

Simulation and Assessment of Long-Term Stormwater Basin Performance under Real-Time Control Retrofits

Zoë K. Schmitt

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Randel L. Dymond, Chair
Clayton C. Hodges
Kevin D. Young

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ACADEMIC ABSTRACT

The use of real-time control (RTC) as an adaptation technique for improving existing stormwater systems has been gaining attention in recent years for its ability to enhance water quality and quantity treatment. A case study RTC retrofit of seven existing detention basins was simulated for a small (162 ha), urbanized watershed in Blacksburg, VA. Two heuristic, reactive control algorithms were tested and compared for their ability to improve hydraulic conditions at each detention basin and the watershed outlet through manipulation of an actuated valve, under various permutations of RTC retrofitting (single facility, multiple facilities, etc.). Change in peak flow during 24-hour design storms was assessed. RTC only reduced peak flows at some of the facilities for storms with a return period of 2 years or less. For larger storms, RTC maintained or increased peak flow rates. During a 15-year simulation with historic precipitation data, total duration of erosive flows was reduced for most facility retrofit simulations; however, the duration of high intensity flows increased, or remained unchanged. This result was also reflected at the watershed outlet.

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GENERAL AUDIENCE ABSTRACT

Stormwater management helps protect natural waterways from the harmful impacts of human development. A growing field of research is investigating the potential for “smart” technologies to improve the efficiency of existing stormwater facilities. This study investigates the application of a “smart” stormwater retrofit, known as real-time control (RTC), to existing stormwater management facilities located in a small case study watershed. The RTC system is composed of hypothetical internet-connected sensors and control valves which control flows at several points within the test watershed. Two control algorithms were tested, and compared to the current conditions (scenario with no RTC), for a large range of storm events. Results of this study found that RTC would lead to improved stream health for most rainfall events, but could potentially worsen conditions for the largest, most rare storm events. In addition, RTC was found to be much more effective at some points in the watershed than other points. Prediction of where RTC will be most effective should be the focus of future research.

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1. Introduction

1.1 Background

The purpose of stormwater management is to protect people and property from flood hazards and mitigate the harmful impact of urbanization on natural waters – both problems of growing importance in today’s world. The increased impervious cover resulting from development restricts infiltration and increases runoff volumes, leading to higher and longer peak discharges and increased sediment loading on waterways (Dietz and Clausen 2008; McGrane 2016). This leads to “urban stream syndrome”, which is characterized by streambed erosion, decreased water quality, and loss of aquatic habitat and biodiversity, extending far downstream of the urban area (Jackson and Booth 1997; Vietz et al. 2015).

Low Impact Development (LID) is a common methodology for reducing the hydrologic impacts of urbanization. LID aims to mimic the pre-development hydrology of a site through retention, infiltration, and evaporation of stormwater close to its source (Prince George’s County 1999). Specific structures used in LID, called stormwater control measures (SCMs), include detention basins, green roofs, and bioretention filters. These measures are capable of mitigating peak flows; however, due to the static nature of this infrastructure, SCMs may only improve conditions for rainfall events similar to those for which they were designed (Hixon and Dymond 2014; Nehrke and Roesner 2004). Most SCMs are designed and implemented on a local (parcel-level) scale. However, past research shows that local stormwater controls, while successful in reducing the peak flow leaving a site, may not produce desirable downstream outcomes (Emerson et al. 2005; Goff and Gentry 2006; McCuen 1979).

The introduction of “smart” technologies into stormwater management is a concept that has been gaining traction around the world in recent years (García et al. 2015; Mullapudi et al. 2017; Schütze et al. 2004; Shishegar et al. 2018). Smart stormwater systems join the science of urban hydrology with the technology of the *Internet of Things (IoT)* to adapt to changing watershed conditions and optimize stormwater management. A promising form

of smart stormwater management is real-time control (RTC). Through internet connected sensors and actuators (such as motorized valves and pumps), RTC allows for runoff to be stored in parts of the urban drainage system that have excess capacity, relieving pressure from other, more overburdened areas in the system. To date, this technology has most commonly been used in combined sewer systems (CSSs) to mitigate combined sewer overflow (CSO) events. Compared to traditional infrastructure updates, installing RTC is equally (if not more) effective, less intrusive, and lower cost. For example, RTC implemented in South Bend, IN reduced CSO volumes by as much as 50%. Achieving the same CSO reduction through traditional infrastructure updates would have cost an additional \$150 million (Montestruque and Lemmon 2015). This form of RTC retrofitting has been implemented since the 1980s in cities around the world, including Paris, France; Philadelphia, PA; Quebec City, Canada; and Barcelona, Spain (Cheung et al. 2005; Ocampo-Martinez et al. 2013; Stinson et al. 2000).

In contrast to combined sewers, the application of RTC to separate sewers with the purpose of improving stormwater outcomes remains a relatively new area of research. Past examples display how RTC can be used to retrofit existing SCMs and create local hydrologic benefits. For example, by installing actuated valves in retention ponds previously used only for flood-mitigation, the outlet orifice can be closed to detain runoff from smaller storms, creating water quality improvements through increased detention time and sedimentation (Middleton and Barrett 2008; Muschalla et al. 2014; Opti RTC and Geosyntec Consultants Inc. 2017). However, the use of RTC at multiple points within a watershed has only been investigated by a limited number of studies (Wong and Kerkez 2018). Furthermore, a large focus in many studies has been on the potential for water quality improvements with RTC during small storm events, rather than the impact of RTC on hydraulic conditions over a large range of precipitation conditions. Therefore, the need remains to demonstrate how the installation of multiple RTC-retrofits within a catchment may impact local and system-wide long-term stormwater quantity outcomes.

1.2 Purpose and Objectives

The research presented here aims to advance the understanding of how a RTC retrofit of multiple existing stormwater detention basins may impact hydraulic conditions in a watershed. A calibrated hydrologic model of the Central Stroubles watershed in Blacksburg, VA was subjected to a simulation of real-time control on the outlets of seven existing detention basins. A large variety of rainfall conditions were applied to the test watershed in order to observe the robustness of the RTC strategy under a large variety of conditions.

This study has the following objectives:

1. Review relevant literature, focusing on RTC in separate stormwater systems.
2. Simulate RTC retrofits of detention basins using a calibrated hydrologic model.
3. Compare performance between two RTC algorithms; one novel approach and one from a previous study.
4. Assess the effect of RTC on peak flow rate for various synthetic design storms.
5. Assess the effect of RTC on the flow duration curve and critical flow rate exceedance time for a long-term simulation with real rainfall data.
6. Analyze the results for the outlet of each facility (local) and at the watershed outlet (regional/downstream).

2. Literature Review

Real-time control systems take form in varying degrees of complexity. The original “real-time control” consists of an operator manually adjusting valves, gates, or weirs on site, known as manual local control (Vitasovic 2006). This level of RTC, while simplistic in nature, is a practical, low cost option for sites requiring only intermittent adjustments, such as for the maintenance of extended detention ponds (Nashville and Davidson County 2009; Oregon Department of Transportation 2014; USEPA 2009). Remote supervisory control is made possible by installing a motorized actuators and a means of data transmission. In this slightly more complex form of RTC, the human operator is still central to decision making, but the control actions (physical changing of a valve position) are executed remotely, via a digital signal (Vitasovic 2006).

RTC may be automated by replacing the operator with a computer control algorithm which uses live sensor data to make decisions on how actuators will be manipulated. Automation is becoming increasingly feasible thanks to the dropping cost of *IoT* technology (Sundmaeker et al. 2010), and this form of RTC is the focus of this study. When implementing automatic control logic, there are many considerations that will impact the system operation and decision making process. A summary of the different types of automatic RTC systems is given in Table 1, which has been adapted from work by Vitasovic (2006) and García et al. (2015).

Table 1. Classifications for RTC systems

<i>Aspect of RTC</i>	<i>Classification Definitions</i>
Type of Urban Drainage System	<p>Combined – wastewater and stormwater enter into one drainage network, eventually leading to a wastewater treatment plant.</p> <p>Separate – stormwater is conveyed by a drainage system that does not lead to a wastewater treatment plant, but drains directly to a receiving water body.</p>
Scope of Control	<p>Local – the control algorithm makes decisions for each RTC location independently of conditions elsewhere in the system.</p> <p>Global or System-Wide – all locations within the drainage system are controlled simultaneously. Control logic decisions made at one location are influenced by system-wide conditions.</p>
Type of Control Logic	<p>Heuristic or Rule-Based – non-optimal control strategies that are developed off-line. Often written with simple logical “rules”, which prescribe system manipulations based on conditions.</p> <p>Optimization-Based – control actions are determined by an algorithm that uses mathematical optimization, such as the minimization of a cost function.</p>
Inclusion of an Online System Model	<p>Yes – control algorithm decisions are dependent on a mathematical model of the drainage system that is “online”, or making system calculations in real time.</p> <p>No – control algorithm decisions are not dependent upon an online model of the system.</p>
Timing of inputs	<p>Reactive or Feedback – control decisions are made based on existing system states that have been measured.</p> <p>Predictive or Feedforward – control decisions are made based on system states predicted to occur in the future. These may be predicted from an online system model, or gathered from an external source like a precipitation forecast.</p>

In addition to the classifications shown in Table 1, there are several categories to consider when physically implementing RTC, such as the level of system supervision, or the method of data transmission between system elements (Vitasovic 2006). These considerations were not included as they do not affect computer simulation of RTC. The categories listed are only concerned with aspects of control systems that are significant for theoretical modelling (i.e. the control algorithm), as this is the main focus of this study. The following sections will present a review of relevant literature for both types of control logic and a discussion of existing research gaps.

2.1 Rule-Based RTC

The simplest form of automated RTC is local, rule-based control (RBC), also known as heuristic control logic. In RBC, the control actions are set manually before the RTC system is online, typically in the style of an “if-then-else” logic structure. Because of this, RBC systems typically require expert knowledge of the UDS for their design and implementation (Vitasovic 2006). The control algorithm must be pre-programmed to handle all possible circumstances, which is why these systems are often developed in an iterative way (Gaborit et al. 2013; Goodman and Quigley 2015).

Jacopin et al. (2001), in an early study of rule-based control, tested two “extreme” control schemes. The first maintains maximum capacity of detention basins at all times to prevent flooding during large storms. The second detains water to promote sedimentation during smaller events. Jacopin’s work established that both hydraulic control and water quality objectives can be met with RTC, but the decision making process to switch between the two strategies was left to future research.

In work by Gaborit et al. (2013), simple control rules based on pond depth, current precipitation measurements, and water accumulation time are used to maximize the hydraulic retention time of stormwater runoff in a detention basin and reduce large discharge rates. Further modeling of this system with a calibrated water quality model showed improvement in the detention basin’s nutrient treatment capabilities from the RTC installation (Muschalla et al. 2014), which was also verified by field experimentation of the system (Carpenter et al. 2014). The use of RTC has been shown to improve water quality treatment through prolonged retention time in a variety of BMPs, such as green roofs, constructed wetlands, and wet ponds (Bartos et al. 2018; Lefkowitz et al. 2016; Middleton and Barrett 2008; Opti RTC and Geosyntec Consultants Inc. 2017).

Another heuristic control innovation uses a flow-duration curve to match post-development BMP outflows to an approximation of pre-development runoff rates (Goodman and Quigley 2015). Rather than only reduce the peak flow from a few low-frequency events,

such as using multi-stage outflow risers to address 2- and 10-year peak flows, this technique would allow for full flow-regime management, which is shown to more effectively reduce unnatural erosion of waterways (Palhegyi 2010; Tillinghast et al. 2011; Vietz et al. 2015). However, the curve-matching approach presented by Goodman and Quigley (2015) requires extensive modeling and many iterations – a potentially expensive endeavor. Additionally, the concept of pre-development flow has no universally accepted definition, made clear by the myriad definitions for “pre-development flow” given in US stormwater regulations (USEPA 2016).

While the majority of RBC is implemented locally, some attempts have been made to apply regional coordination. A simple technique is described by McCarthy (1994) to coordinate two detention pond flows so that they do not exceed capacity of a downstream channel. Another study by Mullapudi et al. (2017) balanced the discharges from two detention basins into a wetland to maximize its treatment and to prevent overflow. In an experimental RTC set up, the releases from two detention ponds were alternated to create on-phase and off-phase interaction of flows at a downstream point (Mullapudi et al. 2018). This method uses experimentally-gathered travel time and shape of downstream hydrographs from each detention basin. This work provides important advances for coordination of several RTC elements, however the interactions of more than two RTC elements in the same watershed is an area that remains poorly understood. Thus far, urban drainage system operators and academics have turned toward global optimization-based control approaches to address this problem.

2.2 Optimization-Based RTC

Optimization methods help to predict the interactions of complex, nonlinear systems, such as in an urban drainage system, which is why many academics have embraced optimization-based RTC algorithms (García et al. 2015; Lund et al. 2018). An optimization-based control algorithm employs mathematical techniques to maximize benefits or minimize costs for a system of inputs and outputs. When applied for system-wide control, this is referred to as global optimal real-time control (GO RTC). The

algorithmic families most commonly applied for GO RTC of urban drainage systems, loosely ordered from most to least prevalent, include Model Predictive Control (MPC), Linear Quadratic Regulators (LQR), Evolutionary Algorithms (EA), and Population Dynamics (García et al. 2015).

MPC and LQR both incorporate an online system model for their execution, which allows for the control logic to have a system-wide perspective. Many advancements in LQR control have been developed for reservoir routing (Wasimi and Kitanidis 1983) and operation of irrigation canals (Balogun et al. 1988; Lemos and Pinto 2012), but LQR has also been applied for the control of urban drainage system in both combined (Marinaki and Papageorgiou 2003) and separate sewers (Wong and Kerkez 2018). MPC incorporates future disturbances, such as forecasted rainfall and runoff, allowing for feedforward, as well as feedback, control. This use of predictive information is particularly relevant to urban drainage systems as it allows for anticipatory actions based on weather forecasts, such as the drawdown of storage facilities before a large storm. Many scholars agree that Model Predictive Control has the greatest potential for optimal management of urban drainage systems (García et al. 2015; Lund et al. 2018), but its complexity may be hindering this potential. A 2018 review of applications of MPC in urban drainage systems found few examples of real operations actively employing MPC (Lund et al. 2018). This directly contrasts with the conclusion from García et al. (2015) that MPC is one of the most used forms of GO RTC. This contradiction may indicate that work in MPC to this point has been largely theoretical and simulation based, rather than applied, possibly due to hesitation by local governments to implement such a complex and opaque control strategy.

Evolutionary Algorithms are well suited for multi-objective optimization problems with nonlinear inputs (Muschalla 2008). In most of the existing literature, EA is used for off-line analysis of urban drainage systems (Barreto et al. 2010; Cho et al. 2004; Muleta and Boulos 2007; Muschalla 2008), with limited examples of EA used for online real-time control (Vezzaro and Grum 2014). Similarly, application of Population Dynamics to RTC remains relatively unexplored (García et al. 2015). Work by Barreiro-Gomez et al. (2015)

appears to be the only example in which Population Dynamics is applied for the control of an urban drainage system.

2.3 Existing Research Gaps

The existing body of research on RTC shows its great potential to improve urban drainage systems. However, past studies have common drawbacks that should be addressed by future work. One such drawback is the lack of comparison between control approaches in the existing literature. The majority of papers apply their novel control approach to a test watershed or drainage network, but only compare the RTC scenario to a static control scenario (or to an uncontrolled scenario, as in Bilodeau et al. 2019). No two sewersheds are alike, making it unfeasible to assess how alternate strategies would function in a different urban drainage system without a direct comparison. This problem is exacerbated by the fact that many studies do not include enough specific detail on the control algorithm (including both heuristic and optimization-based) to allow follow-up investigations by other research. This must be resolved by future RTC studies so that the efficacy of RTC strategies may be verified.

Another common drawback of RTC studies is that they only evaluate control scenarios over a short period of real precipitation data or a limited number of synthetic design storms (Degraeve et al. 2013; Dong et al. 2017; Jacopin et al. 2001; Joksimovic and Sander 2016; De Korte et al. 2009; Middleton and Barrett 2008). In order to verify the robustness of a control approach for a range of scenarios, it is necessary to subject it to both an extended period of real precipitation data, as well as a wide range of synthetic design storms (Pitt and Clarke 2008; Rohrer and Armitage 2017; Wong and Kerkez 2018).

3. Simulation and Assessment of Long-Term Stormwater Basin Performance under Real-Time Control Retrofits

3.1 Introduction

As urban development continues to increase, the role of stormwater management becomes crucial to the sustainability of expansion. Urbanization is known to alter flow regimes of surface and ground waters by restricting infiltration, resulting in larger runoff volumes and “flashier” flows characterized by higher peak discharges and velocities (Dietz and Clausen 2008; McGrane 2016). Hydrologic changes result in degradation of surface waters downstream of developed areas due to erosion, increased sediment loading, and loss of aquatic habitat and biodiversity (Jackson and Booth 1997; Vietz et al. 2015).

Integration of Real-Time Control (RTC) with existing stormwater infrastructure is a promising, low cost adaptation for improving functionality, or adjusting to a changing hydrologic environment (Kerkez et al. 2016). RTC combines the science of urban hydrology with the technology of the *Internet of Things (IoT)* to allow for adaptive stormwater management. A RTC system employs internet-connected sensors (depth sensors, precipitation gauges, flow meters, etc.) to observe conditions and actuators (motorized valves, pumps, etc.) that respond to stimuli by manipulating outlet discharge almost instantaneously, or in “real time”. For the purpose of this study, the term RTC may be considered equivalent to the term Continuous Monitoring and Adaptive Control (CMAC) found in previous literature (Lefkowitz et al. 2016; Roman et al. 2017; Wright and Marchese 2018).

RTC has been used in combined sewer systems to mitigate harmful combined sewer overflow (CSO) events. By taking advantage of existing capacity, RTC implemented in South Bend, IN reduced CSO volumes by as much as 50%, and cost approximately \$150 million less than a traditional infrastructure upgrade (Montestruque and Lemmon 2015). Similar results have been achieved for other case studies in the United States, Canada, Germany, Denmark, and Spain (Nielsen et al. 2010; Ocampo-Martinez et al. 2013;

Seggelke et al. 2013; Stinson et al. 2000). The application of RTC to separate storm sewers is a relatively new area of research, with objectives that differ from those of combined sewer systems.

While stormwater infrastructure is largely static, dynamic valves, gates, and weirs have long been recognized for their ability to more closely achieve desired hydraulic conditions. The use of manually adjustable valves is common practice in the design and maintenance of extended detention ponds, and can be applied for emergency facility drawdown, dredging purposes, or other maintenance activities. (Nashville and Davidson County 2009; Oregon Department of Transportation 2014; USEPA 2009). With recent advancements and reduced cost of internet connected sensors and actuators, it is feasible to add automatic controls to previously passive (or manually controlled) stormwater facilities (Bartos et al. 2018; Kerkez et al. 2016). Automation of RTC commonly applies a rule-based – or heuristic – control algorithm (Gaborit et al. 2013; Goodman and Quigley 2015; Jacopin et al. 2001; Middleton and Barrett 2008). Here, control rules are manually programmed before the RTC system is online, typically in the style of an “if-then-else” logic structure. Rule-based control (RBC) systems typically require expert knowledge of the urban drainage system for their design and implementation (Vitasovic 2006).

Jacopin et al. (2001), in an early study of RBC, successfully demonstrated the ability of RTC to meet two objectives: maintaining maximum capacity of detention basins for flood prevention during large events, and increasing detention time to promote sedimentation during smaller events. The decision-making process to switch between the two objectives, however, was left to future research. Gaborit et al. (2013) applied simple control rules based on pond depth and precipitation to maximize the hydraulic retention time and reduce discharge rates for a detention basin. Further modeling of this system with a calibrated water quality model demonstrated improvement in the detention basin’s nutrient treatment capabilities due to the RTC installation (Muschalla et al. 2014). The use of RTC has been shown to improve water quality treatment through prolonged retention time in a variety of best management practices (BMPs), such as green roofs, constructed wetlands, and wet

ponds (Bartos et al. 2018; Lefkowitz et al. 2016; Middleton and Barrett 2008; Opti RTC and Geosyntec Consultants Inc. 2017).

The water quality benefits due to gravitational settling in dry detention facilities, however, are short term in nature; sediments will likely be re-suspended during the next large event without regular dredging. The RTC of detention basins can best improve water quality by limiting the duration and intensity of erosive flows which cause streambank instability, typically from high frequency storm events (smaller than the 2-year storm; Jackson and Booth 1997; Palhegyi 2010; Tillinghast et al. 2011; Vietz et al. 2015). Goodman and Quigley (2015) addressed this idea with an innovative control method which uses a flow-duration curve to match post-development BMP outflows to an approximation of pre-development runoff rates, allowing for comprehensive flow-regime management.

While the majority of RBC is implemented locally, some attempts have been made to apply regional coordination. Works by McCarthy (1994) and Mullapudi et al. (2017) both present simple techniques to balance discharges from two detention ponds to prevent downstream capacity exceedance. Despite these advances, the interactions of more than two RTC stormwater elements in the same watershed remain poorly understood. Thus far, RTC researchers and practitioners have turned toward global optimization-based control approaches, such as linear-quadratic regulators and model predictive control, to address this problem (García et al. 2015; Marinaki and Papageorgiou 2003; Wong and Kerkez 2018). However, these systems are computationally intensive and decisions are made in a “black box”, where they cannot be easily understood and adjusted by operations personnel (Vitasovic 2006). The novelty of RTC technology for stormwater applications may be a hindrance to its adoption, but the implementation of translucent, rule-based control strategies could mitigate this issue.

3.2 Research Objective

This research aims to advance the understanding of how a rule-based RTC retrofit of several dry detention basins will affect ecologically significant hydraulic factors, both

locally and downstream, with emphasis placed on cumulative impacts over a long simulation period with varying degrees of precipitation intensity and inter-event time. This is done through the simulation of RTC on existing detention facilities in a case study watershed using two RBC algorithms. The algorithms tested here are reactive (based on existing, not future, conditions) and locally implemented.

3.3 Methods

3.3.1 Study Watershed and Model Development

The RTC test watershed, located in Blacksburg, VA, was chosen to represent a typical urbanized headwater catchment; it has an area of 162 ha, of which 26% is impervious, with a mixed land use, composed of residential, commercial, and public areas. About 65% of the watershed area drains to one (or two in series) of seven stormwater detention facilities within the study watershed (Figure 1). The detention basin ID corresponds to the facility's storage volume in m³.

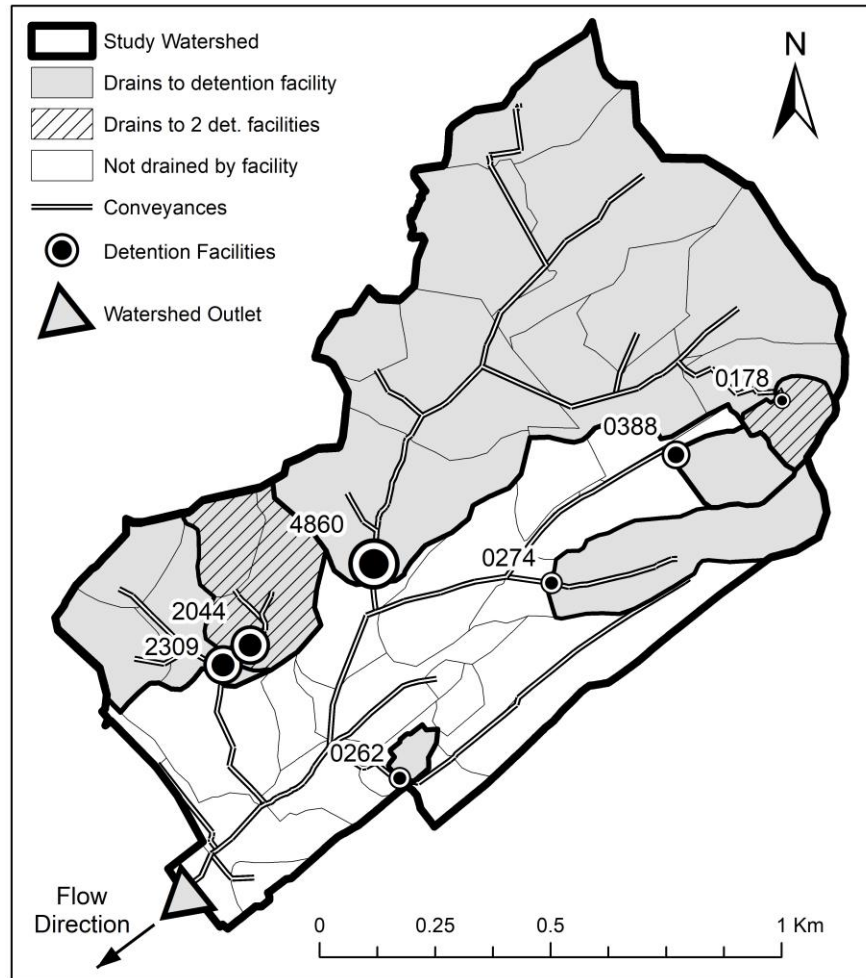


Figure 1. Study watershed in Blacksburg, VA

The test watershed was modeled in EPA SWMM 5.1, an open source program for hydrologic and hydraulic simulation from the U.S. EPA (Rossman 2015). SWMM is commonly used for RTC simulations as control algorithms may be programmed directly into the model or applied externally via a programming wrapper (Degraeve et al. 2013; Gaborit et al. 2013, 2016; Goodman and Quigley 2015; Heusch and Ostrowski 2011; Joksimovic and Sander 2016; Muschalla et al. 2014; Wong and Kerkez 2018). SWMM model inputs included high resolution land cover, topographic, and infrastructure datasets from the Town of Blacksburg's GIS database and soil characteristics from the NRCS SSURGO Database ("Web Soil Survey" 2018). The model was calibrated and validated using data from an in-channel stream sensor at the watershed outlet according to guidelines

from Titterton et al. (2017). Runoff was modeled with the default SWMM Runoff method and the Green-Ampt infiltration model (Rossman 2015). System hydraulics were represented with dynamic wave routing using a routing time step and conduit lengthening step of 15 seconds, each.

3.3.2 Simulation of a Real-Time Control Retrofit

Real-time control of the test watershed model was simulated using PySWMM, a Python programming language package that allows for the step-wise observation and modulation of SWMM models as they execute (McDonnell et al. 2016). PySWMM tools may observe and manipulate nearly any parameter in the SWMM model; however, to create a realistic scenario, RTC was applied using only data that could be feasibly monitored in a real-world application. RTC scenarios were simulated with the following assumed real-time components:

- Depth sensors in each detention basin
- Actuated valves in each detention basin outlet (diameters vary based on the original orifice diameter – see Table 2)
- Rain gauge (one for entire test watershed).

The control algorithm is executed at a 5 minute time step, which allows for adequate temporal resolution, while still maintaining a realistic interval to receive and transmit data and control commands (Bartos et al. 2018). At this interval, PySWMM interrupts the SWMM simulation and retrieves the relevant measurements (current depth, precipitation, etc.). This information is fed into the control algorithm, which decides the percentage open for the detention basin outlet valves. PySWMM sets the actuator to the required position, and the SWMM simulation continues until the following time step.

A RTC retrofit must work within the confines of local stormwater regulations, which has implications for the design of control logic. In Virginia, where the test watershed is located, detention basins must maintain 30.48 cm (1 foot) of freeboard from the top of berm during a 100-year storm, if an emergency spillway is present (VADCR 1999). Therefore, the

maximum control depth of each detention basin is 30.48 cm below its maximum depth. Many detention basins also have a primary spillway designed to pass a moderate storm event (the 10-year storm in Virginia). For detention basins with a primary spillway (facilities 4860, 2309, and 0274 in Figure 1), the maximum control depth was chosen to be 10 cm below the primary (10-year) spillway elevation. Physical characteristics of the detention basins and their contributing drainage areas (CDAs) are provided in Table 2.

Table 2. Detention Basin and Drainage Area Characteristics: (a) Basin ID equals total facility volume in m³, (b) Height from outlet invert to top of berm, (c) Depth above which control rules are suspended, (d) Volume below the maximum control depth (CV), (e) Outlet control valve diameter, (f) Contributing drainage area, (g) CDA as proportion of watershed area, (h) CDA % impervious, (i) Ratio of control volume to CDA, (j) Ratio of CV to CDA impervious area, (k) Ratio of length of sewer to CDA, and (l) Ratio of CV to maximum control depth.

<i>Physical Parameters</i>						<i>Indicator Variables</i>					
(a) Basin ID	(b) Max. Depth (m)	(c) Max. Ctrl Depth (m)	(d) Control Vol. (m ³)	(e) D _{Valve} (cm)	(f) CDA (ha)	(g) CDA / WSA (%)	(h) CDA _{imp} (%)	(i) CV / CDA (mm)	(j) CV / CDA _{imp} (mm)	(k) Drainage Density (m/m ²)	(l) CV / Ctrl Depth (m ³ /m)
4860	1.98	1.57	2,547	38.10	73.6	45.5	21.1	3.5	16.4	6.0	1,624
2309	1.70	1.19	1,272	30.48	18.2	11.3	24.8	7.0	28.1	4.3	1,065
2044	1.72	1.43	1,444	38.10	8.5	5.3	22.6	16.9	75.0	3.3	1,017
0388	1.51	1.20	237	30.48	3.1	1.9	39.2	7.7	19.8	14.3	197
0262	1.83	1.52	198	30.48	.84	0.5	62.5	23.6	37.8	9.5	130
0274	1.83	1.65	199	50.80	8.7	5.4	15.4	2.3	14.9	3.4	121
0178	1.13	0.83	87	38.10	2.4	1.5	33.9	3.6	10.6	8.0	106

3.3.3 Control Algorithms Tested

Two algorithms (RTC-1 and RTC-2) were applied to simulate real-time control of the detention basin outlet valves. The first algorithm was adapted from a control methodology originally presented by Gaborit et al. (2013), and further examined by Gaborit et al. (2016). The second algorithm is a new approach developed during this study. Both control strategies are local, heuristic, and reactive.

RTC-1: Approach from Existing Literature

This strategy was developed with the following objectives: maximize detention time, avoid overflow, capture the first-flush, drawdown pond volume smoothly, and minimize valve operations (Gaborit et al. 2013). Of the several RTC methods tested in the original paper, “Evolved C” was found to be the most effective, and therefore was chosen for use in this study. The algorithm uses real-time measurements of pond depth, current and accumulated rainfall depth, and detention time. The depth-based control rules were converted from the original facility to the seven test facilities studied herein using the depths relative to each facility’s maximum control depth. The control algorithm was developed specifically for the detention basin to which it was originally applied; therefore, performance differences between this study and the original results were expected.

RTC-2: Development of New Rule-Based Control Approach

Since the facilities in this case study are dry detention basins, the biggest improvements to water quality will come from hydraulic modifications that reduce the quantity and duration of erosive flows to promote downstream channel stability. The primary objective of this RTC strategy, therefore, was water quantity improvement and improved valve stability when compared to RTC-1.

The RTC-2 control rules are based on measurable hydrologic parameters; therefore, they are non-site specific. Data inputs for this strategy include real-time water depth, current and accumulated rainfall depth, and detention time. RTC-2 also uses the stage-storage curve, CDA, curve number (CN), and time of concentration (t_c) as control calibration inputs. Runoff volume from the rainfall over the last respective “ t_c ” minutes to each facility is calculated using the NRCS runoff curve number method (NRCS 1986), and compared to the excess volume (max. control volume - current pond volume) to assess how rapidly to drawdown the facility (Figure 2). The control logic’s “percent open” equates to the fraction of the orifice’s effective flow area compared to fully open conditions. However,

in real-life implementation with a butterfly valve, this effective area must be translated to a rotation angle.

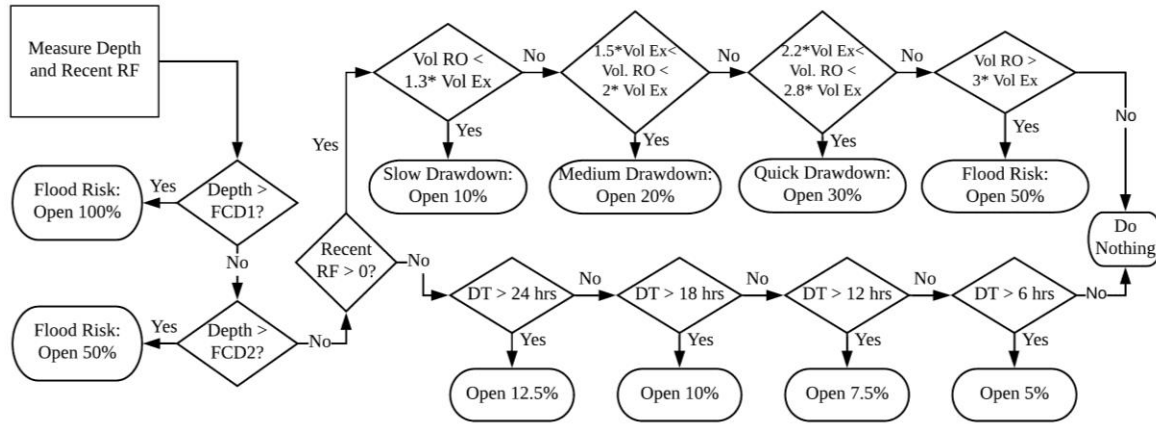


Figure 2. RTC-2 control logic, executed every five minutes. RF = rainfall. FCD1 = flood control depth #1, equal to elevation of maximum control depth. FCD2 = flood control depth #2, elevation 5% of volume below FCD1. Vol RO = volume of runoff estimated from recent RF using NRCS curve number method. Vol Ex = control volume – current volume of water in facility. DT = detention time.

Both strategies incorporate deadband in the control rules to improve stability (i.e. reduce large fluctuations of motorized valve). RTC-2 has additional rules aimed to improve stability over that of RTC-1. Upon reaching one of two critical depth thresholds (FCD1 and FCD2 in Figure 2), rules are suspended for 30 minutes. In addition, a “slowing mechanism” prevents the valve from closing by more than 5% in a time step (5 minutes). Both of these factors prevent the rapid opening and closing of the actuated valve, which would lead to hydraulic shocks and overuse of the actuated valve. Stepped drawdown in both methods aims to prevent hydraulic shock to downstream channels. In RTC-1, the valve remains closed after an event until 48 hours have passed. RTC-2 gradually increases the valve % open starting at 6 hours after the storm event; the facilities drain in < 48 hours, as required per local regulations (VADCR 1999).

3.3.4 Conditions Tested

Retrofit Permutations

Fourteen permutations of RTC retrofitting within the test watershed were tested for each of the two RTC strategies. This included seven permutations where RTC was applied to each facility individually (with all other facilities static), and seven permutations of combined RTC retrofit scenarios (two or more facilities have RTC). Results of the seven individual RTC scenarios were analyzed at the outlet of each facility and at the watershed outlet. Results of the seven combined scenarios were assessed at the watershed outlet.

Baseline Watershed Conditions

In addition to the RTC scenarios, static and predevelopment scenarios were modeled. The static condition, with all basin outlets fully open and unmoving, was evaluated to establish a baseline of current stormwater management in the watershed. A predevelopment condition was simulated, with assumed land cover values of 70% forest, 27% open space, and 3% impervious surface. Channel roughness (Manning's n coefficient) of 0.030 was used. These parameters represent a reasonable estimate for the watershed's pre-urbanized state and allow for comparison of RTC performance to hydraulic conditions that promote local stream health.

Precipitation Scenarios

All watershed test conditions (static, predevelopment, RTC-1, and RTC-2) were subjected to both synthetic design storms and real precipitation data. The design storms consisted of NRCS Type II storms, with a duration of 24 hours and return periods (T_R 's) ranging from 0.25 years (3 months) to 100 years. In addition, 15 years of regional NOAA precipitation data was used to evaluate the net performance of RTC under realistic, irregular rainfall conditions over a long duration (5,479 days of simulated weather). The 15-year rainfall record had an average annual precipitation of 1,170 mm, which is higher than the local long-term average of 1,038 mm.

3.4 Results and Discussion

The simulated RTC retrofits were analyzed using the following criteria:

1. Impact on peak outflow and duration of erosive flows at the facility outlet.
2. Impact on peak outflow and duration of erosive flows at the watershed outlet.
3. Level of algorithm instability (as characterized by a high rate of valve fluctuations).

In addition, the relationship between facility RTC performance and facility physical characteristics is discussed.

3.4.1 Impact of RTC on Local Conditions (at Facility Outlet)

RTC Performance during Discrete Storm Events

The peak flow of each design storm was found at the outlet of each facility under static conditions, RTC-1, and RTC-2. The RTC scenarios were each compared to the static scenario to find the percent change in peak flow. Results plotted in Figure 3 show that performance varied significantly across the facilities. The only consistent result appears to be that peak flow rates for the largest magnitude precipitation events were typically made worse, or remained unchanged, in the presence of real-time control. For events with a return period of 2 years and less, some detention ponds experience significant reductions in peak flow rate; e.g. $Q_{p-0.25yr}$ of facility 0262 decreased by 82 and 85% using RTC-1 and RTC-2, respectively. However, for the same storm events, other ponds experience increased peak flows, up to 150% greater than static condition (Q_{p-1yr} for facility 0274). For storms with $T_R \geq 5$ years, there is no observed benefit to peak flow with RTC at any of the detention basins. The negative impact of RTC seems to lessen as storm magnitudes increase from the 5-year to the 100-year, as expected. For the largest storms, the relative impact of RTC lessens (as the outflow valve is likely completely open for most of the event), and therefore the change in peak flow with respect to the static condition approaches zero percent. Because the peak flows and volumes of smaller storm events are relatively small, the

change due to RTC has the potential to be very high, in both positive and negative directions.

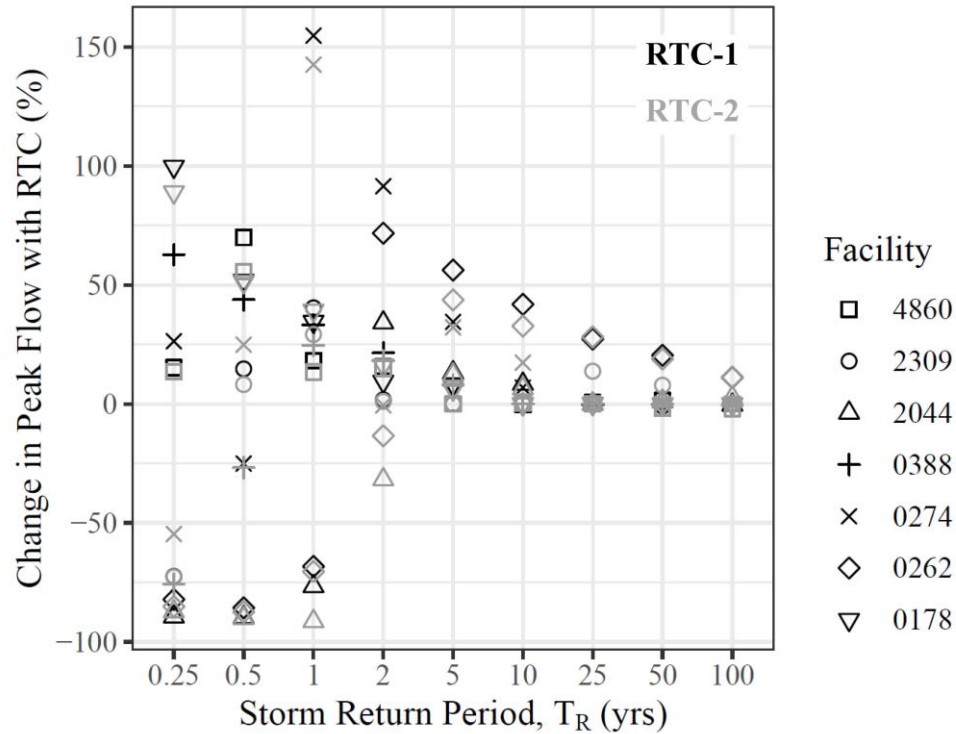


Figure 3. Change in peak flow with RTC for NRCS 24-hour Synthetic Design Storms of varying return periods. Positive % change indicates increased peak flow with RTC compared to static, and vice versa.

Figure 4 details more of the processes influencing these changes in peak flow. The left hand plots in the figure (*a1* to *d1*) show the behavior of facility 2044 during the 1-year storm, demonstrating an example where improvements were made with RTC. The right hand plots (*a2* to *d2*) show the same facility's behavior during the 5-year storm, when RTC causes increased peak flow.

As seen in Figure 4(*b1*), the 1-year peak flow is reduced from 0.24 m³/s to 0.05 m³/s with RTC-1 and 0.02 m³/s with RTC-2. In the hydrograph for the larger storm (Figure 4(*b2*)), both RTC methods cause peak flow to increase by about 13%. This is likely caused by the reactive nature of the RTC strategies tested. Both strategies restrict outflow and retain volume more than the static condition at the beginning of the event. At a certain point, the

volume of water in the detention basin approaches critical flood risk levels, causing the valve to quickly open to 50% or 100% of its total area. Although the orifice size in the RTC scenario is no larger than that of the static, the RTC orifice head is higher than the static water level at the moment of valve opening (Figure 4[d2] and [c2]), causing a higher peak discharge. This behavior causes the increased peak flows seen in Figure 3. It is likely that the incorporation of quantitative precipitation forecasts to estimate future runoff would mitigate the negative effects of RTC during large storm events, as the technique has demonstrated positive outcomes in field experimentation (Marchese et al. 2018; Opti RTC and Geosyntec Consultants Inc. 2017). In addition, computer simulations of predictive RTC have found it to improve conditions for large storm events (Bilodeau et al. 2019; Gaborit et al. 2016; Wong 2017).

Depth oscillations occur with RTC-1 but not with RTC-2 (Figure 4[d2]). This is due to the rule-suspension programmed into RTC-2 which prevents the valve from closing for 30 minutes after water depth exceeds a flood risk level (Figure 4[d2], light gray dotted lines). Without this measure, RTC-1 causes the valve to close and open two additional times before the runoff finally diminishes.

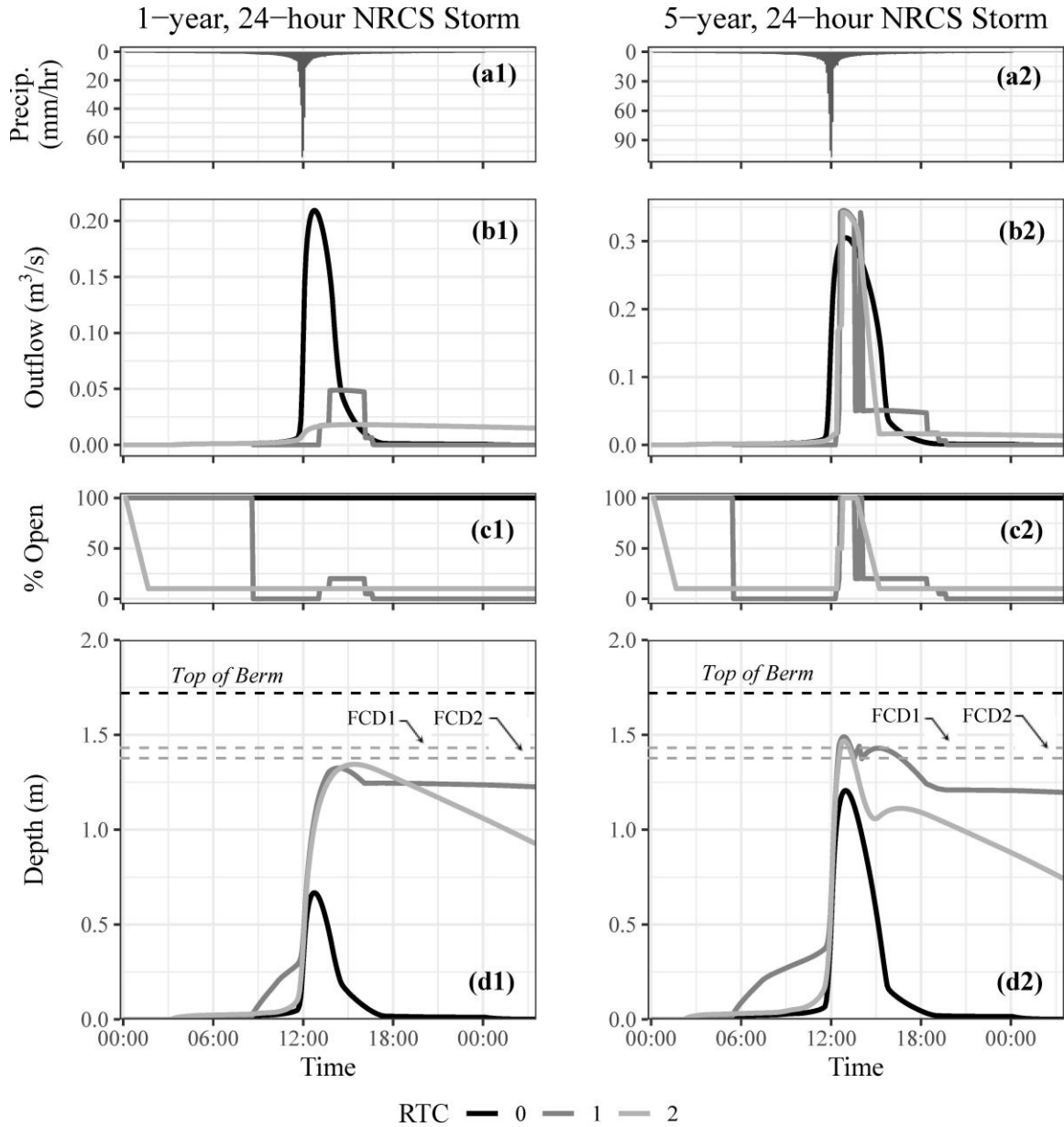


Figure 4. Performance of facility 2044 with no control (static: shown in black), RTC-1 (middle gray), and RTC-2 (light gray) for the 1-year and 5-year design storms. Precipitation, basin discharge, valve position (% open), and depth of water in the basin are depicted. Basin top of berm (black dashed) and flood control depths (gray dashed) depicted (d1,d2).

RTC Performance during 15-Year Simulation

While the peak flow rate is an important consideration of any stormwater management strategy, current literature has found the flow duration curve (FDC) to be a more scientifically sound tool for assessing the efficacy of a management technique (Goodman and Quigley 2015; Jackson and Booth 1997; Marchese et al. 2018; Nehrke and Roesner 2004; Palhegyi 2010). The FDC shows the frequency with which flows of varying magnitudes are exceeded and is useful to understand the impact a control measure has on the entire flow regime.

While many stormwater regulations focus on mitigating the 2- and 10-year peak flows, it is likely that smaller, more frequent events cause the majority of geomorphological impacts on the stability of a stream channel (Tillinghast et al. 2011). The critical flow rate is the minimum discharge associated with streambank erosion (Jackson and Booth 1997), and this parameter can be used to quantify the net effect of RTC on total erosive flows. To accurately quantify the critical flow rate, analysis of local hydraulics and stream bed characteristics is needed; however, this type of analysis is outside of the scope of this study. From Jackson and Booth (1997), one half of the 2-year predevelopment peak flow rate is considered an appropriate estimate of critical flow rate. This metric was used for establishing the critical flow rate throughout this analysis.

Flow duration curves of the 15-year simulation were computed for the outlet of each facility, allowing for comparison between RTC and static scenarios across the full flow regime (Figure 5). Where the RTC curve is below the static curve, RTC has reduced the duration of the corresponding flows (ordinates of Figure 5). Where the RTC curve is above the static curve, the duration of those flows has increased. For ordinate values above Q_{crit} , reduced duration of flows has a positive impact on improving stream stability, and vice versa. Differences between RTC and static scenarios below Q_{crit} are likely insignificant to geomorphological change.

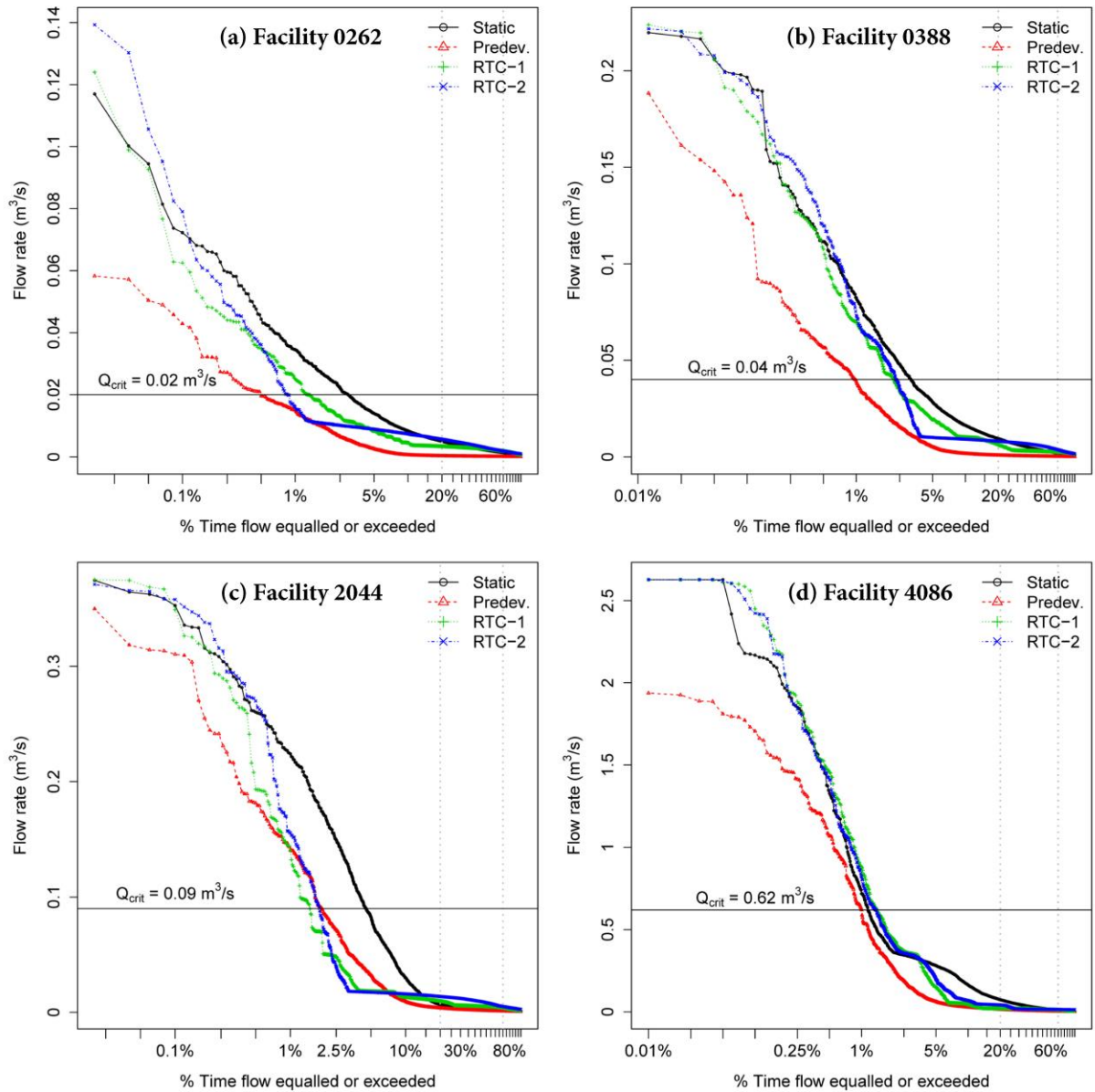


Figure 5. Flow Duration Curves at outlets of four facilities.

The majority of FDCs show mixed results, where RTC reduced the duration of a certain range of flows while increasing the duration of another. Four FDCs are shown in Figure 5 to demonstrate the range of impacts the RTC strategies have on flow regimes at the facility outlets. Both RTC-1 and RTC-2 cause reduced duration of flows just above Q_{crit} in facilities 0262 and 2044 (Figure 5Figure 5[a] and [c]). However, the RTC improvements diminish

for the lower frequency, high magnitude flow rates. RTC-1 approaches the static condition and RTC-2 exceeds the static condition for greater discharges in facilities 0262 and 2044. The FDC for facility 0388 shows a similar pattern, but the improvements from RTC are less, since these flow duration curves do not stray far from the static condition. Conditions at facility 4860 are only made worse, or remain unchanged, by RTC for all discharges exceeding the critical flow rate. FDCs from the facilities 0274 and 0178 (not shown) closely resemble that of facility 0388, and the FDC of facility 2309 (not shown) has a similar pattern to that of facility 4860.

To summarize the quantity of erosive flows, the total time that flows exceeded the critical flow rate, or Q_{crit} exceedance time (ET), was calculated for each facility outlet, for the four watershed conditions (static, predevelopment, RTC-1, and RTC-2). Changes in Q_{crit} ET for RTC-1, RTC-2, and predevelopment scenarios were normalized as a percent deviation from the static condition of each facility (Figure 6[a]). This process was repeated with two additional flow rate thresholds: the two-year predevelopment peak, Q_{p2yr} , and the 10-year predevelopment peak, Q_{p10yr} . These additional flow rate thresholds were used to differentiate the behavior during more extreme flows (Figure 6[b] and [c]).

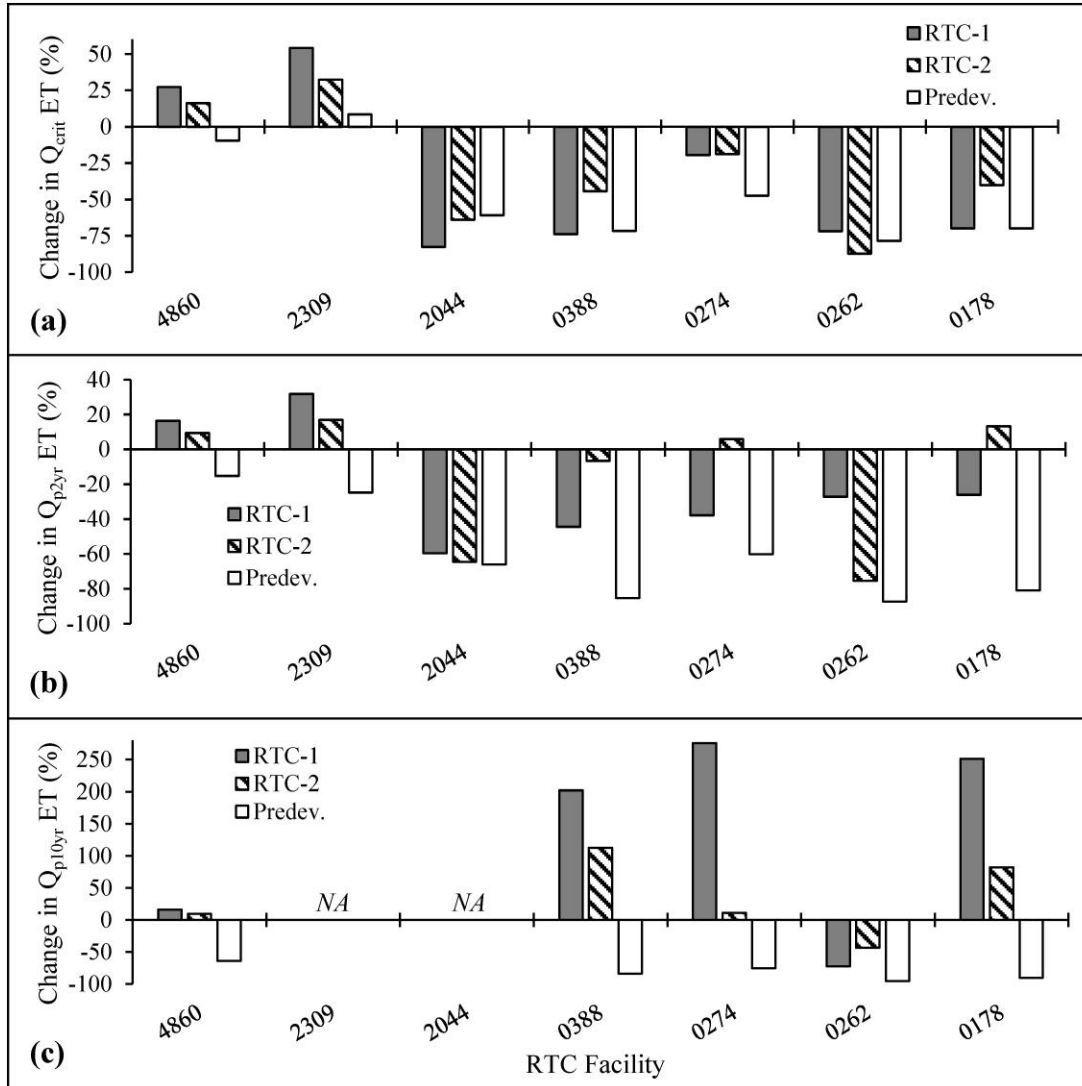


Figure 6. Change in time exceeding selected flow rates at outlet of each detention basin, as compared to static: (a) critical flow rate (equal to $\frac{1}{2}$ of the predevelopment 2-year peak flow), (b) predevelopment 2-year peak flow, (c) predevelopment 10-year peak flow.

Q_{crit} ET was reduced by both RTC strategies for the five smallest facilities, often coming close to the predevelopment value (Figure 6[a]). RTC of the two largest detention basins (4860, 2309) caused increased Q_{crit} ET compared to the static scenario. Interestingly, for both of these detention basins, the static and the predevelopment conditions had similar values for Q_{crit} ET (<10% difference), meaning that there was little room for improvement by RTC over static control.

Q_{p2yr} ET increased for the two largest basins and decreased for three of the basins in both RTC strategies (Figure 6Figure 6[b]). Facilities 0274 and 0178 experienced reduced Q_{p2yr} ET with RTC-1 and increased Q_{p2yr} ET with RTC-2. Figure 6(c) shows that four of five facilities experienced worsened conditions (increased Q_{p10yr} ET) due to RTC. Conditions for facility 0262 were improved with RTC (decreased Q_{p10yr} ET). Facilities 2309 and 2044 had no flows above Q_{p10yr} during the 15-year simulation, and could not be compared.

In general, the net effect of RTC was positive for most detention basins; however, conditions were often worsened for more extreme (rarer) events, consistent with previous research examining the effect of RTC on FDC (Parolari et al. 2018). This impact caused the duration of flooding to increase in the presence of RTC for all seven facilities by as much as 7 hours during the 15-year simulation.

3.4.2 Impact of RTC on Downstream Conditions (at Watershed Outlet)

Results of RTC retrofitting were evaluated at the watershed outlet in order to assess the extended impact that local RTC may have on downstream conditions.

RTC Performance during Discrete Storm Events

The impact of RTC on peak discharge at the outlet of the watershed was inconsistent across detention basins and over storms of varying magnitudes (Table 3). The only consistently positive result was for the smallest storm ($T_R = 0.25$ years), where RTC on any detention basin reduced peak flow at the watershed outlet by 0.1% to 20.5%. This finding is curious since four facilities with RTC-1 and two facilities with RTC-2 experienced increases in *local* peak flow during the same 0.25-year storm (Figure 3). This result may be due to shifts in runoff peak arrival at the downstream location. Additional downstream peak flow reductions were observed, despite local peak flow increases. For example, during the 5-year storm, Figure 3 shows that RTC did not reduce peak flows at any basin outlet, but Table 3 shows that RTC caused slight reductions in peak flow at the watershed outlet in most cases. RTC may positively influence downstream peak flows, but the potential for worsened conditions must also be considered.

Table 3. Percent change in peak flow at watershed outlet with RTC relative to the static condition. Increased peak flow is shown in bold, and decreased peak flow is shown in italics.

		<i>Change in Peak Flow (%)</i>													
<i>Facility:</i>		4860		2309		2044		0388		0262		0274		0178	
<i>RTC</i>															
<i>Method:</i>		1	2	1	2	1	2	1	2	1	2	1	2	1	2
<i>Event Return Period (yrs)</i>	0.25	-20.5	-19.6	-7.2	-6.3	-0.5	-1.5	-4.8	-3.1	-5.4	-5.1	-1.1	-0.2	-1.3	-0.1
	0.5	1.0	3.3	1.4	2.2	2.7	-2.0	-5.3	-4.7	-1.4	-1.1	-2.7	-1.0	-0.6	-0.3
	1	58.1	0.4	-2.0	-1.7	-0.2	-0.8	-3.5	-2.9	-3.0	-3.3	-1.1	-0.2	-1.7	-0.9
	2	-20.9	-18.5	-0.7	-4.5	3.6	6.3	-0.7	-1.8	0.6	-1.5	6.9	7.0	4.3	6.9
	5	4.5	7.0	0.1	-0.5	-1.0	-5.6	-0.2	-0.6	-1.3	-1.7	-0.3	-0.5	-0.2	-0.1
	10	-2.9	-0.7	0.0	0.6	0.3	-0.1	-1.0	-1.6	-0.4	-2.2	-1.3	-0.4	-0.5	-0.5
	25	9.5	1.3	3.2	3.2	-0.9	-1.8	-1.8	-3.4	-2.1	-3.7	-3.1	-2.4	0.2	-1.1
	50	17.3	7.5	1.2	1.9	2.5	0.5	0.1	0.8	-0.9	0.5	0.1	0.8	0.3	2.1
	100	-0.8	-0.8	-3.7	-3.9	-1.0	-0.9	0.3	-0.1	0.2	-0.2	0.3	-0.3	0.1	0.2

RTC Performance during 15-Year Simulation

Critical flow rate was calculated for the watershed outlet point using the same method discussed previously. RTC scenarios included seven permutations of single basin retrofits and seven combination retrofits (Table 4). The Q_{crit} ET at the watershed outlet was reduced in almost every RTC retrofit permutation (Figure 7[a]). The performance at the watershed outlet differs from the performance at the basin outlet in this regard, as RTC *increased* the duration of erosive flows of facility 4860 and facility 2309 at the detention basin outlet. This indicates that worsened local conditions may have some net positive effect on conditions downstream (as with peak flows, discussed before).

Table 4. Combined RTC retrofit scenarios

	<i>Facilities Controlled</i>							<i>% of Watershed with RTC</i>
	4860	2309	2044	0388	0274	0262	0178	
Combo #1	X	X	X	X	X	X	X	64.5%
Combo #2	X	X	X	X		X		59.1%
Combo #3	X	X	X			X		57.3%
Combo #4	X	X	X					56.7%
Combo #5				X		X		2.4%
Combo #6		X	X	X		X		13.7%
Combo #7			X			X		5.8%

The impact of a single facility retrofit on downstream duration of erosive flows was found to be relatively small (less than 4% change). This impact does not scale linearly with the percent of watershed area draining to a given detention basin; for example, a retrofit of facility 4860 lead to similar downstream performance as that of facility 2044, despite the fact that the facilities drain vastly different proportions of the watershed area: 45.5% and 5.3%, respectively.

Compared to single facility retrofits, the combined RTC scenarios had a greater magnitude of impact at the watershed outlet. The largest reductions in Q_{crit} ET were from Combo # 1 and # 2 using RTC-2. In both of these combinations, a majority of the watershed area drains to a RTC stormwater facility (65 and 59%, respectively), but similar results were found for Combo #6, where RTC affect only 14% of the watershed area (Table 4).

RTC's impact on watershed Q_{p2yr} and Q_{p10yr} ET showed mixed trends (Figure 7[b] and [c]). RTC on facility 4860 and facility 2309 increased Q_{p2yr} ET (Figure 7[b]); a retrofit of these locations would likely exacerbate conditions for larger, less frequent discharge events. The remaining detention basins succeeded in reducing ET for the 2- and 10-year predevelopment peak flows, with facility 2044 having the greatest benefit.

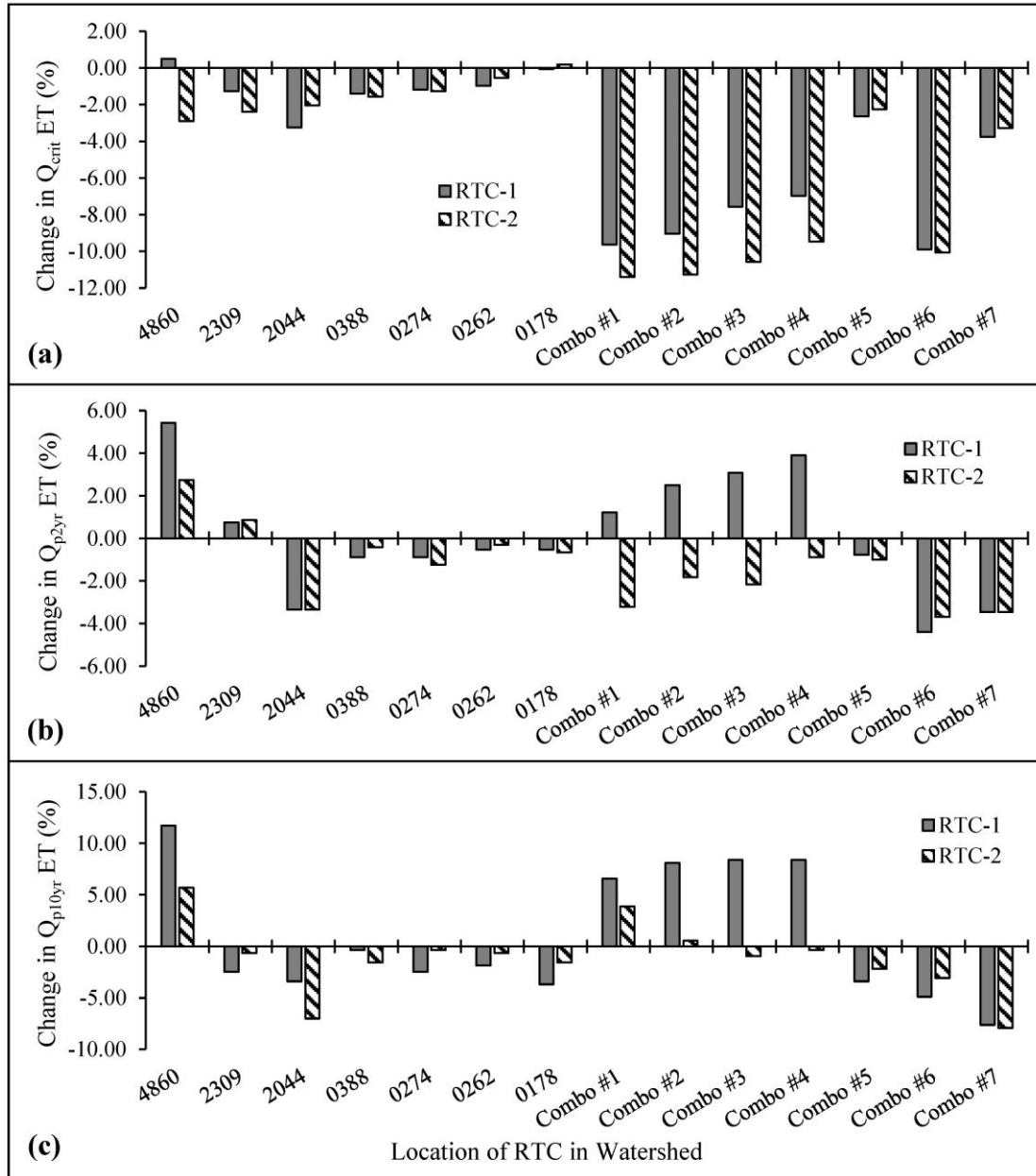


Figure 7. Change in time exceeding selected flow rates at watershed outlet, as compared to static: (a) critical flow rate (equal to $\frac{1}{2}$ of the predevelopment 2-year peak flow), (b) predevelopment 2-year peak flow, and (c) predevelopment 10-year peak flow. RTC was simulated at the location indicated, either on a single detention basin, or a combination of detention basins.

For RTC strategy 1, combined control scenarios tended to worsen ET of Q_{p2yr} and Q_{p10yr} if facility 4860 was included in the combined control (Combo #1 – 4). Combination scenarios of RTC-2 also had a more positive impact if they did not include RTC at facility 4860

(Figure 7[b] and [c]). Neither RTC algorithm was superior in all instances, although RTC-2 reduced Q_{crit} ET the most in the combined scenarios. Additionally, many conditions where RTC-1 had a negative impact (increased ET), RTC-2 was found to have a positive impact, or a lesser negative impact (Figure 7).

The differences between predevelopment and static exceedance times (ETs) were calculated to be -46% (Q_{crit} ET), -51% (Q_{p2yr}), and -81% (Q_{p10yr}). When these numbers are compared with the ordinate scale values in Figure 7, it is clear that the downstream impacts of RTC were far from achieving predevelopment ET values.

3.4.3 Comparison of Algorithm Stability

The stability of the control algorithm (i.e. its resistance to rapid fluctuations/oscillations in valve position) is an important aspect of RTC performance. If the algorithm is unstable, the valve will be subjected to more rapid wear and tear. Additionally, spikes in discharge due to sudden changes in valve position are more likely to induce hydraulic shocks in downstream channels, potentially leading to streambank erosion.

The total movements in valve position during the 15-year simulation were summed across the seven detention basins (Figure 8). RTC-1 caused more changes in valve position compared to RTC-2 for all facilities except 4860. In addition, RTC-1 caused more medium and large fluctuations in valve position (> 5% change in effective area) across all detention basins. Certain stabilizing characteristics of the RTC-2 algorithm are believed to have caused this improved stability, such as the time-based rule suspension employed if pond depths exceed flood risk levels. Additionally, because the valve is never fully closed in RTC-2, a change in valve position is not needed for many small storm events.

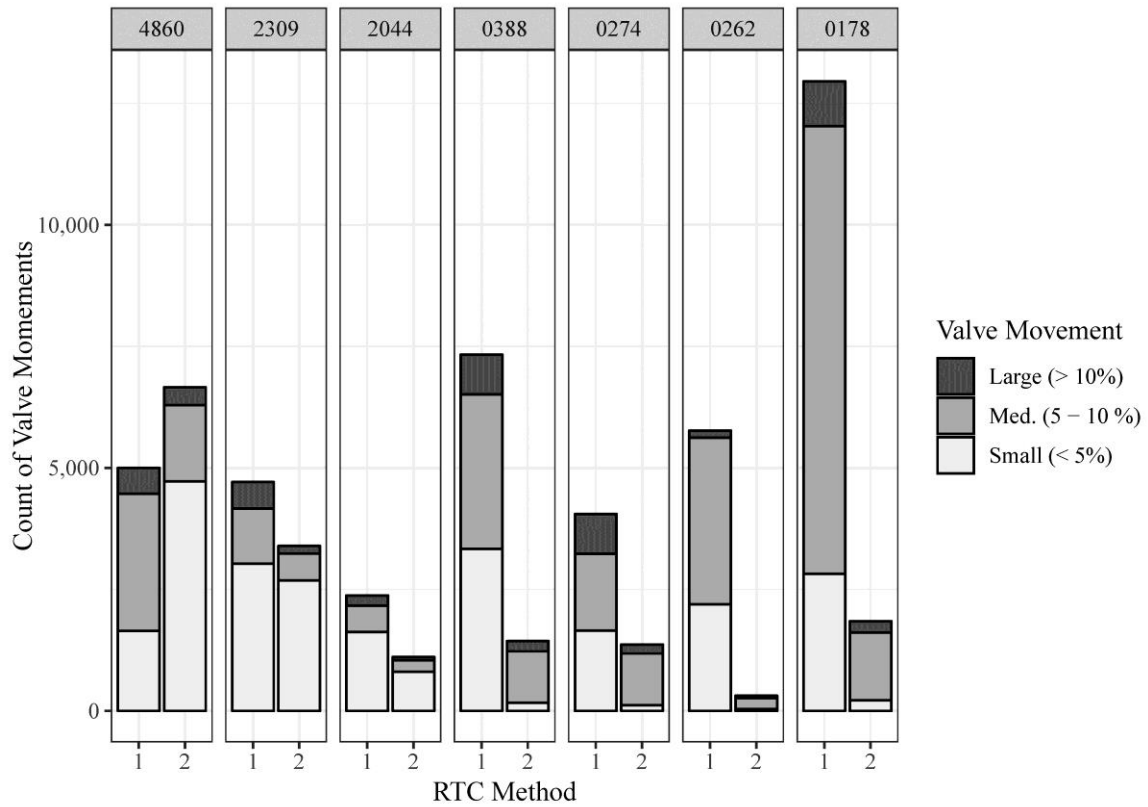


Figure 8. Count of valve movements over 15-year simulation.

Additional problems with algorithm instability of RTC-1 are illustrated in Figure 9. The real precipitation event shown, which is equivalent to a 10-year, 24-hour storm, was extracted from the 15-year simulation. During the event, RTC-1 causes 23 total valve movements, and RTC-2 causes 65 total valve movements. Large fluctuations in discharge occur with RTC-1 because the movements have larger oscillatory amplitude ($> 10\%$). Most of the 65 valve moves with RTC-2 were small adjustments, allowing for much smoother discharge despite a larger total quantity of movements.

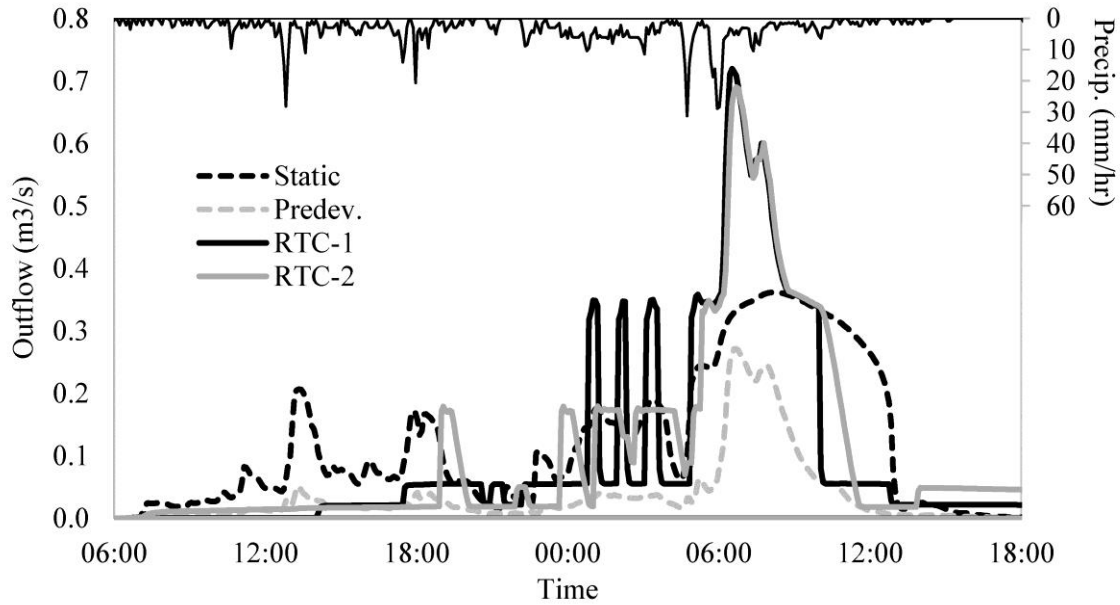


Figure 9. Outflow hydrograph of facility 4860 during a storm event for four conditions: static, predevelopment, RTC-1, and RTC-2.

3.4.4 Comparison of RTC Performance to Facility Indicator Variables

Due to large variability of results, a concise statement about which facilities were best suited for a RTC retrofit is impractical. It is easy to conclude that facility 4860 performed the worst in nearly every metric. Locally, peak flows and Q_{crit} ET were both made worse, and at the watershed outlet, the RTC of this basin increased duration of the highest flow rates. Facility 2309 would likely be ranked as the second worst-suited for retrofit since real-time control of this basin also caused increased ET of Q_{crit} , Q_{p2yr} , and Q_{p10yr} locally. An argument could be made for the superior performance of RTC on facilities 2044 and 0262. The RTC of both basins significantly reduced peak flows for all design storms up to TR = 1-year with RTC-1, TR = 2-year with RTC-2, and contributed to reduced ET of all threshold flow rates at the watershed outlet.

Correlation of a facility's RTC retrofit potential with one or more physical attributes of the detention basin or its drainage area would be beneficial, as this type of relationship would allow engineers and city officials to make informed RTC retrofit decisions without extensive modeling. The following simple indicator variables were considered (Table 2):

1. CV/CDA: the ratio of control volume to contributing drainage area
2. CV/CDA_{imp}: the ratio of control volume to impervious contributing drainage area
3. Drainage density: the ratio of the CDA to the length of storm sewer within CDA
4. CV/Control Depth: the ratio of basin control volume to the maximum control depth

Of these four parameters, the first two were found to loosely correspond to a basin's RTC performance. The worst-performing detention basin (4860) has the second lowest value of CV/CDA (3.5 mm), and third lowest value of CV/CDA_{imp} (16.4 mm). The two best-performing basins (2044 and 0262) had the two highest values of CV/CDA (16.9 mm and 23.6 mm) and of CV/CDA_{imp} (75.0 mm and 37.8 mm, respectively). For context, the facility original tested by Gaborit et al. (2013), which had largely positive results from RTC-1, had values of 24.6 mm and 74.4 mm for CV/CDA and CV/CDA_{imp}, respectively. Neither of the other two parameters appeared to correspond with facility RTC performance.

This finding is statistically inconclusive due to the large variation in RTC results and the relatively small sample size ($n = 7$ facilities). Nonetheless, it is logical that the ratio of CV/CDA would be positively correlated to RTC potential, as this ratio represents the depth of runoff that the facility can store. If a facility's capacity is limited in the static condition, then it would not be able to retain the additional water needed for RTC benefits. However, with excess capacity, RTC may make a positive impact.

3.5 Conclusion

A small headwater catchment was modeled for RTC retrofit of its existing stormwater detention basins in order to assess the potential hydraulic benefits that may be gained from this type of modification. Two RTC algorithms, both heuristic, reactive, and local, were tested for synthetic design storms of varying magnitudes, and for 15 years of real precipitation data from the region. The resulting hydraulic conditions with and without RTC were assessed locally (at the outlet of each detention basin) and downstream, at the watershed outlet. From the results, the following conclusions can be made:

1. For smaller, high frequency events ($T_R \leq 2$ -years), RTC reduced peak discharges at the outlets of some detention basins, while increasing the peak flow for others. Across all detention facilities, no reduction in peak flow from RTC was observed for events larger than the 2-year storm. The increase in peak flow rates occurred when the pond depth exceeded a critical flood risk depth, and the outlet valve was forced to open suddenly.
2. The impact of RTC on peak flow rates at the watershed outlet was positive for the 0.25-year storm (0.1 to 20% reduction in peak flow), but had mixed results for all larger storm events (some positive and some negative).
3. The total duration of erosive flows at the facility outlet was reduced by RTC in most cases (five of seven detention facilities). However, even if the net impact on Q_{crit} ET was positive, RTC often exacerbated ET of the highest flows, and caused increased duration of facility flooding in all cases.
4. At the watershed outlet, all single-facility RTC scenarios lead to slightly reduced durations of Q_{crit} ET (reduced by $< 4\%$) compared to the static condition, even those which caused increased Q_{crit} ET locally. Combined RTC scenarios also lessened Q_{crit} ET, with a maximum reduction of 11.4% by applying RTC-2 to all seven detention basins. Worsened ET of Q_{p2yr} and Q_{p10yr} occurred with RTC of the largest facility (4860).
5. In general, algorithm RTC-2 lead to greater stability due to stabilizing aspects of the control logic. RTC-1 tended to lead to a greater number of valve movements (especially oscillations greater than 10%).
6. There is evidence that facility performance under RTC could be linked to certain facility characteristics, such as CV/CDA and CD/CDA_{imp}, but variation is too high and sample size too low to make a confident assertion.

The results presented herein demonstrate that RTC retrofitting of existing structures has the potential to improve hydraulic conditions, both locally and downstream. However, without proper algorithm design and facility selection, results indicate that RTC retrofitting may lead to increased peak flows, duration of erosive discharges, duration of local

flooding, and high instability. These findings underscore the importance of considering a wide range of precipitation conditions when testing new stormwater control measures.

Many negative outcomes observed in this research occurred when RTC did not maintain adequate capacity for the imminent storm. In actual implementation, a human operator would be present, and capable of suspending the RTC preceding a large forecasted rainfall event. Additionally, if rainfall forecasts had been incorporated into the control logic, then these problems can potentially be avoided. The findings presented here demonstrate the importance of the ongoing research regarding predictive RTC methods. Additionally, further research is needed to test the relationship between the physical characteristics of a detention basin and its potential for creating watershed-level benefits with a RTC retrofit, using a large sample size of candidate facilities.

4. Conclusions

a. Summary and Implications

In this study, two reactive, rule-based RTC algorithms were tested at multiple stormwater facilities to assess the long-term hydraulic benefits of a RTC retrofit. Results showed that some hydrologic benefit is to be had from applying RTC to most of the facilities studied; however, there was also the potential for worsened conditions with this technological upgrade in the form of increased peak flow rates and increased duration of the largest flows and facility flooding. These findings show that not all facilities are appropriate for RTC retrofitting. In addition, some control strategies may be effective for small storm events, but ineffective, or even dangerous, when applied during large events. This work emphasizes the importance of testing new technologies, such as stormwater RTC, under adverse conditions which may cause failure. It is by pushing our innovations to their limits that improvements can be made to methods of stormwater management.

b. Future Work

The SWMM model and PySWMM scripts developed for this study were used to test a specific scenario of RTC for existing detention facilities. However, this research by no means exhausted the possibilities for RTC retrofitting within the test watershed. Future simulations of this test watershed may include different control algorithms (e.g. predictive control, optimization-based control) or future climate scenarios with variations in rainfall intensity. To facilitate any future research using the subject watershed in this study, the following items were included in Appendix A through C: detention facility storage and outlet geometries, model calibration and validation results, relevant SWMM input details, and sample PySWMM scripts used to create static, RTC-1, and RTC-2 scenarios. Complete datasets of this study's results are presented in Appendix D. Additionally, to assess how the 5-minute RTC sampling interval affected watershed modelling, the impact of temporal aliasing on different RTC time steps was investigated and the findings are presented in Appendix F. The impact of temporal aliasing on the measurement of peak flow rate – and

therefore assessment of the effect of RTC – was found to vary significantly depending on the interval size (tested from 1-minute to 10-minute intervals). Future research in RTC applications should consider the significance of the sampling interval when designing control algorithms for the efficacy of the RTC strategy and the potential error in results.

Finally, this research represents only a part of a greater effort to integrate smart technology into urban stormwater management, specifically in the Town of Blacksburg (TOB). Current work is underway to create interactive hydrologic analysis tools for use by TOB stormwater managers, similar to those developed by Brendel et al. (2019). These real-time tools go hand in hand with RTC retrofitting to pave the way for the future of smart stormwater management.

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Appendix

Appendix A: Detention Facility Details

- **Detention Basin Stage-Area Curves**
- **Detention Basin Outlet Structures**

Table A1. Detention Basin Stage-Area Curves

<i>Facility 4860</i>		<i>Facility 2309</i>		<i>Facility 2044</i>		<i>Facility 0274</i>	
Stage (ft)	Area (ft ²)	Stage (ft)	Area (ft ²)	Stage (ft)	Area (ft ²)	Stage (ft)	Area (ft ²)
0.454	23	0.578	664	0.658	79	0.887	6
1.454	863	1.578	11,308	1.658	7,976	1.887	683
2.454	12,659	2.578	17,350	2.658	14,342	2.887	1,484
3.454	31,686	3.578	18,620	3.658	17,692	3.887	2,139
4.454	43,872	4.578	21,056	4.658	20,510	4.887	2,879
5.454	51,466	5.578	25,386	5.658	23,265	5.887	3,995
6.454	56,770						

<i>Facility 0388</i>		<i>Facility 0262</i>		<i>Facility 0178</i>	
Stage (ft)	Area (ft ²)	Stage (ft)	Area (ft ²)	Stage (ft)	Area (ft ²)
0.945	482	0.000	108	0.710	431
1.945	2,190	1.000	790	1.710	1,478
2.945	3,354	2.000	1,246	2.710	2,522
3.945	4,635	3.000	1,751	3.710	3,879
4.945	6,165	4.000	1,977		
		5.000	2,222		
		6.000	2,450		

Property	Value	Property	Value	Property	Value
Name	Or12	Name	Or08	Name	Or07
Inlet Node	Owens_Street	Inlet Node	Owens_Street	Inlet Node	Owens_Street
Outlet Node	1363_ControlJunction	Outlet Node	1363_ControlJunction	Outlet Node	1130_ControlJunction
Description		Description		Description	
Tag		Tag		Tag	
Type	SIDE	Type	BOTTOM	Type	BOTTOM
Shape	CIRCULAR	Shape	CIRCULAR	Shape	CIRCULAR
Height	1.25	Height	4	Height	4
Width	0	Width	0	Width	0
Inlet Offset	0	Inlet Offset	5.583	Inlet Offset	5.479
Discharge Coeff.	0.6	Discharge Coeff.	0.6	Discharge Coeff.	0.6
Flap Gate	NO	Flap Gate	NO	Flap Gate	NO
Time to Open/Close	0	Time to Open/Close	0	Time to Open/Close	0

Figure A1. Detention Basin 4860 Outlet Structures (unit = feet)

Property	Value	Property	Value
Name	Or09	Name	Or10
Inlet Node	Wong_Park_1	Inlet Node	Wong_Park_1
Outlet Node	1063_ControlJunction	Outlet Node	1064_ControlJunction
Description		Description	
Tag		Tag	
Type	SIDE	Type	BOTTOM
Shape	CIRCULAR	Shape	CIRCULAR
Height	1	Height	2.25
Width	0	Width	0
Inlet Offset	0	Inlet Offset	4.25
Discharge Coeff.	0.6	Discharge Coeff.	0.6
Flap Gate	NO	Flap Gate	NO
Time to Open/Close	0	Time to Open/Close	0

Figure A2. Detention Basin 2309 Outlet Structures (unit = feet)

Property	Value
Name	Or11
Inlet Node	Wong_Park_2
Outlet Node	1076_ControlJunction
Description	
Tag	
Type	SIDE
Shape	CIRCULAR
Height	1.25
Width	0
Inlet Offset	0
Discharge Coeff.	0.6
Flap Gate	NO
Time to Open/Close	0

Figure A3. Detention Basin 2044 Outlet Structure (unit = feet)

Property	Value
Name	Or02
Inlet Node	The_Vistas
Outlet Node	1179_ControlJunction
Description	
Tag	
Type	SIDE
Shape	CIRCULAR
Height	1
Width	0
Inlet Offset	0
Discharge Coeff.	0.6
Flap Gate	NO
Time to Open/Close	0

Figure A4. Detention Basin 0388 Outlet Structure (unit = feet)

Property	Value	Property	Value
Name	Or03	Name	Or16
Inlet Node	Silverleaf_2	Inlet Node	Silverleaf_2
Outlet Node	1360	Outlet Node	1360
Description		Description	
Tag		Tag	
Type	SIDE	Type	BOTTOM
Shape	CIRCULAR	Shape	RECT_CLOSED
Height	1.6667	Height	1.5
Width	0	Width	3
Inlet Offset	0	Inlet Offset	5.729
Discharge Coeff.	0.6	Discharge Coeff.	0.65
Flap Gate	NO	Flap Gate	NO
Time to Open/Close	0	Time to Open/Close	0

Figure A5. Detention Basin 0274 Outlet Structures (unit = feet)

Property	Value
Name	Or06
Inlet Node	The_Chase
Outlet Node	1017_ControlJunction
Description	
Tag	
Type	SIDE
Shape	CIRCULAR
Height	1
Width	0
Inlet Offset	0
Discharge Coeff.	0.6
Flap Gate	NO
Time to Open/Close	0

Figure A6. Detention Basin 0262 Outlet Structure (unit = feet)

Property	Value
Name	Or01
Inlet Node	Vista_Pointe
Outlet Node	1303_ControlJunction
Description	
Tag	
Type	SIDE
Shape	CIRCULAR
Height	1.25
Width	0
Inlet Offset	0
Discharge Coeff.	0.6
Flap Gate	NO
Time to Open/Close	0

Figure A7. Detention Basin 0178 Outlet Structure (unit = feet)

Appendix B: SWMM Model Details

- **Calibration and Validation Summary of Events**
- **Calibration Events 1, 2, and 3**
- **Validation Events 1, 2, 3, 4, and 5**
- **SWMM Simulation Options and Map**
- **SWMM Subcatchment Parameters I**
- **SWMM Subcatchment Parameters II**

Table B1. Calibration and Validation Summary of Events

	<i>Storm</i>	<i>Precip. (in)</i>	<i>Storm Duration (hours)</i>	<i>Peak Flow (CFS)</i>	<i>Volume (ft3)</i>	<i>NSEC</i>	<i>Error Peak Flow</i>	<i>Error Volume</i>
Calibration	5/26/2009	2.38	60	29.3	573,000	0.66	-17%	24%
	1/17/2010	0.7	8	11.8	137,000	0.91	-15%	-14%
	3/13/2010	1.08	17	20.3	222,000	0.76	41%	16%
Validation	5/15/2009	0.91	4	38.0	157,000	0.75	11.49	23.04
	12/8/2009	1.77	16	27.0	527,000	0.89	-22.33	-28.37
	1/24/2010	1.11	22	18.2	264,000	0.89	5.00	-13.59
	3/22/2010	0.71	7	19.4	118,700	0.67	39.87	17.72
	3/28/2010	0.66	7	19.5	119,200	0.91	19.18	4.51

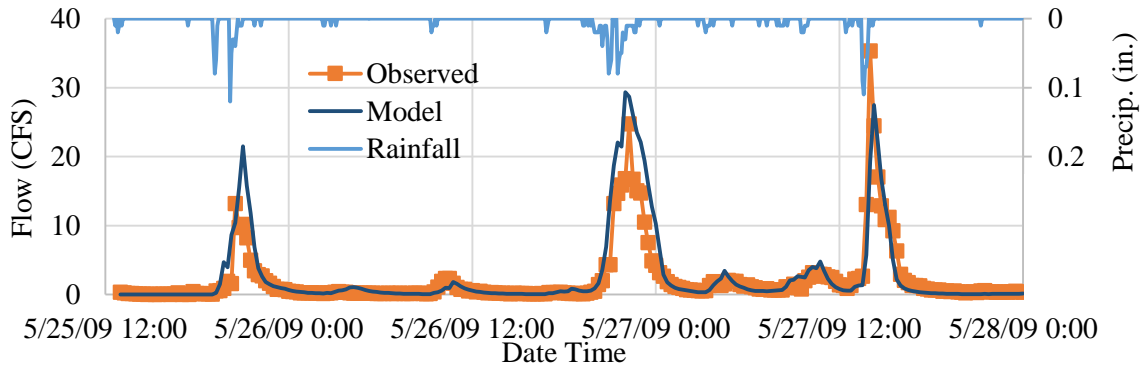


Figure B1. Calibration Event 1 – 5/26/2009

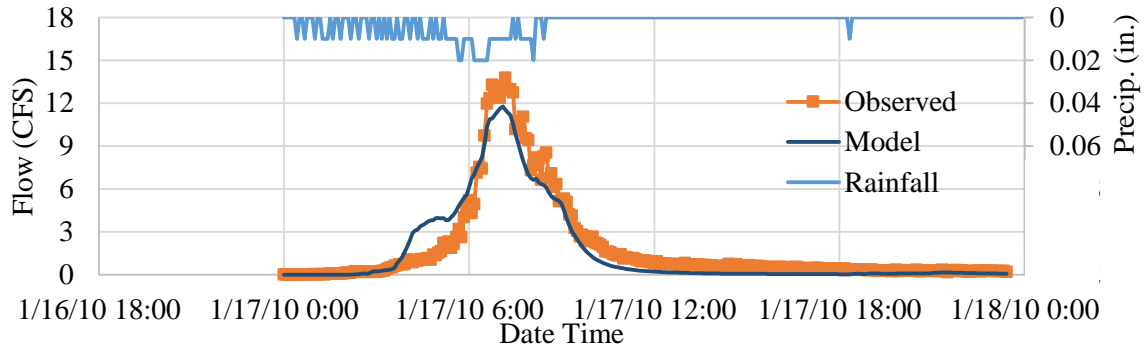


Figure B2. Calibration Event 2 – 1/17/2010

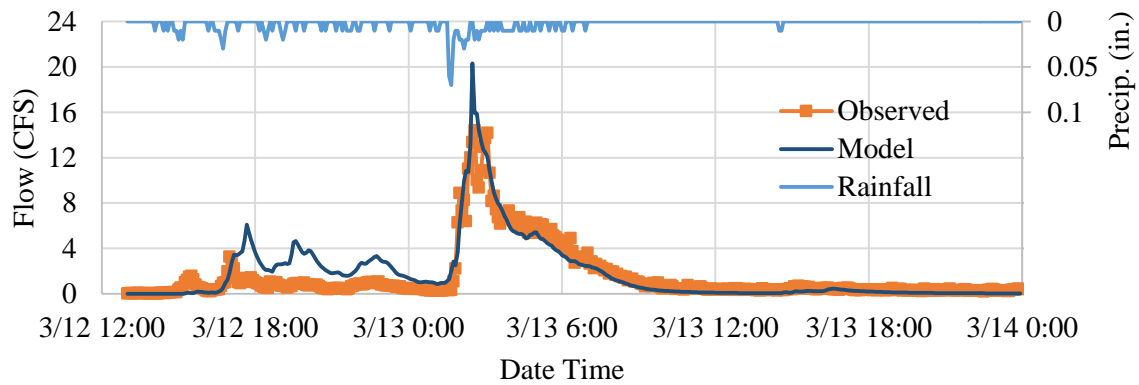


Figure B3. Calibration Event 3 – 3/13/2010

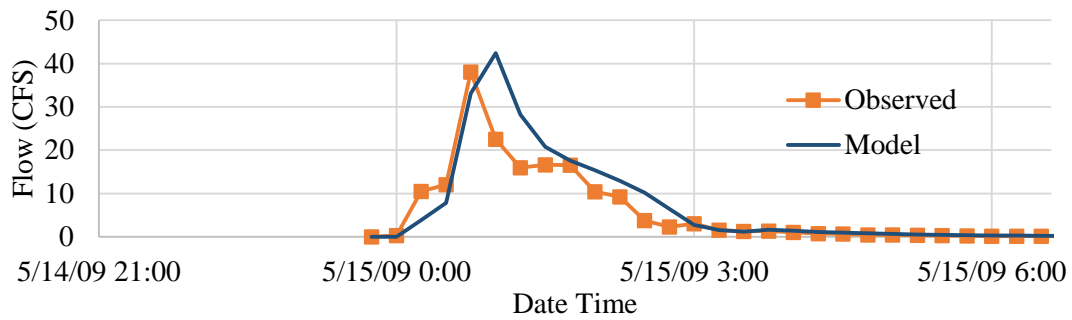


Figure B4. Validation Event 1 – 5/15/2009

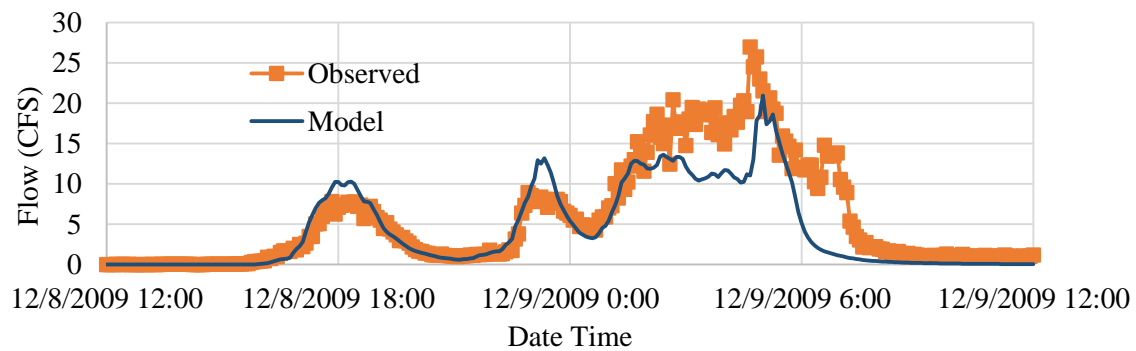


Figure B5. Validation Event 2 – 12/08/2009

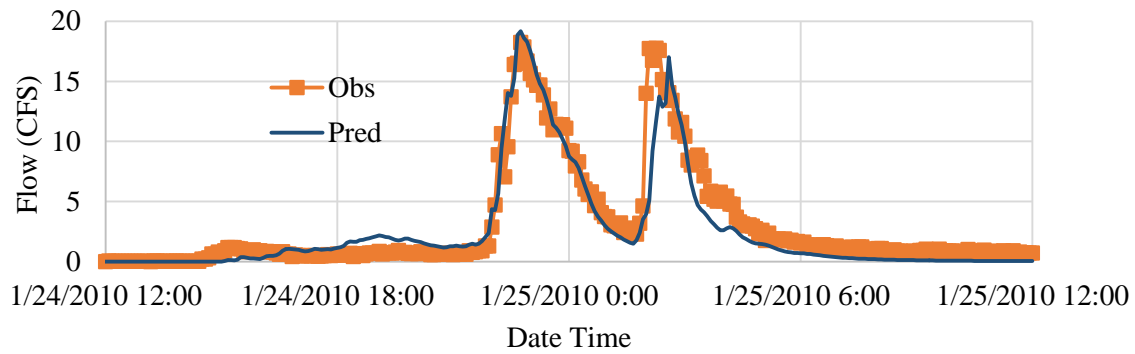


Figure B6. Validation Event 3 – 1/24/2010

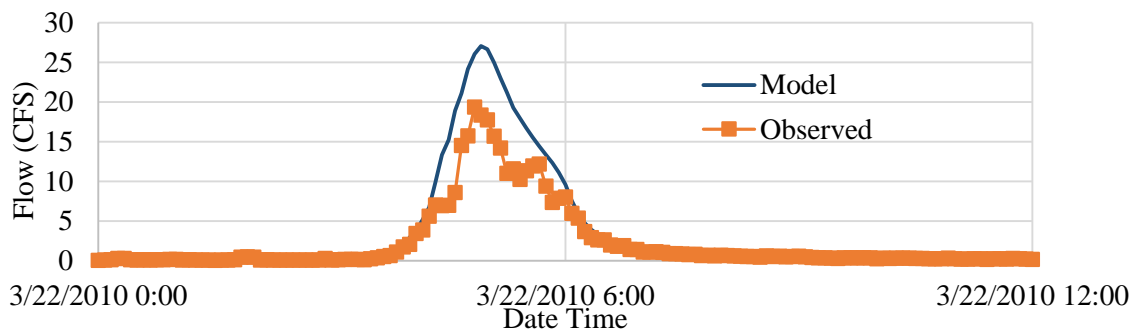


Figure B7. Validation Event 4 – 3/22/2010

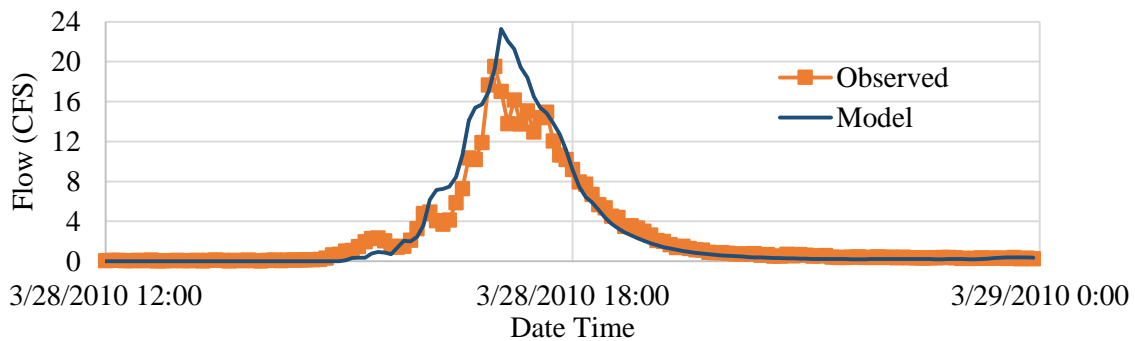


Figure B7. Validation Event 5 – 3/28/2010

General

Dates

Time Steps

Dynamic Wave

Files

Process Models

☒ Rainfall/Runoff
 ☐ Rainfall Dependent I/I
 ☐ Snow Melt
 ☐ Groundwater
 ☒ Flow Routing
 ☐ Water Quality

Routing Model

☐ Steady Flow
 ☐ Kinematic Wave
 ☒ Dynamic Wave

Infiltration Model

☐ Horton
 ☐ Modified Horton
 ☒ Green-Ampt
 ☐ Modified Green-Ampt
 ☐ Curve Number

Miscellaneous

☒ Allow Ponding
 ☐ Report Control Actions
 ☐ Report Input Summary
 Minimum Conduit Slope
 0 (%)

General

Dates

Time Steps

Dynamic Wave

Files

Reporting

Days: 0
 Hr:Min:Sec: 00:05:00

Runoff: Dry Weather

0
 01:00:00

Runoff: Wet Weather

0
 00:01:00

Routing

15
 Seconds

Steady Flow Periods

☐ Skip Steady Flow Periods
 System Flow Tolerance (%) 5
 Lateral Flow Tolerance (%) 5

General

Dates

Time Steps

Dynamic Wave

Files

Inertial Terms

Dampen

Normal Flow Criterion

Slope & Froude

Force Main Equation

Hazen-Williams

☒ Use Variable Time Steps
 Adjusted By 75 %

Minimum Variable Time Step (sec)

0.5

Time Step For Conduit Lengthening (sec)

15

Minimum Nodal Surface Area (sq. feet)

12.557

Maximum Trials per Time Step

8

Head Convergence Tolerance (feet)

0.005

Number of Threads

1

[Apply Defaults](#)

Figure B8. SWMM Simulation Options and Map

Table B2. SWMM Subcatchment Parameters I

<i>Subcatch.</i>	<i>Area (ac)</i>	<i>% Imperv</i>	<i>Width (ft)</i>	<i>%Slope</i>	<i>Suction</i>	<i>Ksat</i>	<i>IMD</i>
SB1000	1.60	67.7	140	1.8	3.50	0.130	0.232
SB1001	3.74	81.5	352	2.2	3.50	0.130	0.232
SB1002	2.79	68.8	233	2.6	3.50	0.130	0.232
SB1003	10.25	63.5	398	3.0	3.50	0.130	0.232
SB1004	30.27	29.8	817	7.0	3.74	0.140	0.236
SB1005	15.27	36.0	402	4.5	3.50	0.130	0.232
SB1006	8.94	14.0	257	4.2	3.50	0.130	0.232
SB1007	11.31	34.4	315	4.2	3.50	0.130	0.232
SB1008	7.74	28.6	372	4.0	3.50	0.130	0.232
SB1009	4.20	36.5	244	4.9	3.50	0.130	0.232
SB1010	14.48	21.4	456	5.3	3.50	0.130	0.232
SB1011	27.43	16.9	601	5.7	3.50	0.130	0.232
SB1012	5.97	33.9	355	5.9	4.03	0.151	0.241
SB1013	7.56	39.2	314	6.5	3.50	0.130	0.232
SB1014	6.37	27.0	366	5.2	3.50	0.130	0.232
SB1015	21.53	15.4	539	6.2	3.50	0.130	0.232
SB1016	3.98	26.6	320	6.3	3.50	0.130	0.232
SB1017	9.13	25.3	379	5.6	3.50	0.130	0.232
SB1018	2.07	62.5	165	4.0	3.50	0.130	0.232
SB1019	15.94	41.5	519	4.1	3.50	0.130	0.232
SB1020	1.07	55.6	161	4.0	3.50	0.130	0.232
SB1021	16.47	20.8	445	4.9	4.42	0.167	0.247
SB1022	24.89	18.7	780	6.0	4.41	0.167	0.247
SB1023	8.78	33.9	382	3.6	3.50	0.130	0.232
SB1024	6.59	25.1	398	5.1	3.50	0.130	0.232
SB1025	6.05	18.8	447	5.1	3.50	0.130	0.232
SB1026	9.20	28.3	307	5.4	4.71	0.179	0.252
SB1027	19.38	20.7	567	5.3	4.07	0.153	0.241
SB1028	10.84	20.6	430	6.2	3.50	0.130	0.232
SB1029	6.21	10.0	323	5.7	3.50	0.130	0.232
SB1030	18.03	13.2	476	3.9	4.08	0.154	0.242
SB1031	13.35	16.7	448	6.0	3.93	0.147	0.239
SB1032	3.44	27.5	259	4.3	3.50	0.130	0.232
SB1033	11.43	21.3	259	6.0	3.50	0.130	0.232
SB1034	16.27	24.0	289	6.3	3.50	0.130	0.232
SB1035	3.87	36.8	226	4.2	3.50	0.130	0.232
SB1036	2.35	49.9	298	3.5	3.50	0.130	0.232
SB1037	2.41	10.8	167	5.7	3.50	0.130	0.232
SB1038	8.83	19.7	284	4.7	3.51	0.130	0.232

Table B3. SWMM Subcatchment Parameters II

<i>Subcatch.</i>	<i>N-Imperv</i>	<i>N-Perv</i>	<i>S-Imperv (in)</i>	<i>S-Perv (in)</i>	<i>PctZero</i>	<i>RouteTo</i>	<i>%Routed</i>
SB1000	0.012	0.295	0.08	0.240	0.25	OUTLET	
SB1001	0.012	0.093	0.08	0.128	0.25	OUTLET	
SB1002	0.012	0.157	0.08	0.183	0.25	OUTLET	
SB1003	0.012	0.329	0.08	0.263	0.25	OUTLET	
SB1004	0.012	0.403	0.08	0.270	0.25	OUTLET	
SB1005	0.012	0.262	0.08	0.229	0.25	OUTLET	
SB1006	0.012	0.287	0.08	0.243	0.25	PERVIOUS	80
SB1007	0.012	0.245	0.08	0.222	0.25	OUTLET	
SB1008	0.012	0.285	0.08	0.236	0.25	OUTLET	
SB1009	0.012	0.313	0.08	0.248	0.25	OUTLET	
SB1010	0.012	0.237	0.08	0.205	0.25	PERVIOUS	80
SB1011	0.012	0.361	0.08	0.259	0.25	PERVIOUS	80
SB1012	0.012	0.231	0.08	0.210	0.25	OUTLET	
SB1013	0.012	0.291	0.08	0.243	0.25	OUTLET	
SB1014	0.012	0.270	0.08	0.225	0.25	OUTLET	
SB1015	0.012	0.287	0.08	0.233	0.25	PERVIOUS	80
SB1016	0.012	0.350	0.08	0.261	0.25	OUTLET	
SB1017	0.012	0.209	0.08	0.201	0.25	OUTLET	
SB1018	0.012	0.279	0.08	0.228	0.25	OUTLET	
SB1019	0.012	0.326	0.08	0.250	0.25	OUTLET	
SB1020	0.012	0.301	0.08	0.230	0.25	OUTLET	
SB1021	0.012	0.320	0.08	0.246	0.25	OUTLET	
SB1022	0.012	0.340	0.08	0.255	0.25	PERVIOUS	80
SB1023	0.012	0.367	0.08	0.268	0.25	OUTLET	
SB1024	0.012	0.280	0.08	0.228	0.25	PERVIOUS	80
SB1025	0.012	0.250	0.08	0.225	0.25	PERVIOUS	80
SB1026	0.012	0.256	0.08	0.224	0.25	OUTLET	
SB1027	0.012	0.265	0.08	0.234	0.25	PERVIOUS	80
SB1028	0.012	0.317	0.08	0.251	0.25	PERVIOUS	80
SB1029	0.012	0.334	0.08	0.265	0.25	PERVIOUS	80
SB1030	0.012	0.161	0.08	0.183	0.25	PERVIOUS	80
SB1031	0.012	0.354	0.08	0.252	0.25	OUTLET	
SB1032	0.012	0.325	0.08	0.240	0.25	OUTLET	
SB1033	0.012	0.363	0.08	0.264	0.25	OUTLET	
SB1034	0.012	0.261	0.08	0.228	0.25	OUTLET	
SB1035	0.012	0.300	0.08	0.241	0.25	OUTLET	
SB1036	0.012	0.272	0.08	0.226	0.25	OUTLET	
SB1037	0.012	0.333	0.08	0.241	0.25	PERVIOUS	80
SB1038	0.012	0.356	0.08	0.255	0.25	PERVIOUS	80

Appendix C: PySWMM Sample Code

- **PySWMM Model Initialization**
- **PySWMM Script for *Static* Scenario**
- **PySWMM Script for *RTC 1* applied to facility 4860**
- **PySWMM Script for *RTC 2* applied to facility 4860**

```

1  # Initialize the Model in PySWMM
2  #       This script goes at the beginning of a PySWMM simulation
3
4  from pyswmm import Simulation, Links, Subcatchments, Nodes, SystemStats
5
6  root = 'C:/Users/Zoe/Documents/Schmitt Research/Model/SWMM/'
7  inpSWMM = 'CentralStroubles8.inp'    # SWMM File
8
9  sim = Simulation(root + inpSWMM)      # Initialize simulation
10
11  link_object = Links(sim)             # initiate links
12  L4860 = link_object["1012"]
13  L2309 = link_object["1072"]
14  L2044 = link_object["1260"]
15  L0388 = link_object["1136"]
16  L0262 = link_object["1248"]
17  L0274 = link_object["1170"]
18  L0178 = link_object["1161"]
19  LwsOutlet = link_object["1333"]
20
21
22  syst_stats = SystemStats(sim)        # System stats allow measurement of precip
23
24  node_object = Nodes(sim)
25  # initiate detention ponds
26  Pond_4860 = node_object["Owens_Street"]
27  Pond_2309 = node_object["Wong_Park_1"]
28  Pond_2044 = node_object["Wong_Park_2"]
29  Pond_0388 = node_object["The_Vistas"]
30  Pond_0262 = node_object["The_Chase"]
31  Pond_0274 = node_object["Silverleaf_2"]
32  Pond_0178 = node_object["Vista_Pointe"]
33

```

Figure C1. PySWMM Model Initialization

```

37 # STATIC #####
38 timedata0 = []
39 precip_cumulativeP = []
40 precip_volumeP = []
41 precip_curr = 0
42
43 LwsOutletflowdata0_OUT = []
44 Pondflowdata0_4860 = []
45 Pondflowdata0_2309 = []
46 Pondflowdata0_2044 = []
47 Pondflowdata0_0388 = []
48 Pondflowdata0_0262 = []
49 Pondflowdata0_0274 = []
50 Pondflowdata0_0178 = []
51
52 PondDepth0_4860 = []
53 PondDepth0_2309 = []
54 PondDepth0_2044 = []
55 PondDepth0_0388 = []
56 PondDepth0_0262 = []
57 PondDepth0_0274 = []
58 PondDepth0_0178 = []
59
60 for step in sim:
61     LwsOutletflowdata0_OUT.append(LwsOutlet_OUT.flow)
62     timedata0.append(sim.current_time)
63
64     precip_cumulativeP.append(syst_stats.runoff_stats["rainfall"])
65     precip_volumeP.append(syst_stats.runoff_stats["rainfall"]-precip_curr)
66     precip_curr = syst_stats.runoff_stats["rainfall"]
67
68     Pondflowdata0_4860.append(L4860.flow)
69     Pondflowdata0_2309.append(L2309.flow)
70     Pondflowdata0_2044.append(L2044.flow)
71     Pondflowdata0_0388.append(L0388.flow)
72     Pondflowdata0_0262.append(L0262.flow)
73     Pondflowdata0_0274.append(L0274.flow)
74     Pondflowdata0_0178.append(L0178.flow)
75
76     PondDepth0_4860.append(Pond_4860.depth)
77     PondDepth0_2309.append(Pond_2309.depth)
78     PondDepth0_2044.append(Pond_2044.depth)
79     PondDepth0_0388.append(Pond_0388.depth)
80     PondDepth0_0262.append(Pond_0262.depth)
81     PondDepth0_0274.append(Pond_0274.depth)
82     PondDepth0_0178.append(Pond_0178.depth)
83
84     sim.step_advance(300) # 5 Minute Time Step (300 seconds)
85 sim.close()

```

Figure C2. PySWMM Script for *Static* Scenario

- Static scenario has no controls applied – only observation of watershed conditions (precipitation, pond depth, flow data at facility and watershed outlets).
- Note: Predevelopment scenario has similar script, except the input SWMM file is that of the predevelopment watershed, and there is no pond depth information because there are no detention facilities.

```

202 # Scenario: RTC 1, Control of Facility 4860 #####
203 WsOutletflowdata1C_OUT = []
204 timedata1C = []
205 precip_cumulative1C = []
206 RF00,RF05,RF10,RF15,RF20,RF25 = 0,0,0,0,0,0
207
208 depth1C_4860 = []
209 Pondflowdata1C_4860 = []
210 OrSetting1C_4860 = []
211 Det_time1C_4860 = []
212 DET_TIME_HRS_4860 = 0
213
214 # Open all valves
215 for orif in orifices:
216     orif.target_setting = 1.0
217
218 for step in sim:
219     L1333flowdata1C_OUT.append(L1333_OUT.flow)
220     timedata1C.append(sim.current_time)
221     precip_cumulative1C.append(syst_stats.runoff_stats["rainfall"])
222
223     # Determine rainfall for last 5, 10, and 25 minutes
224     RF25,RF20,RF15,RF10,RF05,RF00 = RF20,RF15,RF10,RF05,RF00, syst_stats.runoff_stats["rainfall"]
225     if RF00-RF05 > 0.0118 or RF00-RF10 > 0.0157 or RF00-RF25 > 0.0236:
226         EnoughRF = True
227     else:
228         EnoughRF = False
229
230     depth1C_4860.append(Pond_4860.depth)
231     Pondflowdata1C_4860.append(L1012_4860.flow)
232     OrSetting1C_4860.append(Or12_4860.target_setting)
233     Det_time1C_4860.append(DET_TIME_HRS_4860)
234
235     # set Detention Time Parameter 4860 (Timer starts for depth > 0.083 ft, or 1 inch)
236     if Pond_4860.depth < 0.083:
237         DET_TIME_4860 = 0
238         STRT_TIME_4860 = 0
239         DET_TIME_HRS_4860 = 0
240     elif STRT_TIME_4860 == 0 and Pond_4860.depth >= 0.083:
241         STRT_TIME_4860 = sim.current_time
242     else:
243         DET_TIME_4860 = sim.current_time - STRT_TIME_4860
244         DET_TIME_HRS_4860 = DET_TIME_4860.total_seconds()/3600
245
246     ## Reset detention time if RF25 exceeds 0.6 mm
247     if RF00-RF25 > 0.0236:
248         STRT_TIME_4860 = 0
249

```

Figure C3. PySWMM Script for *RTC 1* applied to facility 4860 – Part I

```

249
250     # Facility 4860 control rules
251     ## Rule 1
252     if Pond_4860.depth > 5.0:
253         Or12_4860.target_setting = 1*VF_4860
254     ## Rule 2
255     elif EnoughRF and Pond_4860.depth >= 4.5 and Pond_4860.depth < 4.85:
256         Or12_4860.target_setting = 0.21*VF_4860
257     ## Rule 3
258     elif not EnoughRF and Pond_4860.depth >= 4.5 and Pond_4860.depth < 4.85:
259         Or12_4860.target_setting = 0.11*VF_4860
260     ## Rule 4
261     elif EnoughRF and Pond_4860.depth >= 4.0 and Pond_4860.depth < 4.35:
262         Or12_4860.target_setting = 0.11*VF_4860
263     ## Rule 5
264     elif EnoughRF and Pond_4860.depth < 3.85:
265         Or12_4860.target_setting = 0.01*VF_4860
266     ## Rule 7
267     elif DET_TIME_HRS_4860 > 0.5 and DET_TIME_HRS_4860 < 30 and Pond_4860.depth <= 4.35:
268         Or12_4860.target_setting = 0.01*VF_4860
269     ## Rule 6
270     elif not EnoughRF and Pond_4860.depth >= 4.0 and Pond_4860.depth < 4.35:
271         Or12_4860.target_setting = 0.051*VF_4860
272     ## Rule 8
273     elif DET_TIME_HRS_4860 > 60:
274         Or12_4860.target_setting = 0.11*VF_4860
275     ## Rule 9
276     elif DET_TIME_HRS_4860 > 48:
277         Or12_4860.target_setting = 0.051*VF_4860
278
279     sim.step_advance(300) # 5-minute time step (300 seconds)
280 sim.close

```

Figure C4. PySWMM Script for *RTC 1* applied to facility 4860 – Part II

```

300 # Scenario: RTC 2, Control of Facility 4860 #####
301 sim = Simulation(root + inpSWMM)
302
303 L1333flowdata1Z_OUT = []
304 timedata1Z = []
305 precip_cumulative1Z = []
306 i = 0
307
308 depth1Z_4860 = []
309 Pondflowdata1Z_4860 = []
310 OrSetting1Z_4860 = []
311 Det_time1Z_4860 = []
312 DET_TIME_HRS_4860 = 0
313
314 # Open all valves
315 for orif in orifices:
316     orif.target_setting = 1.0
317
318 for step in sim:
319     L1333flowdata1Z_OUT.append(L1333_OUT.flow)
320     timedata1Z.append(sim.current_time)
321     precip_cumulative1Z.append(syst_stats.runoff_stats["rainfall"])
322
323     depth1Z_4860.append(Pond_4860.depth)
324     Pondflowdata1Z_4860.append(L1012_4860.flow)
325     OrSetting1Z_4860.append(Or12_4860.target_setting)
326     Det_time1Z_4860.append(DET_TIME_HRS_4860)
327
328     Prev_setting_4860 = Or12_4860.target_setting # make sure valve doesn't close > 5% per time step
329
330     ## 4860 ##
331     # set Detention Time Parameter 4860 (Timer starts for depth > 0.083 ft, or 1 inch)
332     if Pond_4860.depth < 0.083:
333         DET_TIME_4860 = 0
334         STRT_TIME_4860 = 0
335         DET_TIME_HRS_4860 = 0
336     elif STRT_TIME_4860 == 0 and Pond_4860.depth >= 0.083:
337         STRT_TIME_4860 = sim.current_time
338     else:
339         DET_TIME_4860 = sim.current_time - STRT_TIME_4860
340         DET_TIME_HRS_4860 = DET_TIME_4860.total_seconds()/3600
341
342     # Determine predicted runoff volume from recent rainfall
343     if i-TC_4860//5 > 0:
344         RRF_4860 = syst_stats.runoff_stats["rainfall"] - precip_cumulative1Z[i-TC_4860//5]
345     else:
346         RRF_4860 = syst_stats.runoff_stats["rainfall"]
347     Dep_ro_4860 = ((RRF_4860 - 0.2*S_4860)**2)/(RRF_4860 + 0.8*S_4860) # Depth of runoff in inches, SCS method
348     Vol_ro_4860 = Dep_ro_4860*CDA_4860*3630 # There are 3630 ft3 in 1 ac-in
349
350     Vol_ex_4860 = Vol_cntrl_4860 - Pond_4860.volume # Pond.volume gives cubic feet
351

```

Figure C5. PySWMM Script for RTC 2 applied to facility 4860 – Part I

```

352 # Control Rules
353 if (sim.current_time - risk_ER_4860).total_seconds()/60 < 30: # time-based rule-suspension
354     pass # do nothing
355 elif Pond_4860.depth > ER_4860:
356     # 95% Capacity Emergency Release
357     Or12_4860.target_setting = 1.0
358     risk_ER_4860 = sim.current_time
359 elif (sim.current_time - risk_MCD1_4860).total_seconds()/60 < 30:
360     pass # do nothing
361 elif Pond_4860.depth > MCD1_4860:
362     #High Flood Risk
363     Or12_4860.target_setting = 1.0*VF_4860
364     risk_MCD1_4860 = sim.current_time
365 elif (sim.current_time - risk_MCD2_4860).total_seconds()/60 < 30:
366     pass # do nothing
367 elif Pond_4860.depth > MCD2_4860:
368     #Medium Flood Risk
369     Or12_4860.target_setting = 0.5*VF_4860
370     risk_MCD2_4860 = sim.current_time
371 elif RRF_4860 > 0:
372     STRT_TIME_4860 = 0 # restart the detention time counter with new Rainfall
373     if Vol_ro_4860 < Vol_ex_4860:
374         Or12_4860.target_setting = 0.1*VF_4860
375     elif Vol_ro_4860 <= Vol_ex_4860*1.3:
376         # Slow drawdown
377         Or12_4860.target_setting = 0.1*VF_4860
378     elif Vol_ro_4860 > Vol_ex_4860*1.5 and Vol_ro_4860 <= Vol_ex_4860*2.0:
379         # Medium drawdown
380         Or12_4860.target_setting = 0.2*VF_4860
381     elif Vol_ro_4860 > Vol_ex_4860*2.2 and Vol_ro_4860 <= Vol_ex_4860*2.8:
382         # Quick drawdown
383         Or12_4860.target_setting = 0.3*VF_4860
384     elif Vol_ro_4860 > Vol_ex_4860*3.0:
385         #Medium flood risk
386         Or12_4860.target_setting = 0.5*VF_4860
387 elif DET_TIME_HRS_4860 > 24:
388     # DRAWDOWN Phase III
389     Or12_4860.target_setting = 0.125*VF_4860
390 elif DET_TIME_HRS_4860 > 18:
391     # DRAWDOWN Phase II
392     Or12_4860.target_setting = 0.10*VF_4860
393 elif DET_TIME_HRS_4860 > 12:
394     # DRAWDOWN Phase II
395     Or12_4860.target_setting = 0.075*VF_4860
396 elif DET_TIME_HRS_4860 > 6:
397     # DRAWDOWN Phase I
398     Or12_4860.target_setting = 0.05*VF_4860
399
400 # STEP DOWN RULES FOR ALL DETENTION PONDS - Can't close by > 5% in 5 minutes
401 if (Prev_setting_4860 - Or12_4860.target_setting) > 0.05:
402     Or12_4860.target_setting = Prev_setting_4860 - 0.05
403
404 i = i+1
405 sim.step_advance(300) # 5-minute time step (300 seconds)
406 sim.close

```

Figure C6. PySWMM Script for RTC 2 applied to facility 4860 – Part II

Appendix D: Simulation Results

- **Peak Flow Results**
- **Exceedance Time Values**
- **Flow Duration Curves**

Table D1. Change in Peak Flows at Detention Basin Outlets (RTC-1 and RTC-2 compared to Static) for NRCS 24-Hour Design Storms

		<i>Change in Peak Flow (%)</i>													
<i>Detention Pond:</i>		<u>4860</u>		<u>2309</u>		<u>2044</u>		<u>0388</u>		<u>0262</u>		<u>0274</u>		<u>0178</u>	
<i>RTC Method:</i>		RTC 1	RTC 2	RTC 1	RTC 2	RTC 1	RTC 2	RTC 1	RTC 2	RTC 1	RTC 2	RTC 1	RTC 2	RTC 1	RTC 2
<i>NRCS Storm Return Period (years)</i>	0.25	15.2	13.6	-72.5	-72.7	-89.4	-87.2	62.7	-75.7	-82.1	-85.1	26.3	-54.7	99.7	89.0
	0.5	69.9	55.5	14.7	8.2	-89.6	-90.1	43.9	-26.7	-85.7	-87.4	-25.0	24.9	51.8	51.3
	1	18.2	13.4	40.4	29.2	-76.6	-91.3	33.2	24.6	-68.3	-70.4	154.8	142.6	34.6	39.3
	2	15.7	14.9	1.7	1.1	34.2	-31.7	21.4	18.1	71.7	-13.4	91.5	-0.6	9.4	16.3
	5	0.0	0.0	0.0	0.0	13.2	12.2	7.8	7.8	56.3	43.7	34.5	32.2	8.2	6.2
	10	-0.2	0.3	0.0	0.0	8.4	6.4	0.0	0.0	41.8	32.7	6.9	17.3	0.0	0.0
	25	0.5	0.0	0.0	13.8	0.0	0.1	-0.2	0.1	27.3	28.1	0.0	0.0	0.1	0.0
	50	1.4	-1.8	-0.9	7.8	1.0	1.2	0.0	0.0	20.4	18.9	0.0	0.0	-0.1	-0.1
	100	-2.0	-2.0	0.0	0.0	-0.4	2.6	-0.6	-0.6	11.1	11.2	0.0	0.0	0.0	0.0

Table D2. Change in Peak Flows at Watershed Outlet (RTC 1 and 2 compared to Static) for NRCS 24-Hour Design Storms (T_R of 0.25- to 5-year)

		<i>Change in Peak Flow (%)</i>									
<i>Storm Return Period:</i>		0.25		0.5		1		2		5	
<i>RTC Method:</i>		RTC 1	RTC 2	RTC 1	RTC 2	RTC 1	RTC 2	RTC 1	RTC 2	RTC 1	RTC 2
<i>RTC on a Single Facility</i>	4860	-20.5	-19.6	1.0	3.3	58.1	0.4	-20.9	-18.5	4.5	7.0
	2309	-7.2	-6.3	1.4	2.2	-2.0	-1.7	-0.7	-4.5	0.1	-0.5
	3044	-0.5	-1.5	2.7	-2.0	-0.2	-0.8	3.6	6.3	-1.0	-5.6
	0388	-4.8	-3.1	-5.3	-4.7	-3.5	-2.9	-0.7	-1.8	-0.2	-0.6
	0262	-5.4	-5.1	-1.4	-1.1	-3.0	-3.3	0.6	-1.5	-1.3	-1.7
	0274	-1.1	-0.2	-2.7	-1.0	-1.1	-0.2	6.9	7.0	-0.3	-0.5
	0178	-1.3	-0.1	-0.6	-0.3	-1.7	-0.9	4.3	6.9	-0.2	-0.1
<i>RTC on Multiple Facilities</i>	Combo #8	-30.5	-28.4	-20.7	-16.9	16.2	-4.5	6.0	-27.6	7.1	0.1
	Combo #9	-30.8	-28.4	-20.7	-17.4	30.5	-5.2	13.2	-28.3	1.0	-1.3
	Combo #10	-29.5	-27.6	-17.1	-13.4	39.5	-2.2	14.4	-28.4	2.0	0.4
	Combo #11	-26.2	-25.1	-10.9	-7.3	38.6	-0.5	13.6	-27.8	4.3	-3.4
	Combo #12	-9.7	-7.4	-6.9	-6.5	-6.6	-6.1	6.0	-0.9	-2.3	-3.0
	Combo #13	-16.5	-13.6	-6.7	-5.5	-7.0	-6.7	-8.1	-8.9	5.7	4.1
	Combo #14	-6.0	-6.6	1.4	-3.5	-3.3	-4.1	3.2	5.0	-2.6	-5.0

Table D3. Change in Peak Flows at Watershed Outlet (RTC 1 and 2 compared to Static) for NRCS 24-Hour Design Storms (T_R of 10- to 100-year)

		<i>Change in Peak Flow (%)</i>							
<i>Storm Return Period:</i>		10		25		50		100	
<i>RTC Method:</i>		RTC 1	RTC 2	RTC 1	RTC 2	RTC 1	RTC 2	RTC 1	RTC 2
<i>RTC on a Single Facility</i>	4860	-2.9	-0.7	9.5	1.3	17.3	7.5	-0.8	-0.8
	2309	0.0	0.6	3.2	3.2	1.2	1.9	-3.7	-3.9
	3044	0.3	-0.1	-0.9	-1.8	2.5	0.5	-1.0	-0.9
	0388	-1.0	-1.6	-1.8	-3.4	0.1	0.8	0.3	-0.1
	0262	-0.4	-2.2	-2.1	-3.7	-0.9	0.5	0.2	-0.2
	0274	-1.3	-0.4	-3.1	-2.4	0.1	0.8	0.3	-0.3
	0178	-0.5	-0.5	0.2	-1.1	0.3	2.1	0.1	0.2
<i>RTC on Multiple Facilities</i>	Combo #8	0.5	2.1	8.4	2.4	6.7	2.5	-0.3	-0.1
	Combo #9	-0.5	3.1	3.6	1.1	1.9	2.9	-1.5	-1.4
	Combo #10	-0.6	3.1	2.0	0.2	1.0	2.4	0.5	-1.0
	Combo #11	2.9	3.6	4.2	2.3	1.4	2.3	-2.1	-1.6
	Combo #12	-1.2	-2.4	-3.1	-4.7	-0.6	0.8	0.3	-0.1
	Combo #13	0.3	-2.1	1.7	3.4	-3.4	-1.4	-2.0	-2.0
	Combo #14	-0.2	-2.3	-2.0	-3.8	1.8	2.5	-1.2	0.0

Table D4. Change in Exceedance Time of Erosive Flows at Detention Basin Outlets

Facility	RTC Method	<i>Impact of RTC at Detention Pond Outlet</i>					
		Change* in Exceed. Time of Q-crit		Change in Exceed. Time of Q-2yr		Change in Exceed. Time of Q-10yr	
		(hours)	(%)	(hours)	(%)	(hours)	(%)
4860	RTC 1	28	27	9	16	6	16
	RTC 2	17	16	5	9	4	9
2309	RTC 1	59	54	24	32	0	NA
	RTC 2	35	32	13	17	0	NA
2044	RTC 1	-194	-83	-60	-60	0	NA
	RTC 2	-150	-64	-65	-65	0	NA
0388	RTC 1	-186	-74	-53	-45	18	202
	RTC 2	-112	-44	-8	-7	10	112
0262	RTC 1	-183	-72	-26	-27	-17	-72
	RTC 2	-223	-87	-71	-75	-10	-43
0274	RTC 1	-33	-19	-25	-38	27	276
	RTC 2	-32	-19	4	6	1	11
0178	RTC 1	-122	-70	-17	-26	30	251
	RTC 2	-70	-40	8	13	10	82

Table D5. Change in Exceedance Time of Erosive Flows at Watershed Outlet

			<i>Impact of RTC at Watershed Outlet</i>					
RTC Location		RTC Method	Change in Exceed. Time of Q-crit (hours) (%)		Change in Exceed. Time of Q-2yr (hours) (%)		Change in Exceed. Time of Q-10yr (hours) (%)	
<i>RTC on a single facility</i>	4860	RTC 1	0.9	0.5	3.9	5.4	3.2	11.7
		RTC 2	-5.6	-2.9	2.0	2.7	1.6	5.7
	2309	RTC 1	-2.5	-1.3	0.5	0.7	-0.7	-2.5
		RTC 2	-4.6	-2.4	0.6	0.9	-0.2	-0.7
	2044	RTC 1	-6.3	-3.2	-2.4	-3.3	-0.9	-3.4
		RTC 2	-4.0	-2.0	-2.4	-3.3	-1.9	-7.0
	0388	RTC 1	-2.7	-1.4	-0.6	-0.9	-0.1	-0.4
		RTC 2	-3.1	-1.6	-0.3	-0.4	-0.4	-1.6
	0262	RTC 1	-1.9	-1.0	-0.4	-0.5	-0.5	-1.9
		RTC 2	-1.1	-0.5	-0.2	-0.3	-0.2	-0.7
	0274	RTC 1	-2.3	-1.2	-0.6	-0.9	-0.7	-2.5
		RTC 2	-2.5	-1.3	-0.9	-1.2	-0.1	-0.4
	0178	RTC 1	-0.1	-0.1	-0.4	-0.5	-1.0	-3.7
		RTC 2	0.4	0.2	-0.5	-0.7	-0.4	-1.6
<i>RTC on a combination of facilities</i>	Combo #1	RTC 1	-18.7	-9.6	0.9	1.2	1.8	6.6
		RTC 2	-22	-11	-2.3	-3.2	1.1	3.9
	Combo #2	RTC 1	-17.6	-9.0	1.8	2.5	2.2	8.1
		RTC 2	-22	-11	-1.3	-1.8	0.1	0.5
	Combo #3	RTC 1	-14.7	-7.6	2.2	3.1	2.3	8.4
		RTC 2	-21	-11	-1.6	-2.2	-0.3	-1.0
	Combo #4	RTC 1	-13.6	-7.0	2.8	3.9	2.3	8.4
		RTC 2	-18	-9	-0.6	-0.9	-0.1	-0.4
	Combo #5	RTC 1	-5.1	-2.6	-0.5	-0.8	-0.9	-3.4
		RTC 2	-4	-2	-0.7	-1.0	-0.6	-2.2
	Combo #6	RTC 1	-19.2	-9.9	-3.1	-4.4	-1.4	-4.9
		RTC 2	-20	-10	-2.6	-3.7	-0.9	-3.1
	Combo #7	RTC 1	-7.3	-3.8	-2.5	-3.5	-2.1	-7.6
		RTC 2	-6	-3	-2.5	-3.5	-2.2	-7.9

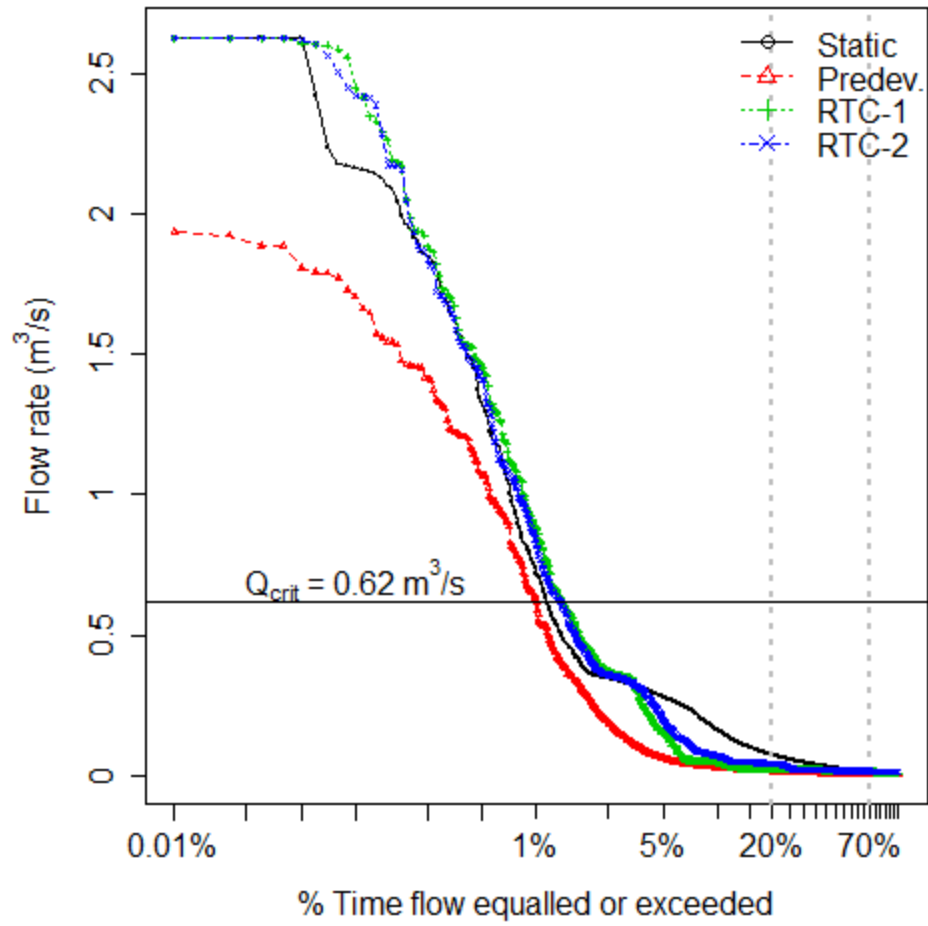


Figure D1. Flow Duration Curve at Facility 4860 Outlet

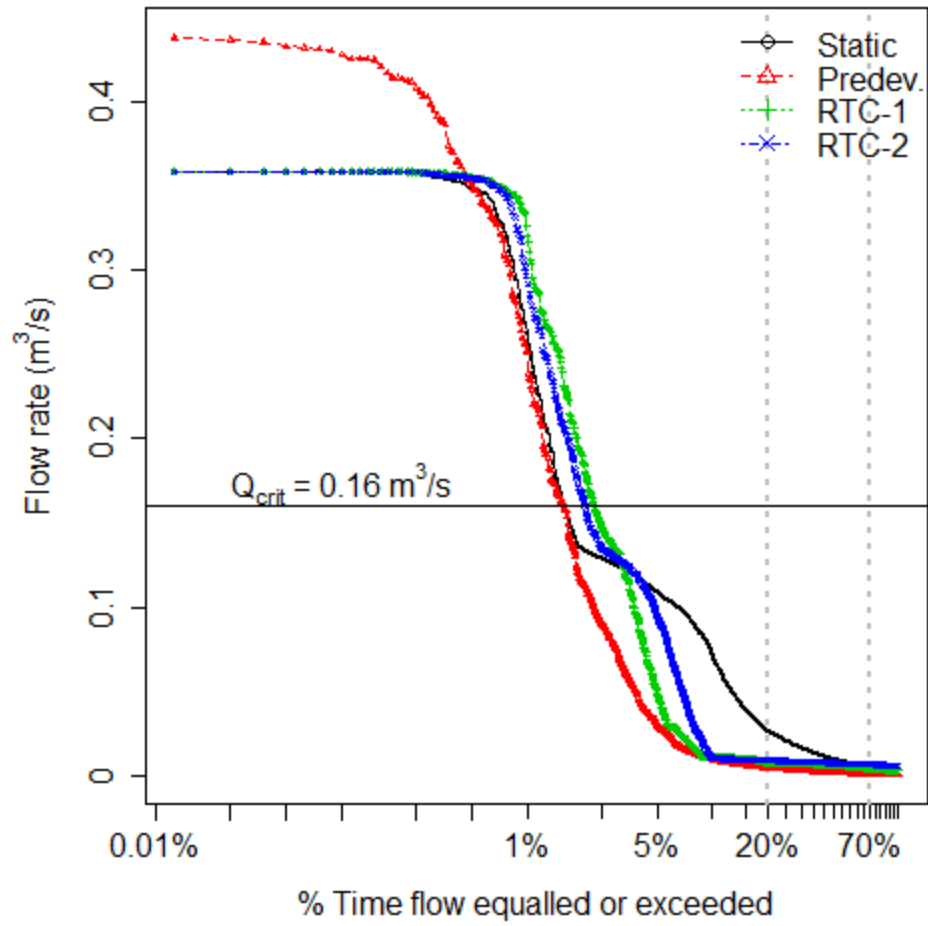


Figure D2. Flow Duration Curve at Facility 2309 Outlet

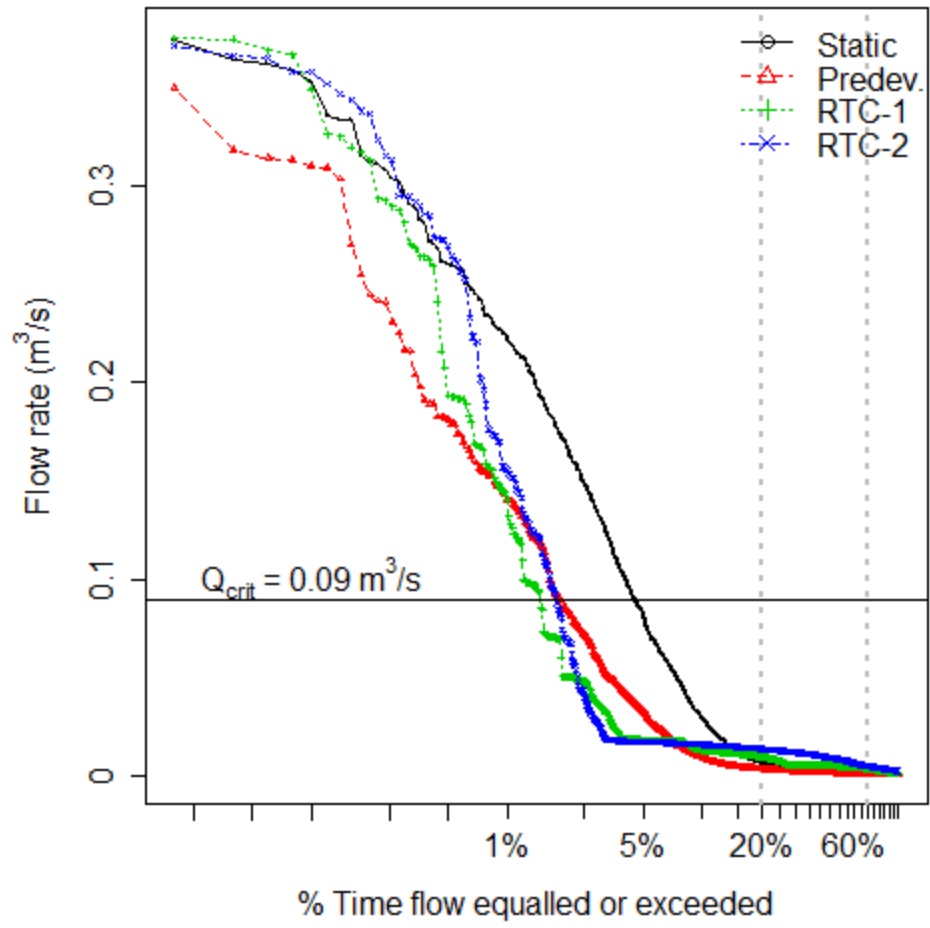


Figure D3. Flow Duration Curve at Facility 2044 Outlet

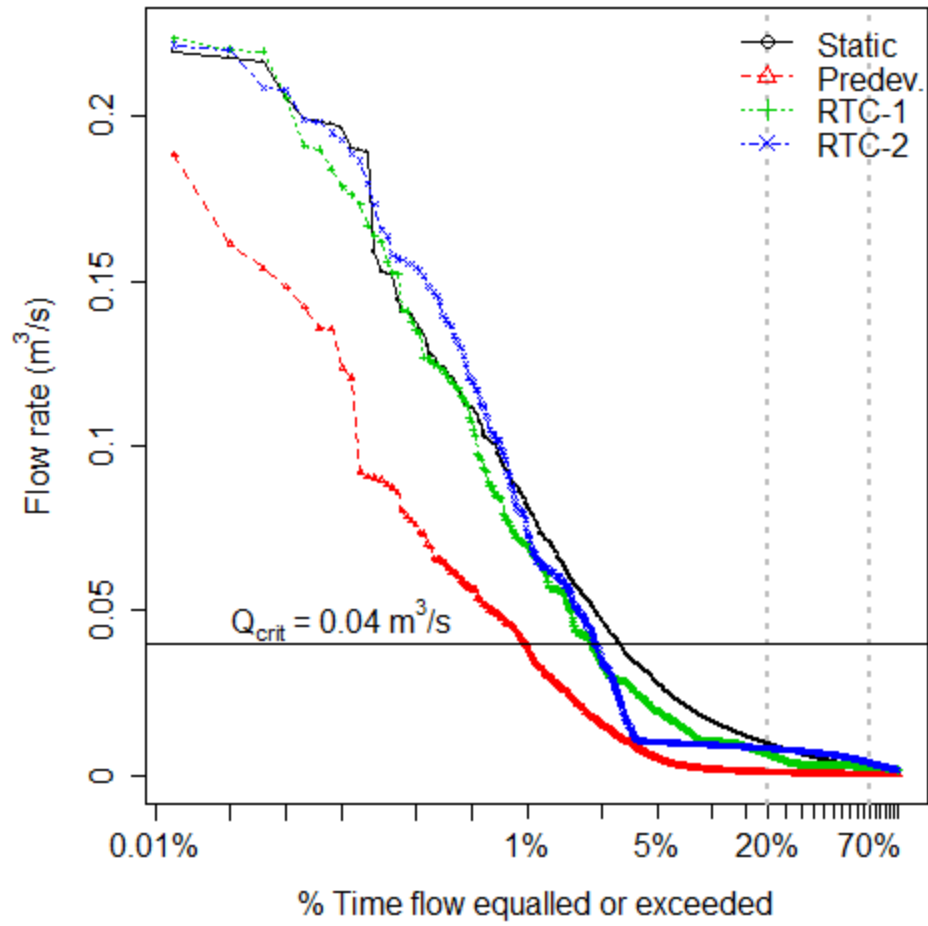


Figure D4. Flow Duration Curve at Facility 0388 Outlet

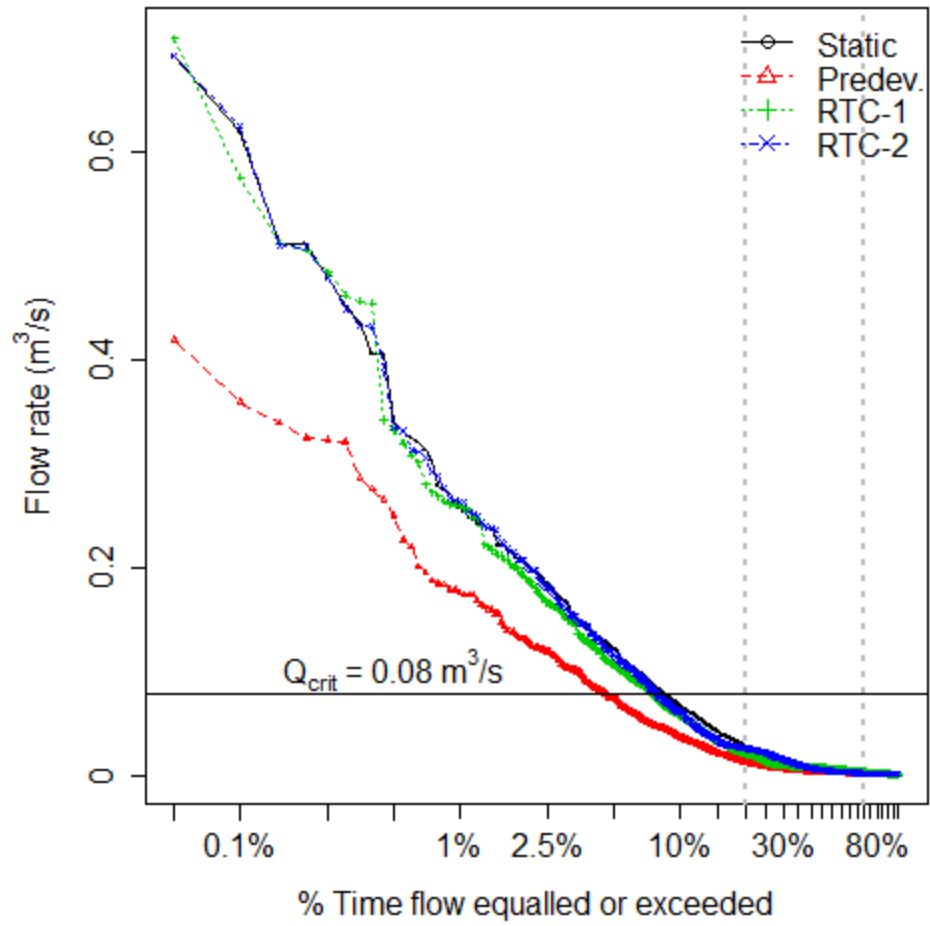


Figure D5. Flow Duration Curve at Facility 0274 Outlet

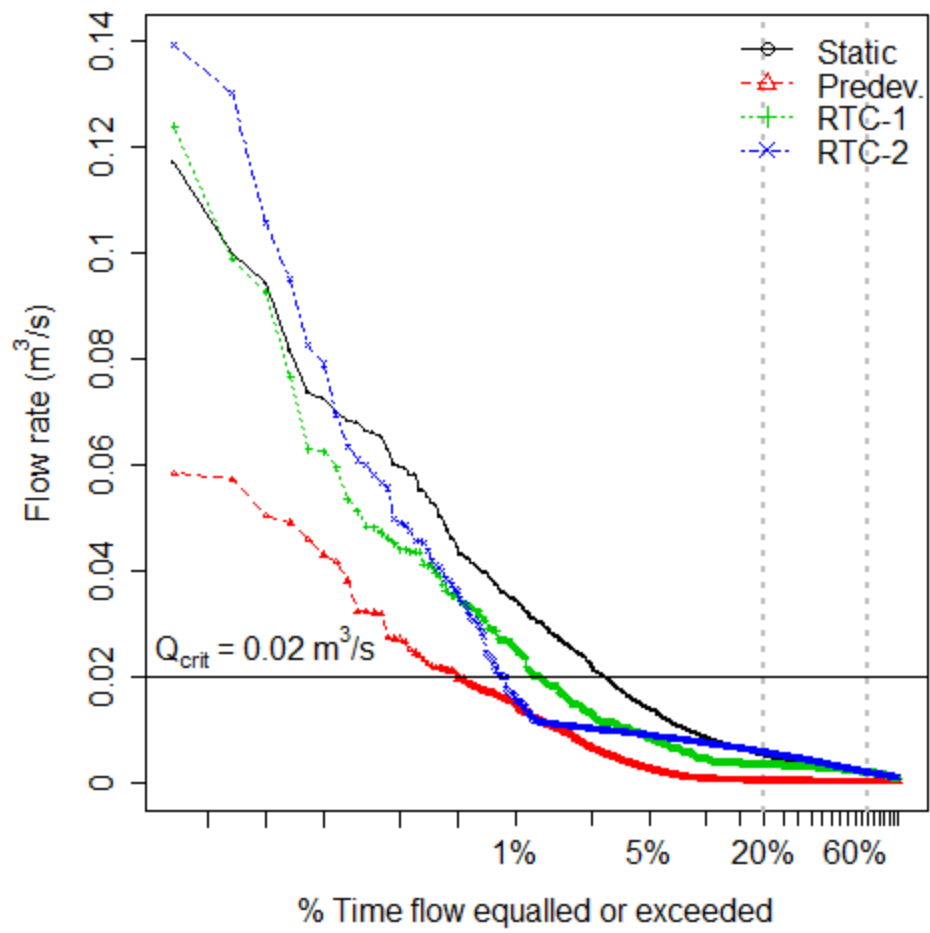


Figure D6. Flow Duration Curve at Facility 0262 Outlet

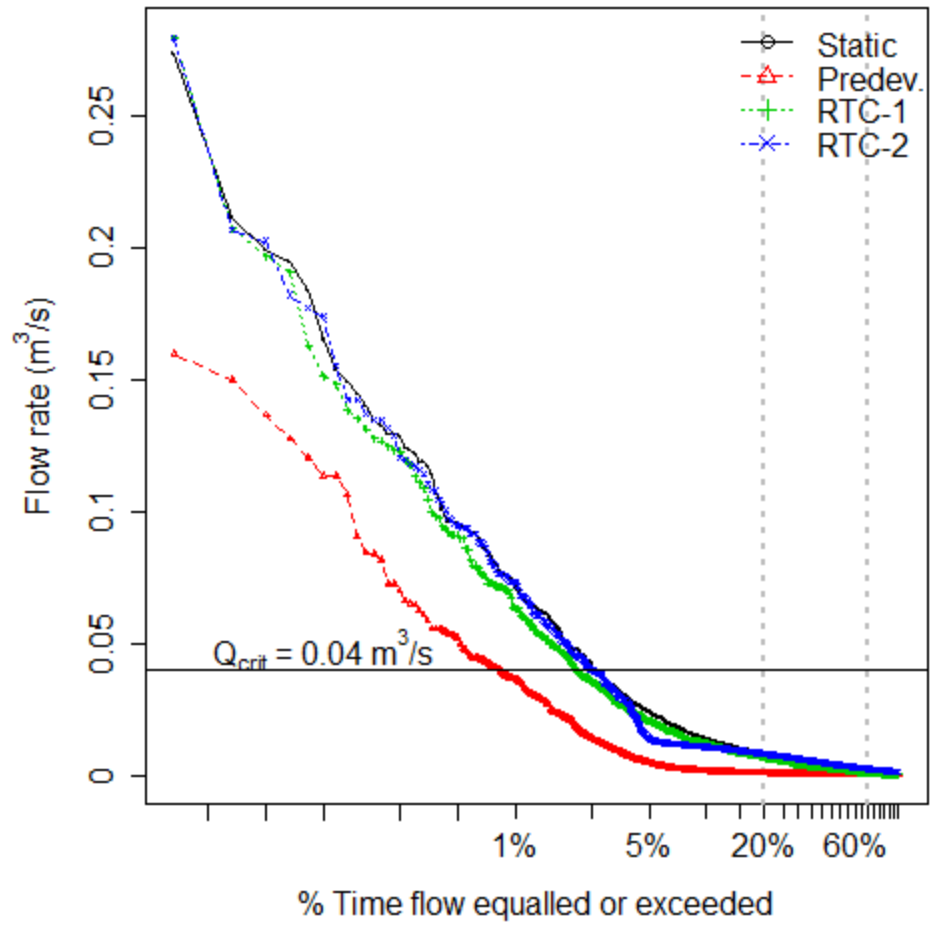


Figure D7. Flow Duration Curve at Facility 0178 Outlet

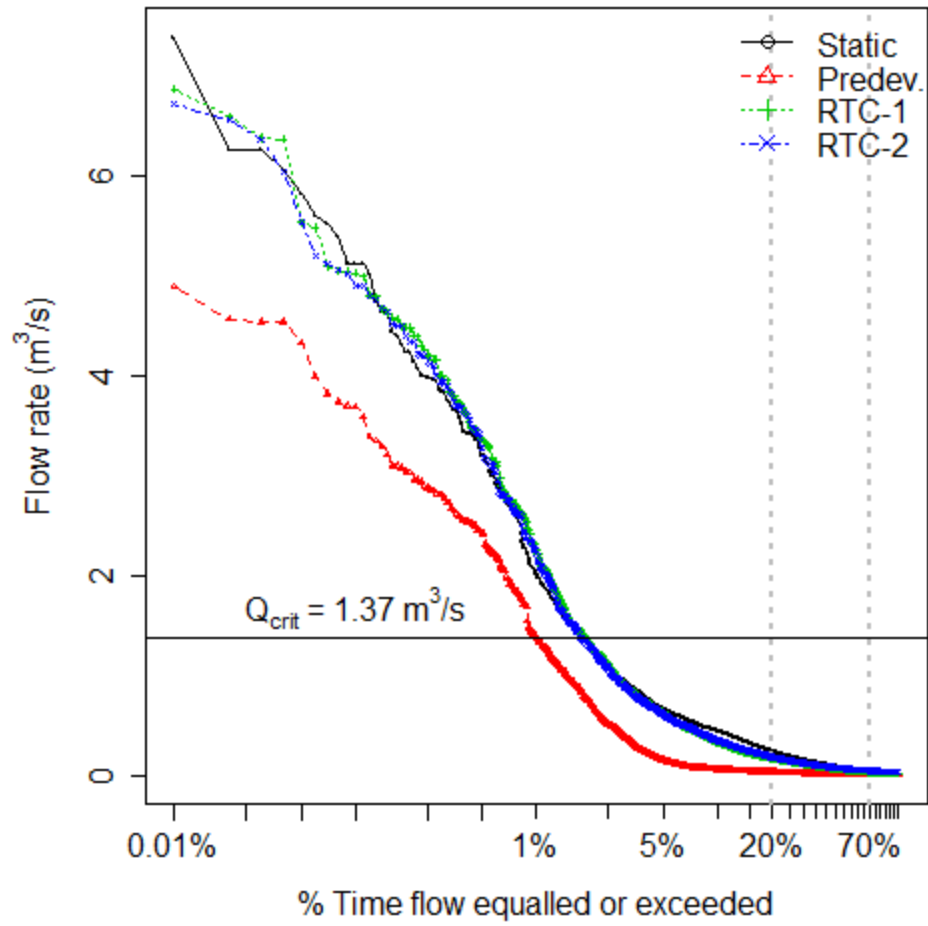


Figure D8. Flow Duration Curve at Watershed Outlet with RTC on Facility 4860

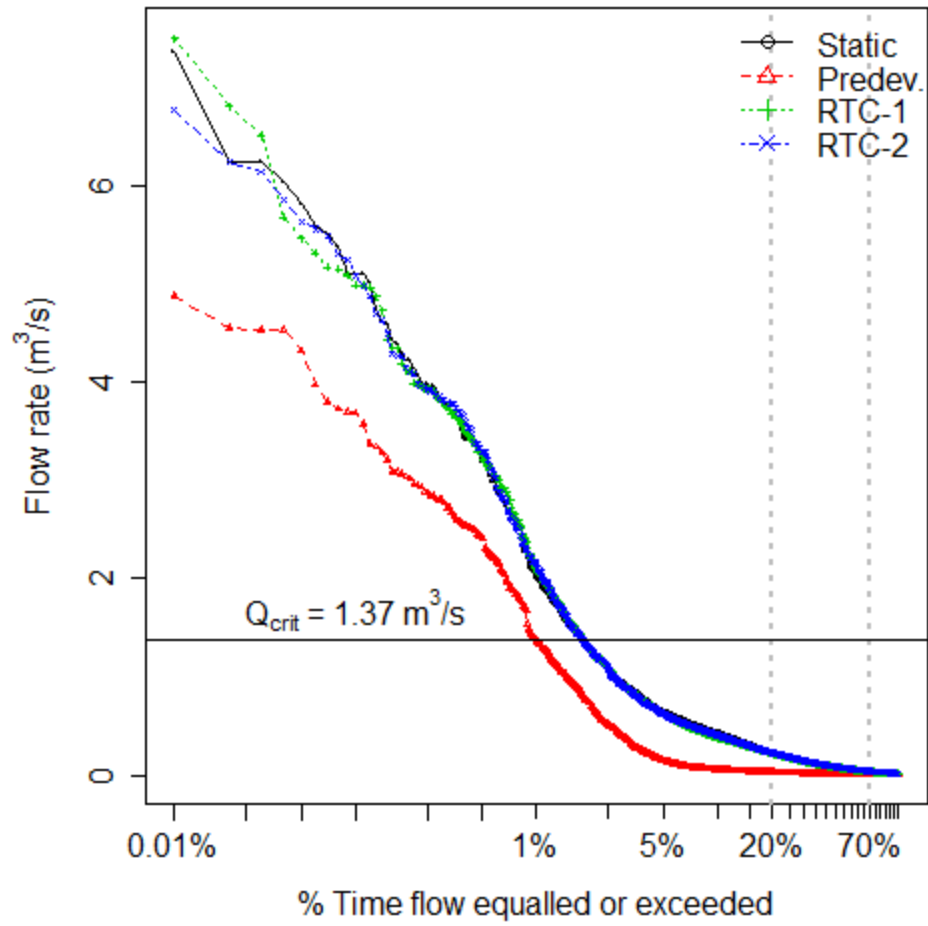


Figure D9. Flow Duration Curve at Watershed Outlet with RTC on Facility 2309

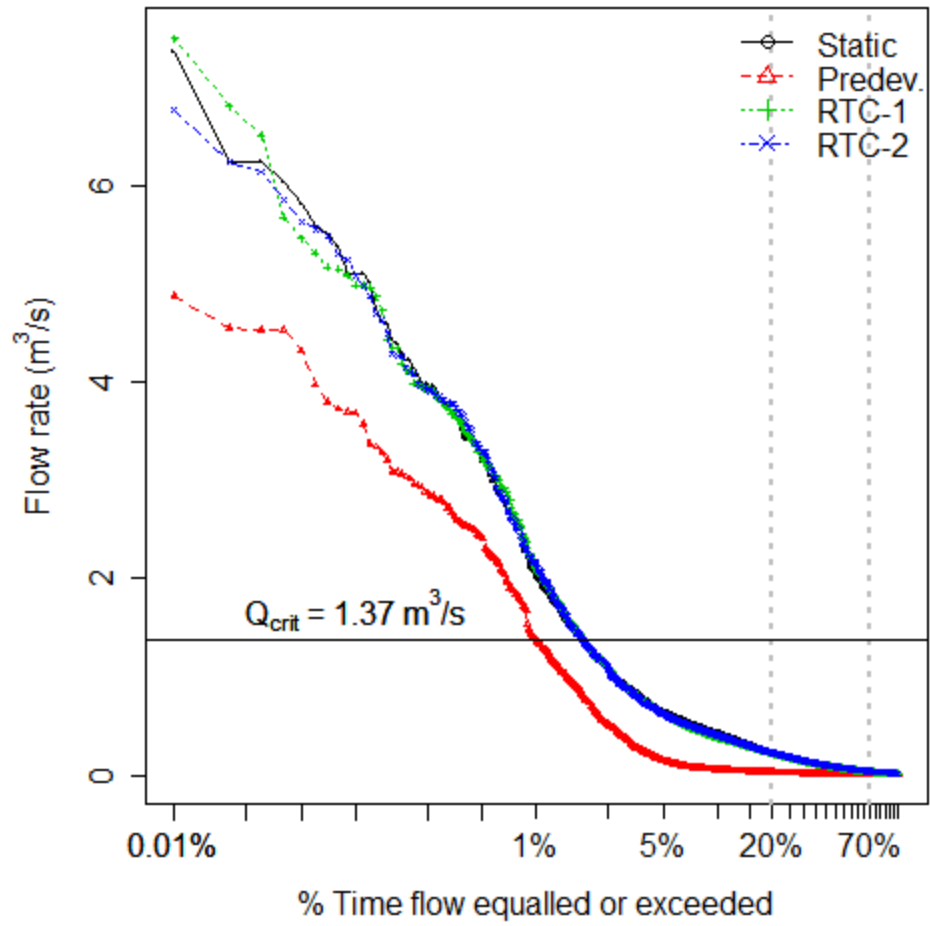


Figure D10. Flow Duration Curve at Watershed Outlet with RTC on Facility 2044

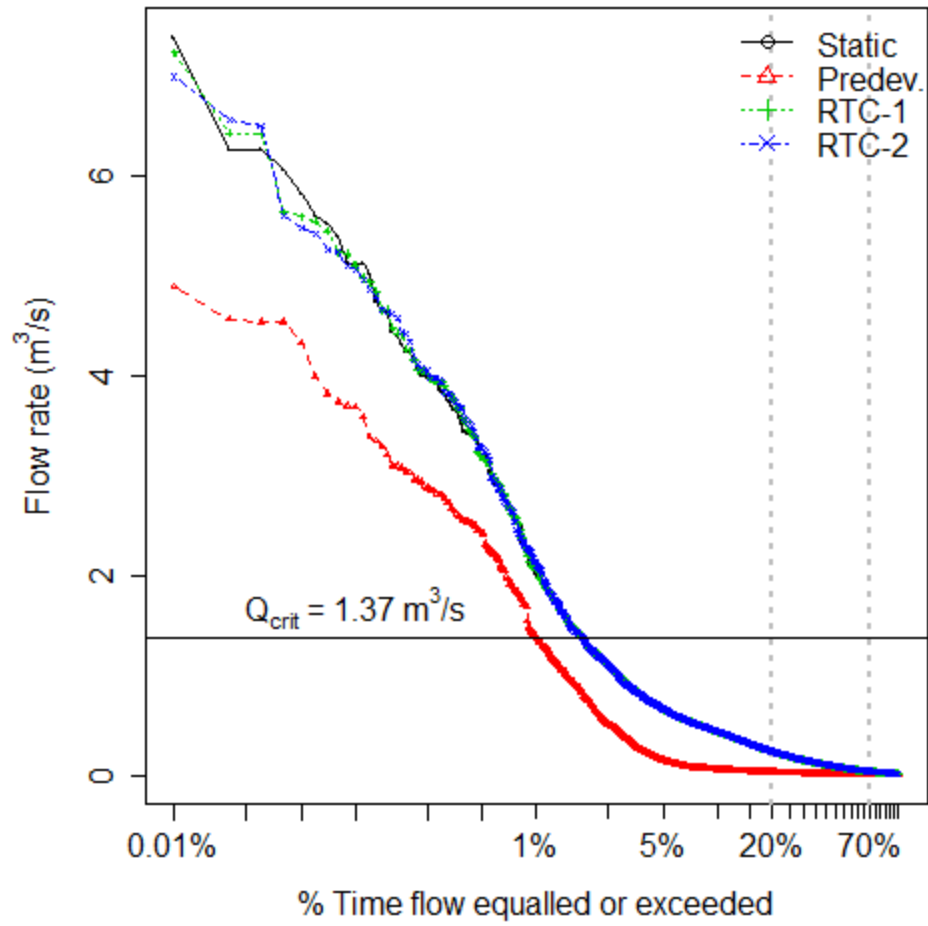


Figure D11. Flow Duration Curve at Watershed Outlet with RTC on Facility 0388

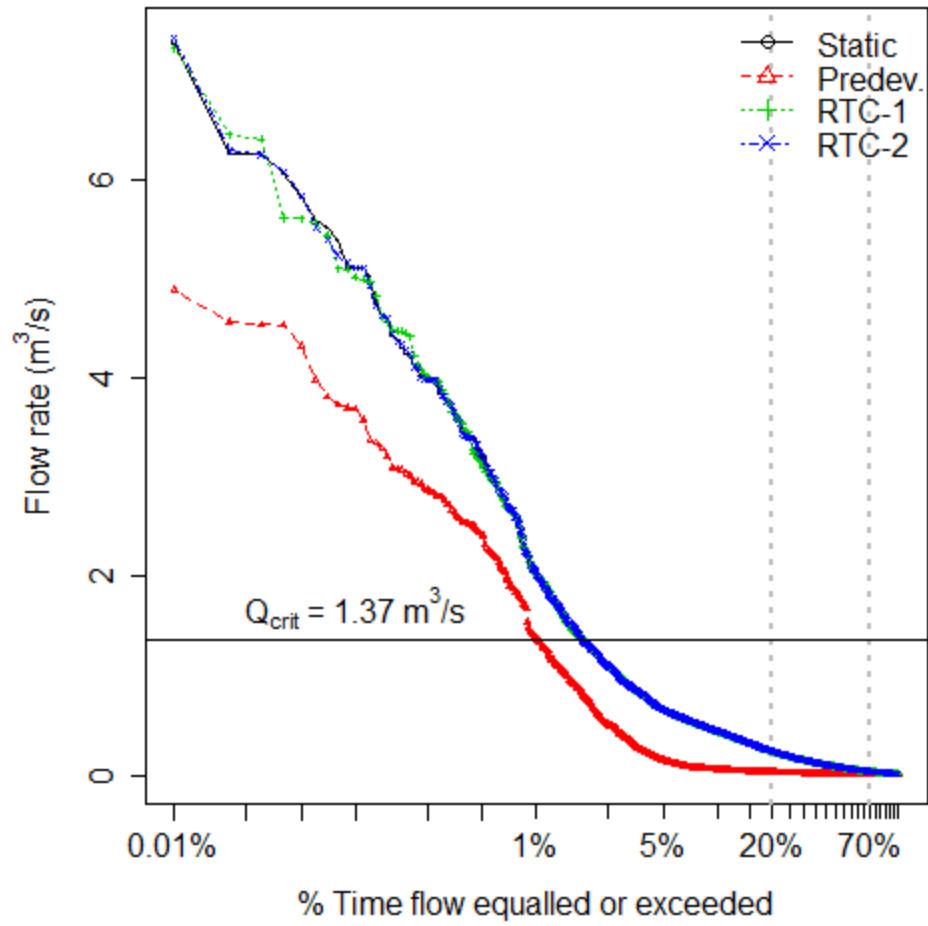


Figure D12. Flow Duration Curve at Watershed Outlet with RTC on Facility 0274

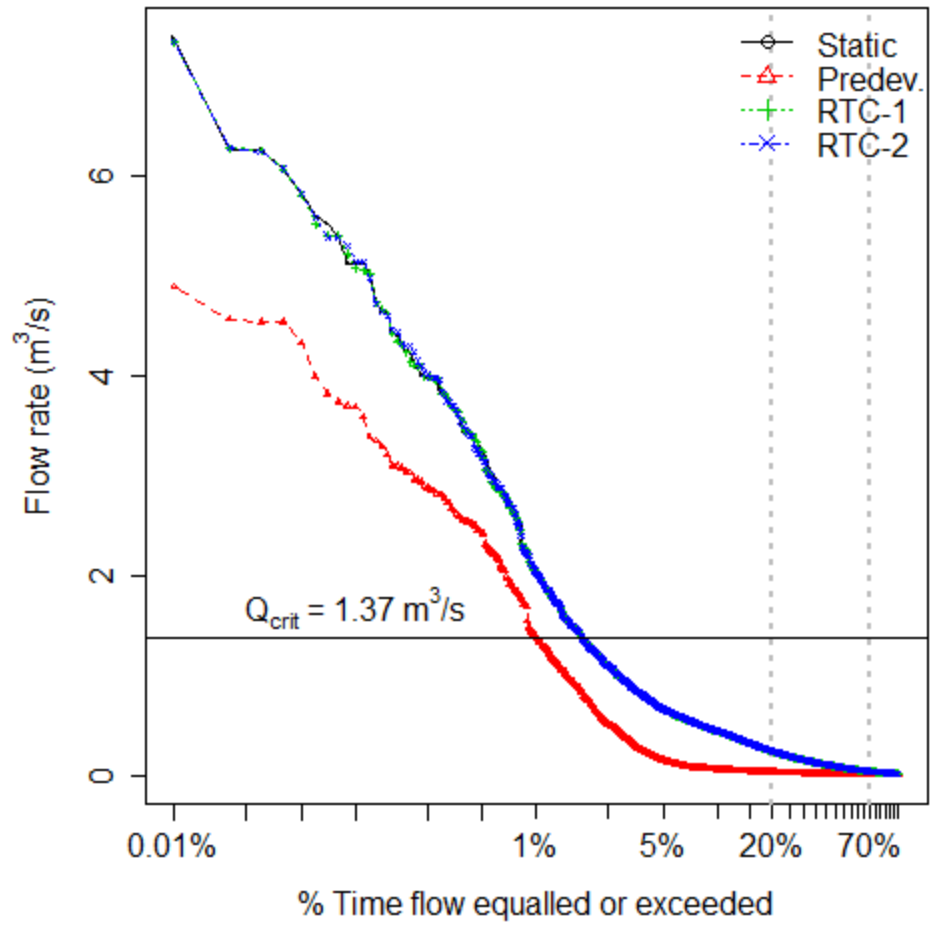


Figure D13. Flow Duration Curve at Watershed Outlet with RTC on Facility 0262

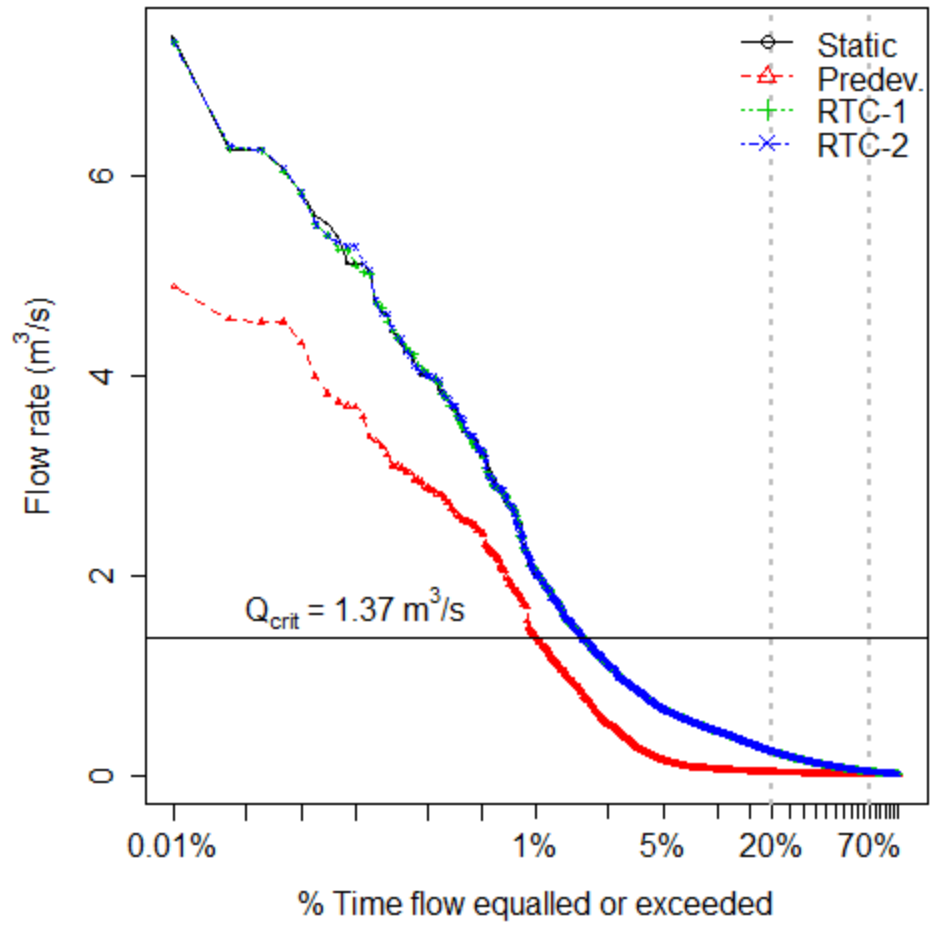


Figure D14. Flow Duration Curve at Watershed Outlet with RTC on Facility 0178

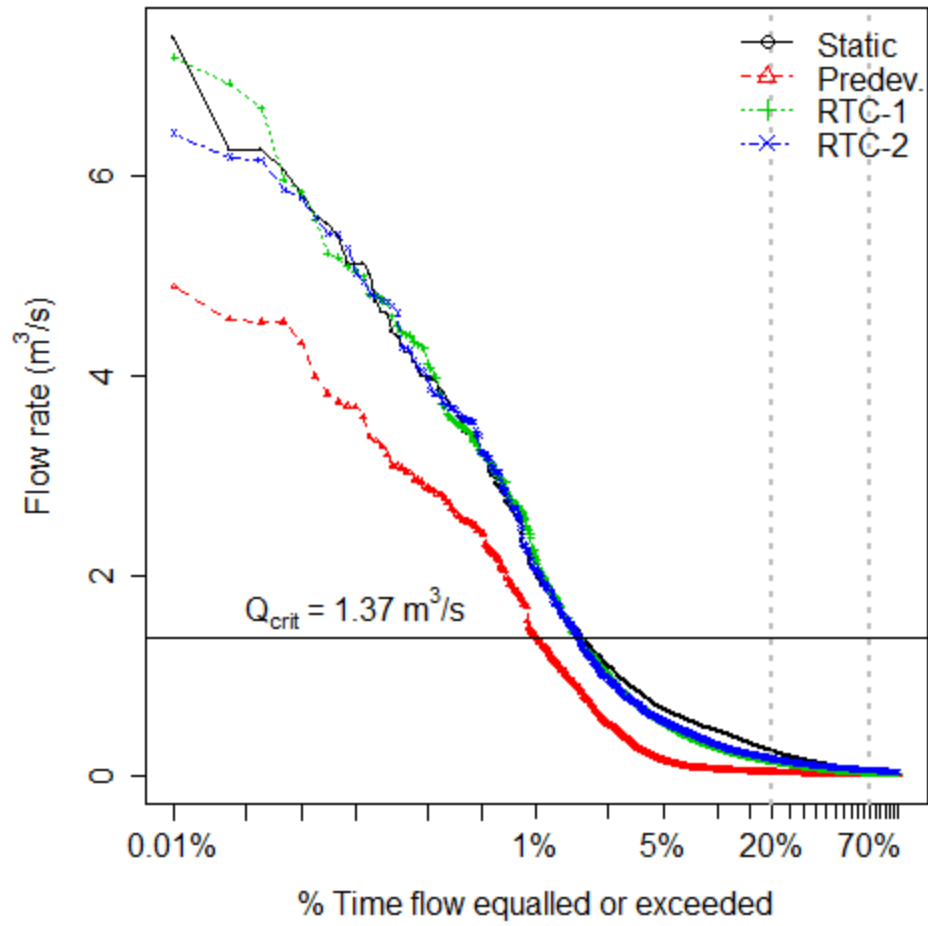


Figure D15. Flow Duration Curve at Watershed Outlet with RTC Combo #1

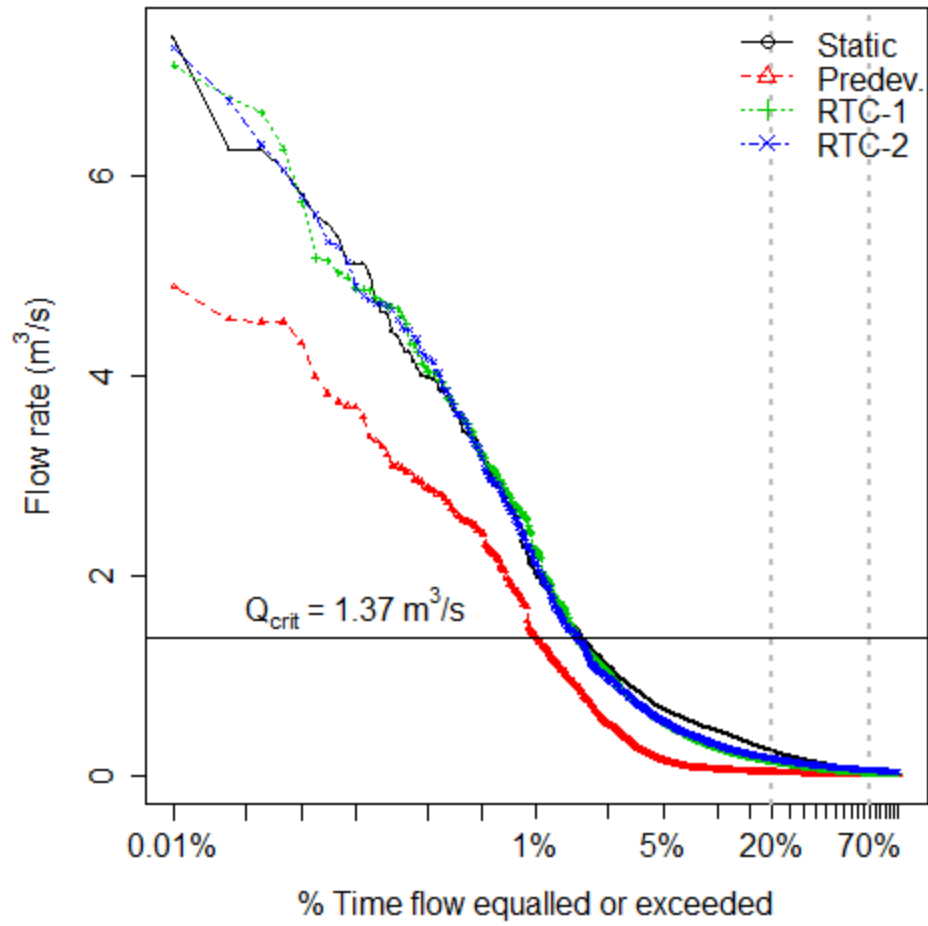


Figure D16. Flow Duration Curve at Watershed Outlet with RTC Combo #2

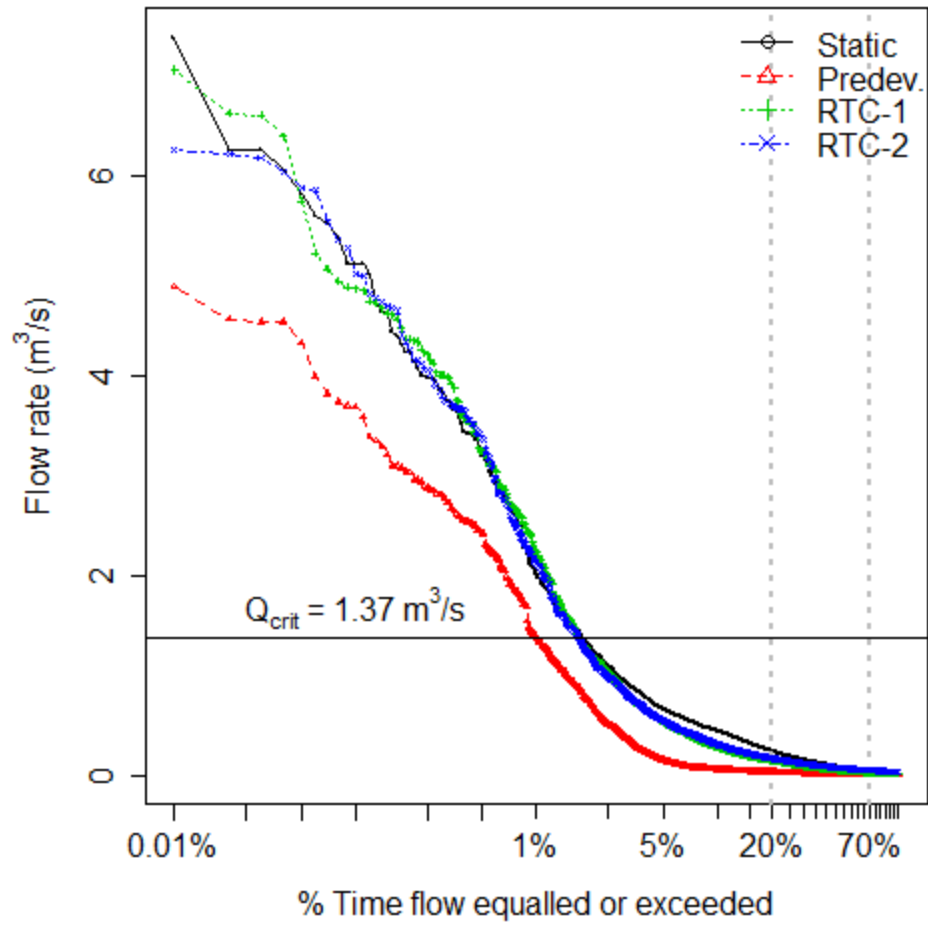


Figure D17. Flow Duration Curve at Watershed Outlet with RTC Combo #3

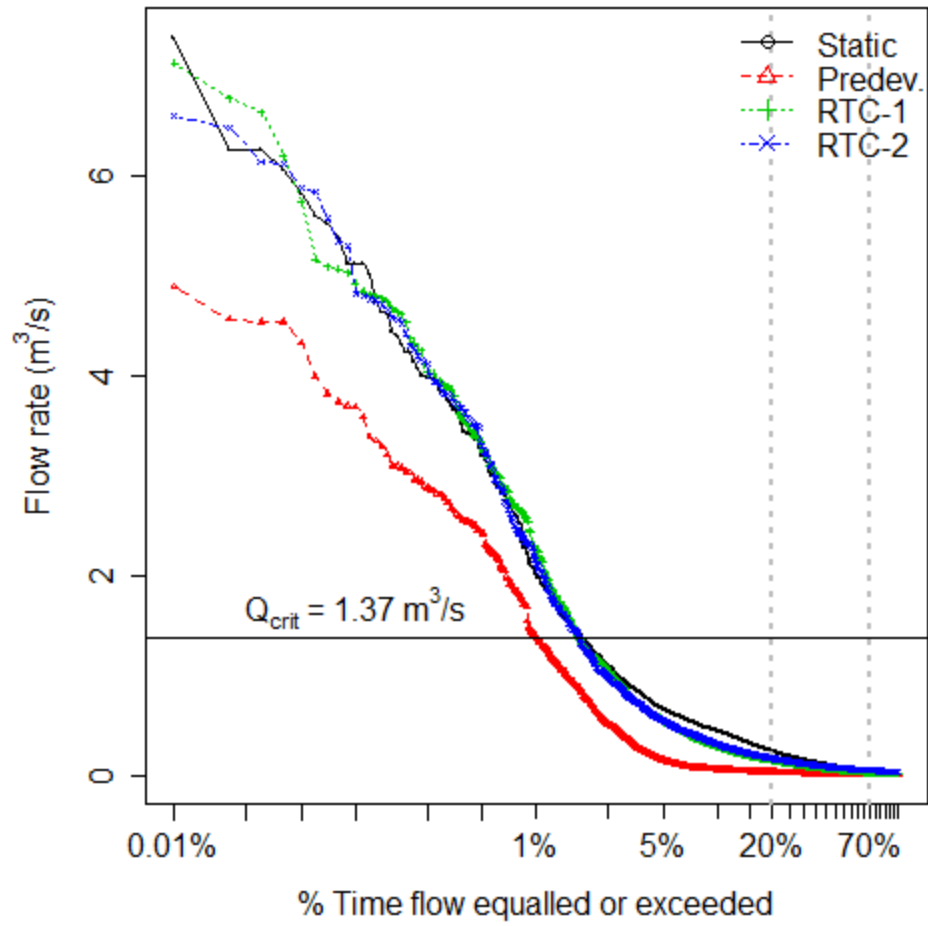


Figure D18. Flow Duration Curve at Watershed Outlet with RTC Combo #4

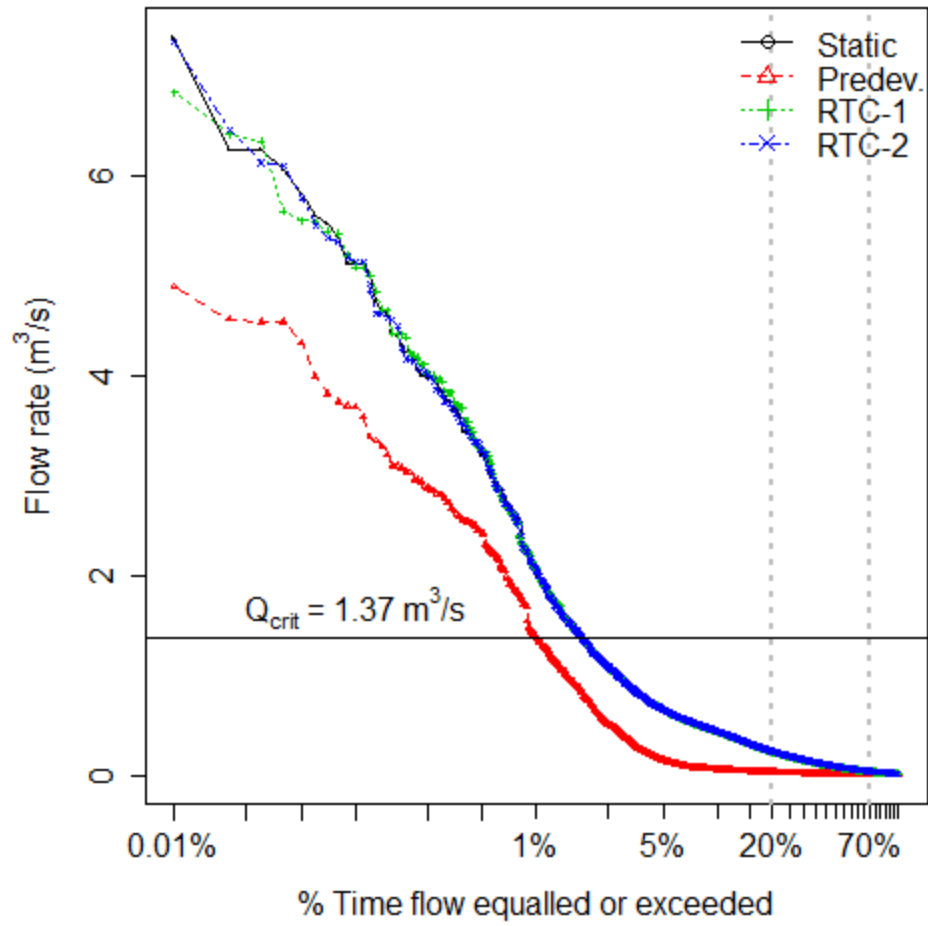


Figure D19. Flow Duration Curve at Watershed Outlet with RTC Combo #5

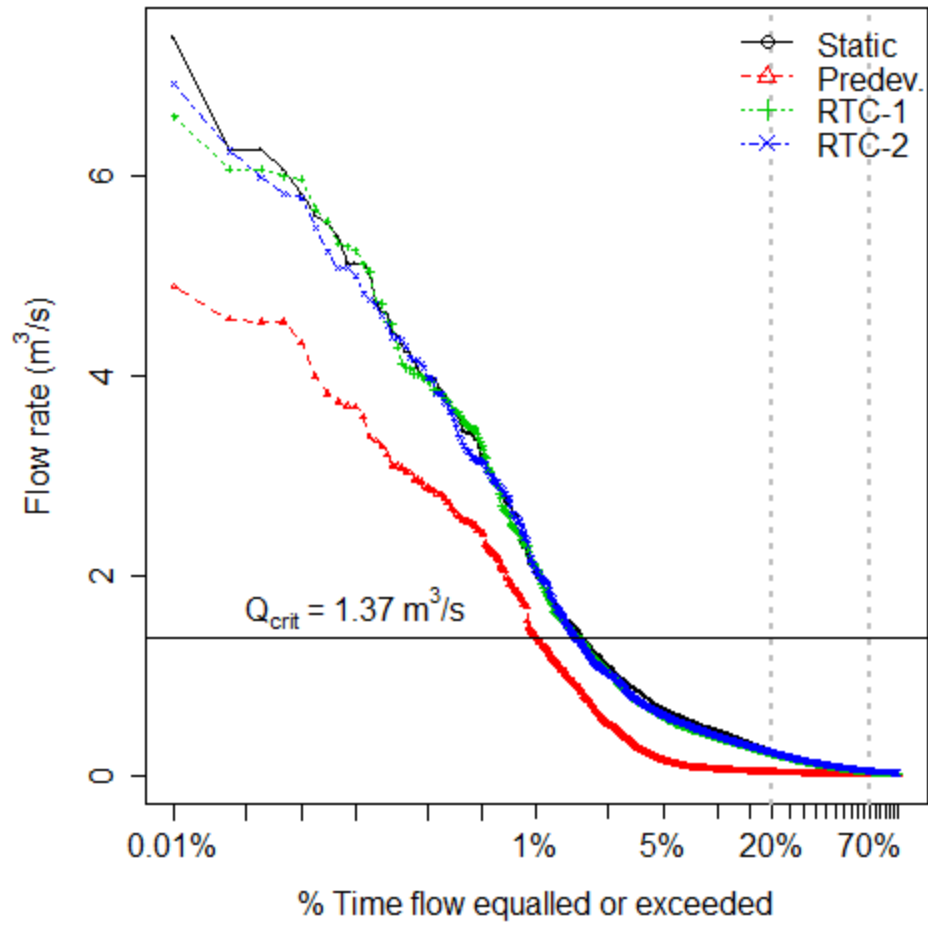


Figure D20. Flow Duration Curve at Watershed Outlet with RTC Combo #6

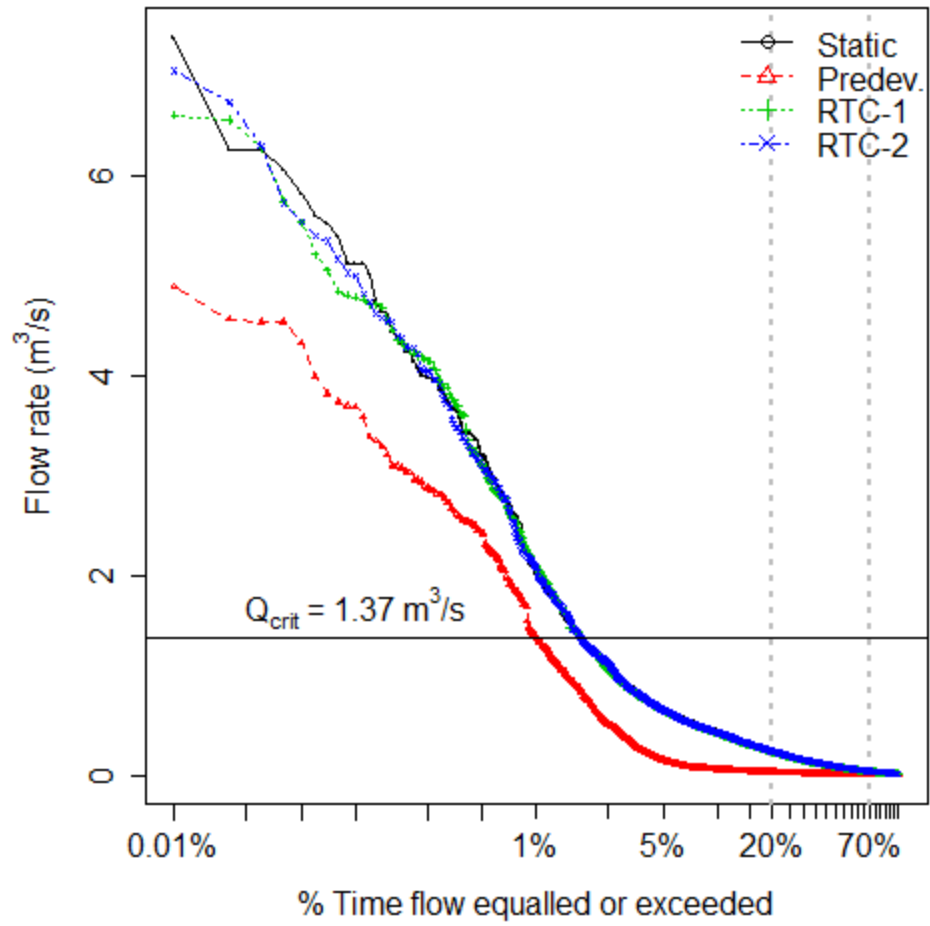


Figure D21. Flow Duration Curve at Watershed Outlet with RTC Combo #7

Appendix E: Temporal Aliasing Investigation

- **Impact of PySWMM Time Step on Peak Flow Measurements**
- **Impact of PySWMM Time Step on RTC Change in Peak Flow**
- **Impact of PySWMM Time Step on Volume Measurements**

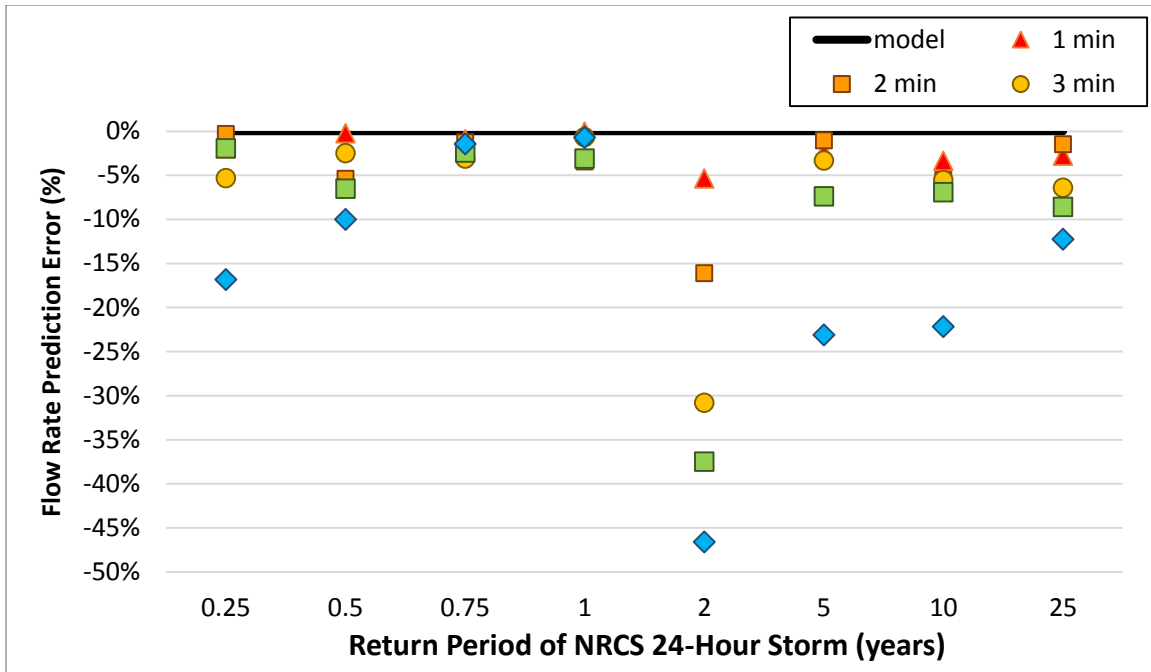


Figure E1. Impact of PySWMM Time Step on Peak Flow – Relative Error

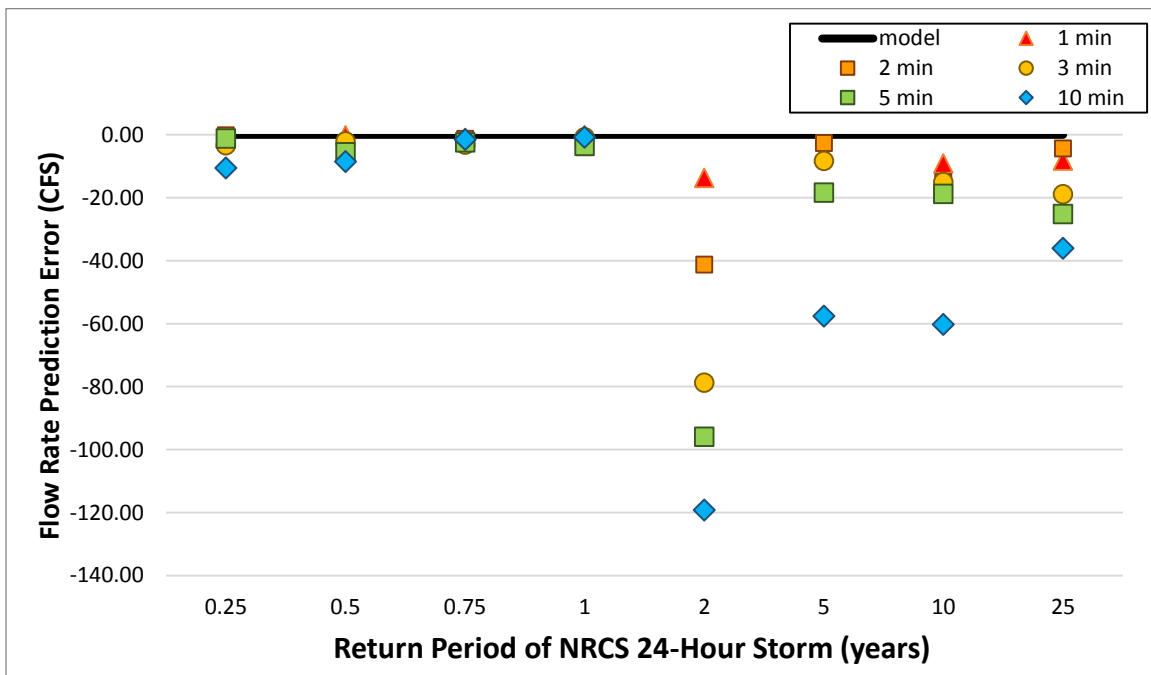


Figure E2. Impact of PySWMM Time Step on Peak Flow – Absolute Error

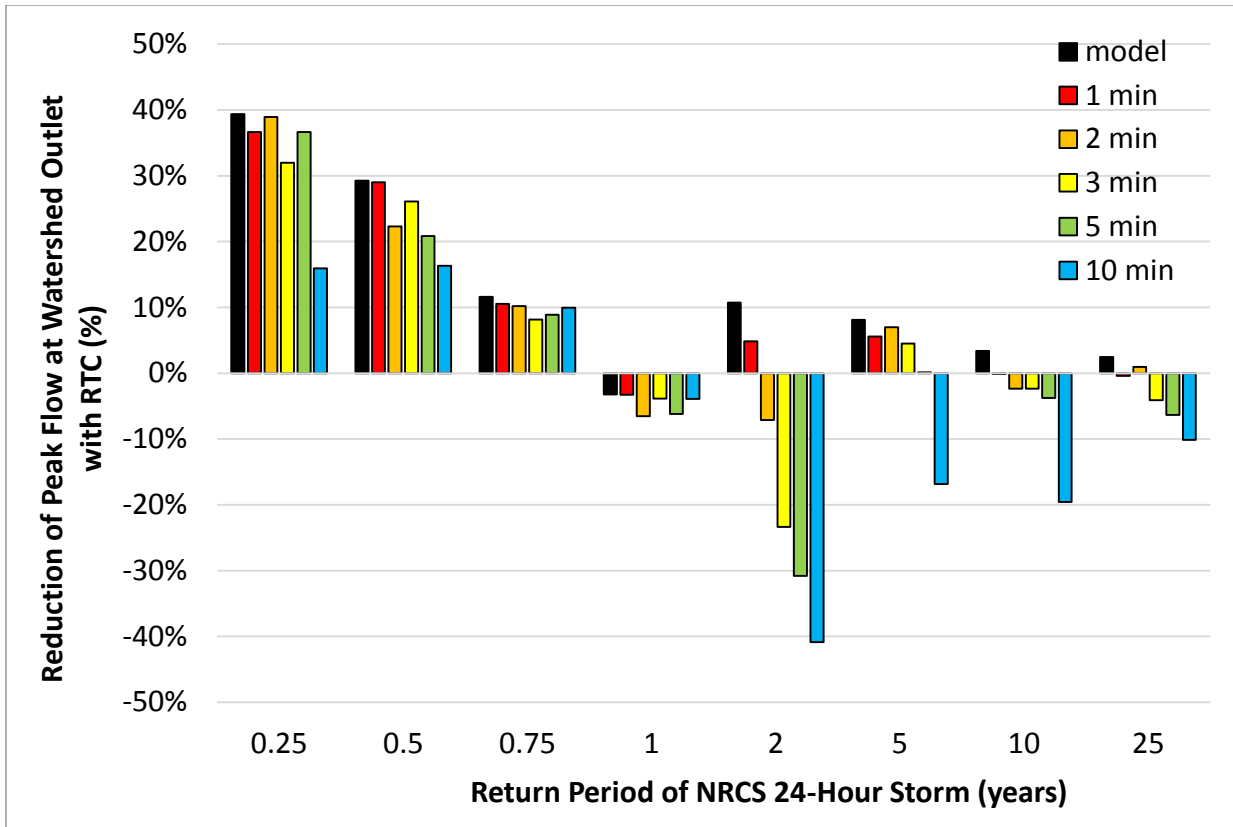


Figure E3. Impact of PySWMM Time Step on resulting RTC Change in Peak Flow

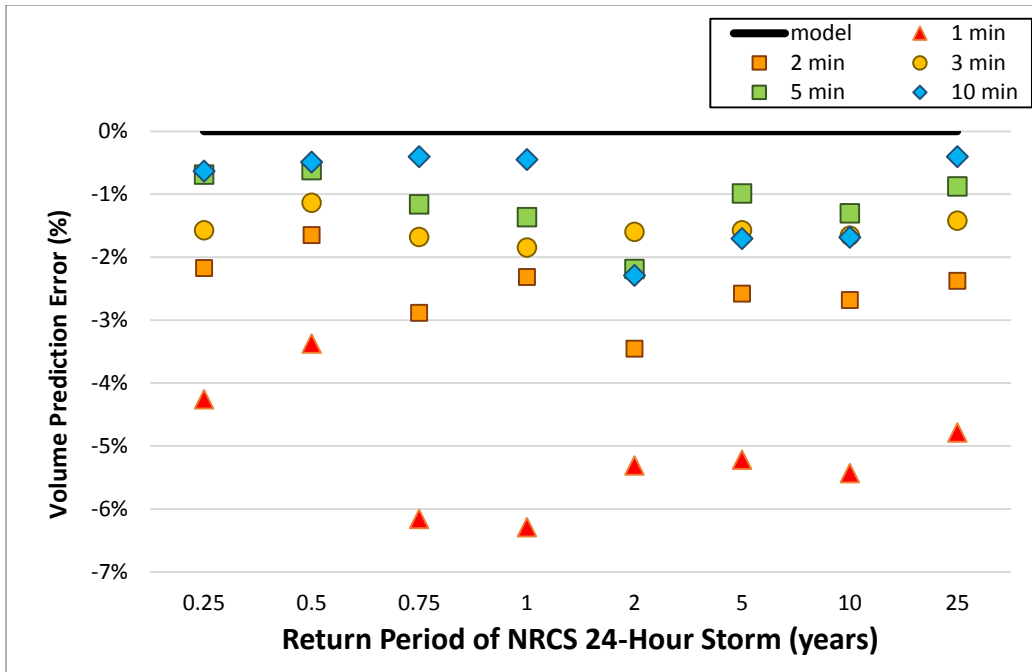


Figure E5. Impact of PySWMM Time Step on Volume – Relative Error

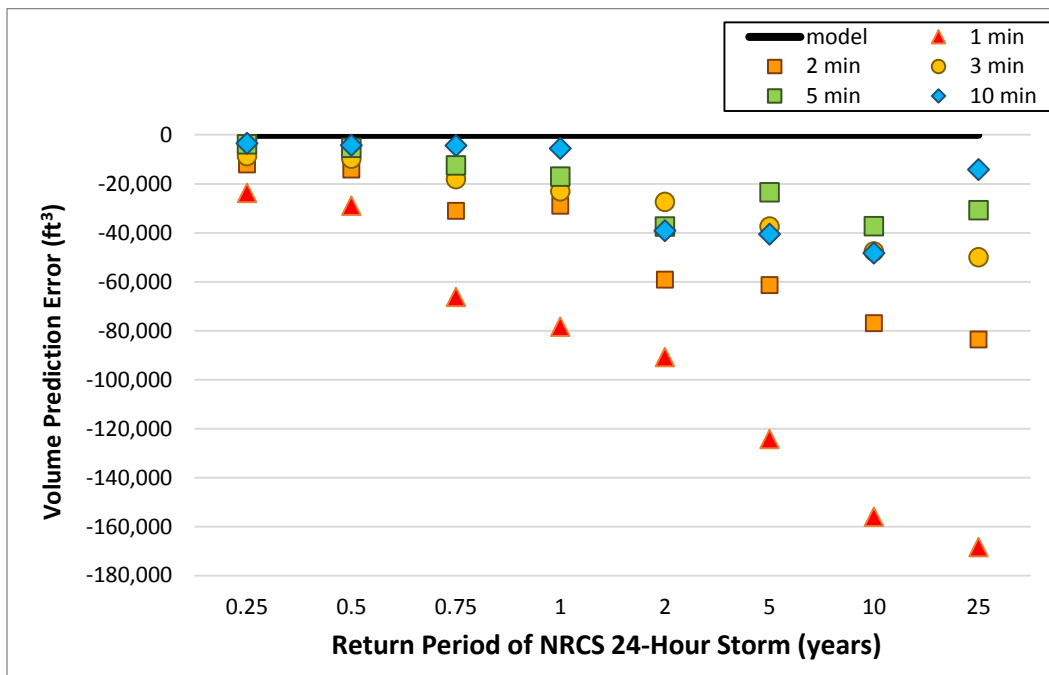


Figure E6. Impact of PySWMM Time Step on Volume – Absolute Error