings

Through integrating the SWMM and MODFLOW models, our ongoing study at Bowers Beach aims to assess the impacts of sea level rise (SLR) on stormwater and groundwater systems. We anticipate pinpointing critical interactions between rising groundwater levels and stormwater infrastructure by simulating various SLR scenarios. We will compare groundwater elevation against stormwater pipe elevations across different time steps, thereby identifying potential vulnerabilities within the system. Another key aspect of our analysis involves examining how surface runoff and groundwater inflow into these pipes vary in response to changing SLR and rainfall patterns. These insights will enable us to identify which parts of the stormwater are most susceptible to climate change impacts. With this information, infrastructure designers will have a foundation for making informed decisions regarding adjustments in pipe sizing, optimal installation depths for new stormwater management and other infrastructures, and other vital management strategies. When designing for coastal communities in Delaware and Maryland, the Straughan team has found methods that help to create designs resilient to the effects of climate change. The Straughan team will present stormwater management case study projects as part of the presentation to support these key findings. We will focus on practices that work most effectively in these environments as well as innovative solutions to enhance practices. Due to the immediate effects of sea level rise and rainfall intensity in coastal communities, these projects must be designed especially with considerations for groundwater interactions and flooding.

Figure 1. Straughan project site at Dagsworthy Street, Dewey Beach, DE

Recommendation

Future stormwater management projects in coastal communities must use the most current methods of climate change modelling to inform design. The compounding effects of climate change in coastal communities can be seen more directly and more severely than in their inland counterparts. Due to these tangible effects, planning for future scenarios and resilience is an important part of stormwater management in coastal communities.

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1HEC-RAS 2D Hydraulic and Sediment Analysis for Dam Removal

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Highlights

- Inundation of upstream bodies of water should be considered during hydrologic modeling analysis.
- The reservoir and downstream channel of this dam saw minimal hydraulic effects post removal.
- The sediment analysis shows an incised channel is expected to start forming approximately 500 to over 800 feet upstream of the dam.

Introduction

This study will explore a dam removal analysis conducted on a dam in Massachusetts. The Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) will be used to perform the hydrologic analysis of the dam's watershed, while the River Analysis System (HEC-RAS) will be used to perform a hydraulic and sediment analysis of existing and post dam removal conditions of the site. A summary of the hydrologic and hydraulic results will be provided as the main focus will be on the sediment modeling approach and results.

Methodology or Background

Hydrologic Modeling

The initial step in completing the downstream assessment for the dam is the development of the hydrologic model to simulate the watershed runoff and flow response (i.e., flood hydrographs) for several flood frequency storms. The HEC-HMS model domain covers watersheds up to the confluence of the dam's downstream channel; a combined watershed area of approximately 47-mi^2. The 47-mi^2 watershed was divided into five sub-watersheds in the HEC-HMS model. Sub-dividing the watershed provides a semi-distributed approach to the simulation, accounting for variability in soil types and lag times, and hydrographs at distinct inflow points for the hydraulic model. Frequency storms were also evaluated in the HEC-HMS model, entered as a "frequency-storm" distribution. The associated rainfall values obtained using NOAA Atlas 14 (NOAA, 2017). The SCS curve number (CN) method was used to estimate the runoff volume (rainfall minus losses due to infiltration and retention) in the HEC-HMS model. CNs were derived from National Engineering Handbook (NEH), Part 630, Chapter 9 (USDA-NRCS, 2004) based on cover type, hydrologic conditions, and hydrologic soil groups (HSGs), obtained from the following sources:

- National Land Cover Database (MRLC Consortium, 2019).
- Soil Survey Geographic database (SSURGO) using the NRCS Web Soil Survey (USDA-NRCS, 2021).

Land cover in the watershed is primarily forested with open water and developed spaces, resulting in average sub-watershed CNs between 57 and 63 using ARC I CNs. Lag time can be calculated using various approaches, including the SCS lag time equation described in Section 630.1502, Equation 15-4a, NEH, Part 630, Chapter 15 (USDA-NRCS, 2010). See Table 1 for key sub-watershed characteristics.

Table 1. Sub-Watershed Characteristics

Sub-Watershed ID	Drainage Area (mi2)	ARC I Curve Number (rounded to nearest integer)	Longest Flow Length (mi)	Average Slope (%)	ARC I Lag Time (minutes)
SW1	21.0	60	12.4	7.7	340.3
SW2	12.3	63	8.5	7.6	234.4
SW3	5.9	61	7.1	7.4	214.3
SW4	6.7	61	7.3	7.3	220.3
SW5	0.8	57	2.2	6.2	102.7

Hydraulic Modeling

A digital elevation model (DEM) was developed using a topographic survey, bathymetric survey and 1-meter resolution LiDAR obtained from the USGS National Map Viewer (TNM Download v2 (nationalmap.gov). The DEM was used to create the for terrain the 2D HEC-RAS model. The 2D flow area mesh consists of 100-ft by 100-ft grids with 50-ft by 50-ft refinement areas along the channels upstream and downstream of the dam. 25-ft by 25-ft refinement areas were used in the dam's reservoir. The internal SA/2D connections have refinement regions of 5-ft by 5-ft cells. Internal connections incorporated into the model include the dam's principal and auxiliary spillways and three bridges downstream of the dam. Manning's n-values for the 2D model were derived using guidance developed by NRCS (NRCS-Kansas, 2016) and estimates based on site photos obtained during the survey. For each flood frequency scenario, the controlling inflow hydrographs to the reservoir were obtained from the HEC-HMS model. Field observations from a December 2023 storm was used as a validation for the model.

Sediment Modeling

The sediment transport model results were evaluated to understand the stream bed's initial response to removing the dam under normal or sunny day conditions and a comparison of sediment transport patterns during a hypothetical high flow event (pre- and post- removal). Scenarios were modeled for existing and post dam removal conditions using the capacity only and mobile bed methods. The capacity only method provides a total transport capacity flux that can be used to compare existing and post dam removal conditions. Transport capacity represents the hydraulic capacity of the stream system, given the grain size distribution, to transport sediment, which was used to identify areas of potential erosion and deposition shortly after the dam is removed. The mobile bed method can show changes in the channel bed based on the sediment properties assigned to the model. Soil properties can include gradation, density, dry bulk density, and shape characteristics for granular material (i.e., roundness and shape dimensions).

Key Findings

The 2-, 5-, 25-, 100-, and 500-year 24-hour flood events for the existing and post-removal conditions were simulated and minimal changes (less than 0.1 ft) were found in the water surface elevation for structures downstream of the dam. The capacity only and mobile bed analysis for sunny day conditions show that an incised channel is expected to start forming approximately 500 to over 800 feet upstream of the dam. Simulations show that sediment will be transported through the downstream channel with isolated areas of deposition. The high flow events show a similar sediment response with higher changes in elevation near the dam during post-removal scenarios.

Recommendations

Recommendations when completing a sediment analysis for a dam removal include starting with completing a well refined hydrologic and hydraulic models. Collecting as much data as possible on existing sediment in the upstream channels, reservoir, and downstream channels. Additionally, having a pre- and post- removal scenario that allows for a comparison to analyze the changes occurring.

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Comparing Calibrated Models of Suburban Karst Watersheds with USGS Regression Equations

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Highlights

- Each study developed and calibrated a PCSWWM model with combined 1D and 2D hydraulic components to represent the watershed and problem areas.
- The studies collected monitoring data at various points throughout each sub catchment allowing for characterization of various landcovers, development styles, and catchment size.
- Each watershed was of sufficient size to allow a comparative analysis with USGS SIR 2019 5094.

Introduction

Pennsylvania is a state with multiple developed and developing areas underlain by karst geology. Karst geology results in many traditional hydrologic engineering tools and models being limited in their applicability. In this case study, each of the watersheds are comprised of 100% karst geology and relatively small, 2 and 6 square miles respectively. This presentation will compare the two watersheds, the events observed during their monitoring period, the methods used to construct and calibrate the models, and how the results of the models compare to the USGS SIR 2019 5094 regression equations that served as a standard for hydrology in ungauged watersheds.

Background

The study watersheds are in the Lehigh River Watershed between Bethlehem and Easton Pennsylvania. They are located adjacent to each other and have experienced historical flooding due to limited or undersized stormwater infrastructure. The historical flooding led to the funding to the initiation of two studies which supported the development of the hydrologic and hydraulic models described in this presentation. As part of the studies monitoring sites were established to provide a record of data for model calibration. Each watershed had three area-velocity flow gauges installed in existing channels and storm sewer infrastructure.

Bethlehem Township – Nancy Run Model

Nancy Run is a perennial stream with a well-established channel and baseflow in its lower reaches transitioning to karst drainageways in its headwaters. Through the development of the watershed various portions of the headwaters karst drainageways were paved, channelized, piped, or preserved providing a complex hydraulic and hydrologic condition. The study that is the subject of this presentation converted and calibrated an Infoworks ICM model of this watershed to PCSWWM. The model runs EPA runoff model utilizes the green ampt as the infiltration component of the model.

Palmer Township – Seip Ave Drainageway

The watershed in Palmer Township is heavily modified with the lower reaches being piped under various roads and commercial properties. This watershed is an ephemeral drainageway with flows only being the result of rainfall events. The lower portion of the watershed is subject to frequent flooding which served as the impetus for the study.

The study that is the subject of this presentation created and calibrated a PCSWWM model of the watershed utilizing the SCS curve number infiltration option.

Key Findings and Recommendations

Both studies resulted in the advancement of infrastructure improvement projects. These projects will utilize the calibrated model flows and hydrographs to attempt to design for the maximum benefit during small to medium sized events. The performance and fit of each model's calibration was varied with the end result being a compromise between multiple gauge locations. This presentation will discuss as a case study the challenges of calibrating models with mixes of run off methods, (rain on grid and traditional sub catchment routing), as well as limitations in observed events during the short observation timeline.

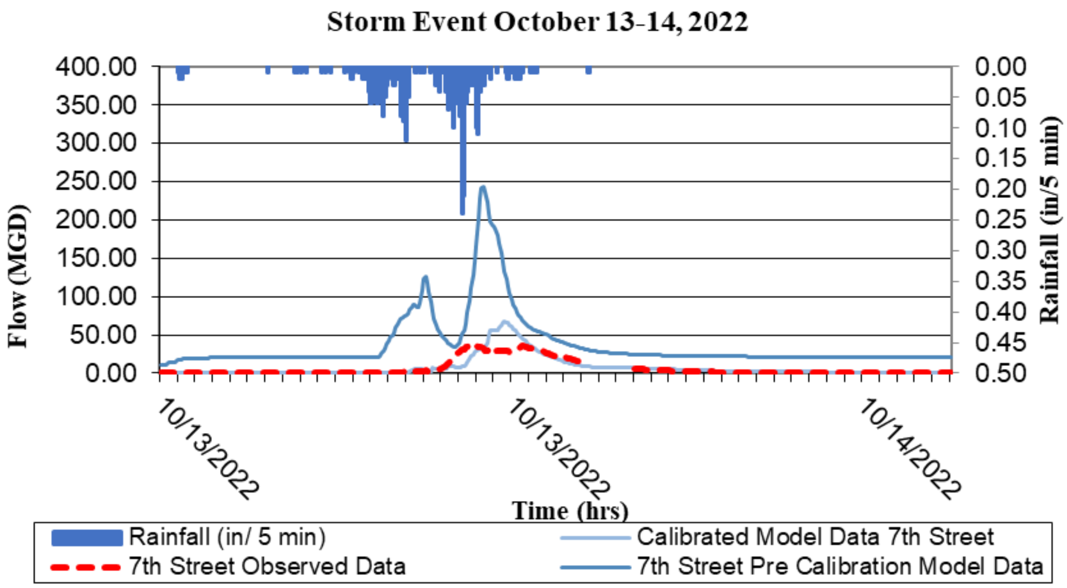

Figure 1. Model Runoff Results at the highest observed point in the Nancy Run watershed

After reviewing the model data the presentation will compare the results to the USGS SIR 2019 5094 regression estimated peaks flows. The findings indicate that the regression peak flows over predict in areas with less directly connected imperviousness and under predict in areas of older development where the impervious is directly connected to the channel or main drainage infrastructure.

Modeling Sediment Capture Efficiency of Roadway Grate Inlets

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Abstract

Roadway grate inlets play a significant role in routing water, sediment, and pollutants into stormwater management systems. However, poorly designed inlets not only increase the risk of flooding but also accumulate sediments, resulting in reduced conveyance capacity and impeding their function over time which necessitates costly maintenance efforts. Their hydraulic function depends on factors including inlet design, approach discharge, roadway slopes and clogging conditions. Despite increased hydraulic research, the link between inlets and sediment is generally unknown, underlining the need for continued research to optimize performance. This research employs laboratory-based physical modeling to explore the sediment capture efficiency, as well as the bypass of roadway grate inlet. Fifty-two modeling cases were tested across different scenarios, and sediment samples were collected and analyzed below the inlet and at the bypass. The results of this research offer guidance for informed design of inlets and stormwater management systems, which could aid in optimizing maintenance plans and facilitate design at the city-scale.

Key words: Stormwater management, Sediment capture, Grate Inlet, Modeling