HOLISTIC WATERSHED MANAGEMENT FOR EXISTING AND FUTURE LAND USE DEVELOPMENT ACTIVITIES: OPPORTUNITIES FOR ACTION FOR LOCAL DECISION MAKERS: PHASE 1 – MODELING AND DEVELOPMENT OF FLOW DURATION CURVES (FDC 1 PROJECT)

SUPPORT FOR SOUTHEAST NEW ENGLAND PROGRAM (SNEP) COMMUNICATIONS STRATEGY AND TECHNICAL ASSISTANCE

TASK 4 TECHNICAL SCOPE / APPROACH, GENERALLY, AND ELUCIDATION OF POTENTIAL FDC METRICS

JAN 25, 2021

Prepared for:

U.S. EPA Region 1

Prepared by:

Paradigm Environmental

Great Lakes Environmental Center

Blanket Purchase Agreement: BPA-68HE0118A0001-0003
Requisition Number: PR-R1-20-00322
Order: 68HE0121F0001

Table of Contents

1.0 INTRODUCTION

The purpose of this document is to identify and discuss the flow metrics that may be employed to better understand the hydrological implications of watershed development (i.e., increase in impervious cover [IC] on in-stream flow conditions and pollutant load export using flow duration curves (FDC). **The Work Plan (Paradigm Enviornmental et al., 2020. Task 0) presents the full technical scope of the FDC 1 project, while this memo provides further evaluation of potential FDC evaluation metrics**. The Work Plan lays out the methodology for developing the models/tools (HSPF/LSPC and SUSTAIN/Opti-Tool) for this project and the application of those models for developing FDCs for selected low-order stream segments under differing watershed development (e.g., pre-development, historic, and existing) and climatic conditions (existing and future). The primary objective of Task 4 is to consider potential flow metrics to be used for assessing both impacts (e.g., high pollutant export, channel destabilization, and ecological degradation) associated with IC and benefits associated with potential watershed management strategies. The Work Plan demonstrates the proposed optimization analysis approach to minimize the area between the FDCs for pre- and post-development scenarios for target flow regimes of interest. Through this project, the Opti-Tool will be enhanced to provide the flexibility to develop in-stream FDCs and conduct similar FDC based management optimization analyses (e.g., minimizing the difference in area between pre- and post-development FDCs for flow regimes that carry the bulk of pollutant washoff load land cause channel destabilization. This document should be considered as an addendum to the Work Plan, which provides more details on the modeling approach and other technical tasks.

The technical steering committee (TSC) has been requested to provide review comments on this and future draft technical documents prepared during the project. Responses to comments received from the first TSC meeting and by email are presented in the Appendix of this memo. For the future and to facilitate TSC review and discussion, draft memos will be provided in advance for review, and comments received prior to TSC meetings will be compiled into PowerPoint presentations for TSC meeting discussion. Comments received after TSC meeting discussion will be incorporated into draft final and final memos as above.

1.1 Problem

Freshwater ecosystems are affected by all characteristics of a long-term flow regime (Walsh et al., 2015). Changes in land cover resulting in increasing impervious cover and associated stormwater runoff tend to be a primary driver behind declining hydrologic and water quality conditions. Stormwater management is often focused on matching pre-development peak flows for a small set of design storms, limited water quality control, and groundwater recharge. Less attention is paid to the cumulative geomorphic and ecological degradation resulting from changes in the frequency, magnitude, and duration of hydrologically induced disturbances over the entire flow regime. For example, while existing detention standards attenuate the peak flow of a large storm, they provide little to no attenuation to lesser flow rates and increased runoff volumes from impervious cover and result in a prolonged period of elevated stream flows that can impact the ecosystem of the receiving waters (Reichold et al., 2010). An analytical framework is needed to help quantify both the hydrologic impacts of the existing condition and the potential benefits of hydrograph restoration associated with stormwater management activities.

The Work Plan of this project details the analytical framework highlighting the methodology for modeling tasks. This task is to present the analytical framework to TSC members as an overview of the Work Plan and in particular to assess how and what flow metrics may be applied and leveraged for purposes of the project.

1.2 Background

Changes to the frequency and magnitude of discharges, as well as associated impacts to water quality, stream geomorphology, and habitat conditions can be measured by changes in watershed hydrology. The FDCs are cumulative frequency curves that provide a valuable indication of the hydrological condition by showing the percent of time-specific discharges that were equaled or exceeded during a given period (Searcy, 1959). FDCs have been used to quantify the effect of channel and floodplain processes on channel characteristics (Naito and Parker, 2019). Fan & Li, (2004) studied the implications of using FDCs to predict stream erosion. Reichold et al., (2010) developed an optimization framework to identify land use patterns that minimize impacts to FDCs. A team that included Paradigm Environmental applied EPA SUSTAIN FDC optimization approach to watershed-scale stormwater planning efforts in the Puget Sound region (Northwest Hydraulic Consultants, 2017). The Taunton River Watershed provides an excellent opportunity as a study-site for which to further develop the application of FDCs to quantify impacts to stream health and investigate the potential benefits of stormwater management and next-generation new development and/or redevelopment (nD/rD) management practices, or Conservation Development (CD) practices. The Wading River subwatershed is a potential study site as it has long-term streamflow and meteorological monitoring records, a mix of land development patterns, and is within the modeling domain of existing and calibrated watershed models, which will be leveraged in this project. These models include a Hydrological Simulation Program—FORTRAN (HSPF) model for hydrology (Barbaro & Sorenson, 2013) and the United States Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS) for hydraulics (Zarriello & Barbaro, 2014) in the Taunton River.

Figure 1 and Figure 2 present a flow duration curve and a low-flow frequency curve for the Wading River for the years 1956-1981 and represent valuable data for calibrating historical flows. The Wading River is regulated to some extent by Lake Mirimichi and other lakes and reservoirs upstream. Upstream of the USGS gage is a diversion for municipal supply for Attleboro, MA, as well as small diversions to and from the basin for other municipal supplies.

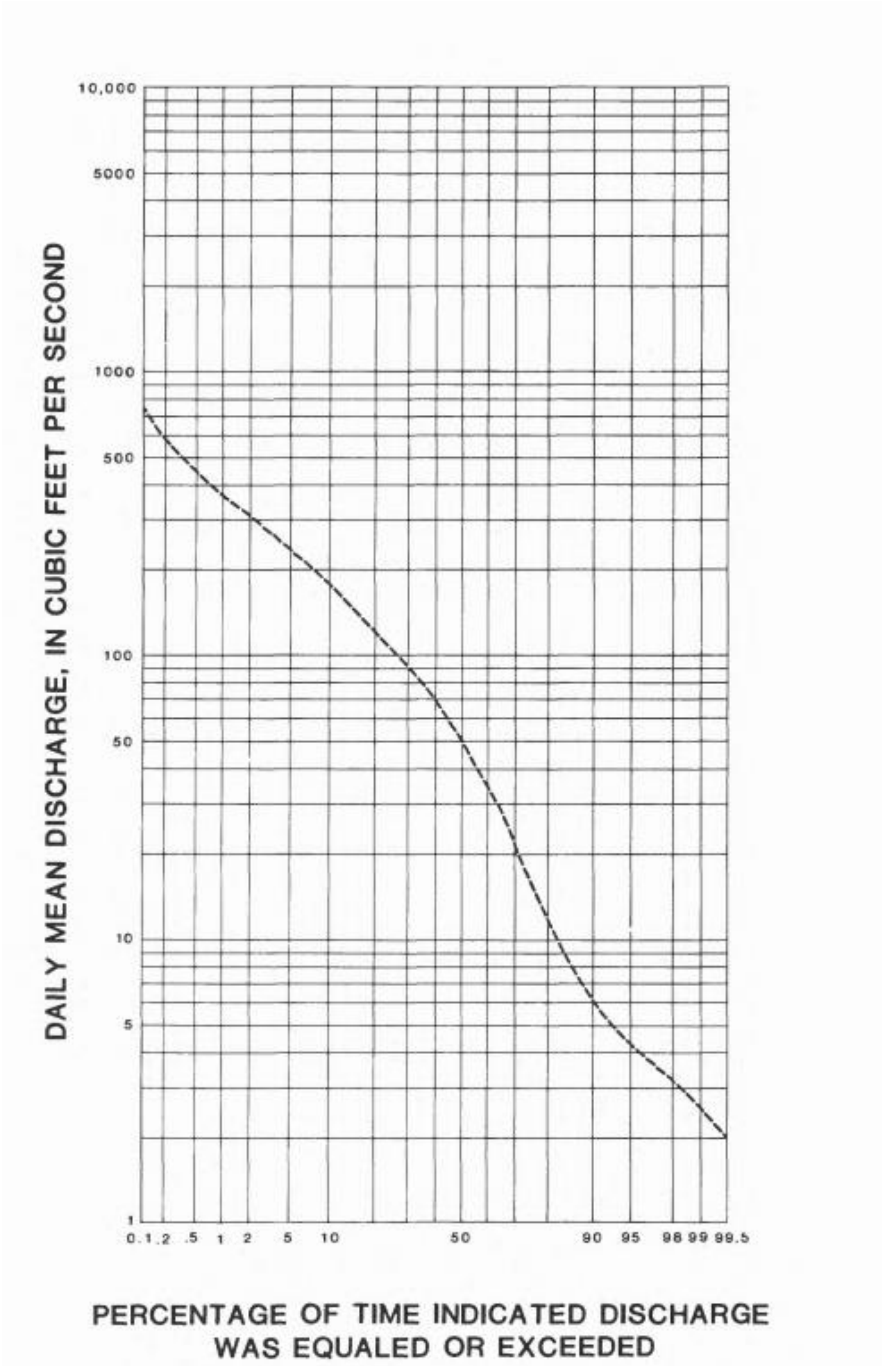

Figure 5.--Flow-duration curve for Wading River near Norton, Mass. (site 47), during 1955-81

Figure 1. Flow-duration curve for Wading River 1955-1981. Source: (Wandle and Keezer, 1984)

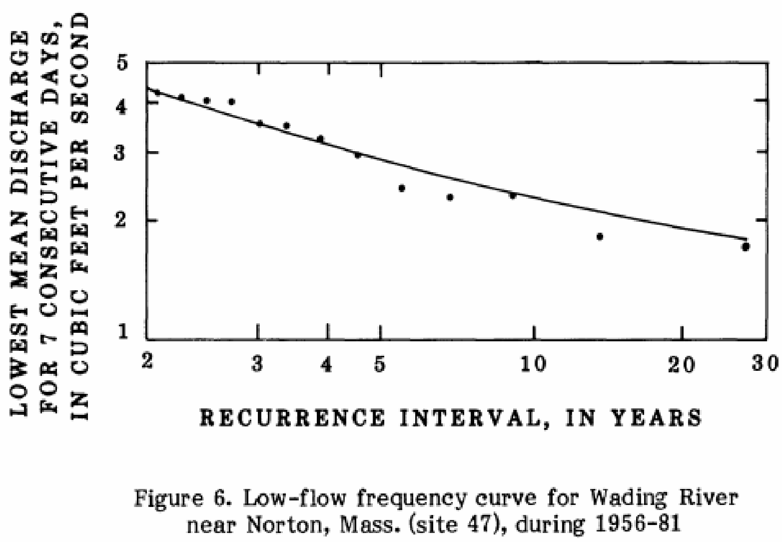

Figure 2. The low flow recurrence interval for the Wading River 1956-1981. Source: (Wandle and Keezer, 1984)

1.3 Overall and Task 4 Project Objectives

The objective of the FDC1 Project is to implement a proof-of-concept demonstration that the Region 1 modified Opti-Tool and associated models can be applied for the development and analysis of FDCs. FDCs will be used to assess a full range of impacts caused by impervious cover conversion on watershed hydrology and for informing the development of management strategies that include stormwater mitigation and the conservation of key watershed resource areas critical for maintaining watershed hydrologic and ecologic health. An approach to quantify average annual unit-area-based changes in heat exchange and carbon sequestration resulting from land-use change/IC conversion will be investigated to provide additional information on the impacts and potential benefits of management solutions. Changes to land use and land cover can affect energy portioning between latent and sensible heat flux. Latent heat is exchanged due to phase changes of water but does not result in a temperature change. Evaporation or condensation are examples of latent heat exchange.

The expanded functionality to Opti-Tool will include groundwater/aquifer components and an FDC evaluation factor. Once configured, the Opti-Tool FDC evaluation factor(s) can be used in Phase 2 of the project to investigate the impacts of next-generation new development and/or redevelopment (nD/rD) practices, or Conservation Development (CD) practices, on watershed hydrology, stream health, and overall pollutant load export. One of the objectives of the overall project is to develop relationships between FDCs and watershed development that can be applied to other watersheds with similar physical characteristics and to present these relationships in clear and simple terms to inform the development of both restoration plans and protective management strategies for increase climate resiliency and future growth (Phase 2). Overall, the project will provide a body of technical documentation that can support communities, especially in the Southeast New England Program (SNEP) region who may consider the adoption of protective ordinances that build resiliency and promote the restoration/protection of local and regional water resources.

The specific objective of Task 4 is to identify a primary set of quantitative metrics representing changes in the frequency, magnitude, and duration of stream flow regimes that would cause geomorphic and ecological degradation of natural streams. It is anticipated to keep the priority evaluation metrics to just a few that are easily understandable (e.g., high pollutant export flows, scouring flows, and bank full flows) and then evaluating how secondary metrics are improved. The optimization target can be set to minimizing the difference between predevelopment and post (i.e. existing conditions) for the flow rates that carry the bulk of the load and cause channel destabilization.

This work will help make the connection between the science of urban stream ecology and management strategies that are accessible to watershed managers, engineers, and developers. The modeling approach will explore the fact that conserving existing resources is vital, as replacing multiple ecosystem and hydrologic functions provided by these natural resources is challenging and costly. For example, wetlands play an important role in the ecology of the watershed, help clean and filter water that moves through them, and prevent flooding. Additionally, the FDCs and optimization results highlighting cost-effective solutions will help support decision making as well as public outreach and education efforts.

1.4 Approach

1.4.1 FDCs and Flow-Based Metrics

The FDC 1 project relies on updating the Visual Basics for Applications (VBA) source code and user interface for the Opti-Tool to adopt the functionality of groundwater/aquifer and FDC optimization evaluation factor from the EPA SUSTAIN version 1.2 model. The functionality will allow Opti-Tool to minimize the area between two FDC curves that are also bounded by upper and lower percentile thresholds. While visual graphics, such as the one presented in (Figure 3) are useful, further quantification of the impacts of watershed development on freshwater ecosystems is required. Flow-based surrogates for measuring and mitigating the impacts of land use change include critical flow values that reflect the occurrence of flooding (overtopping stream bank $Q_{Bankfull}$) and larger flood flows associated with specific return periods as well as key ecological conditions such as scouring flows, baseflow and low flow conditions reliant on groundwater (GW) recharge, and sensitive temperature flow regimes dependent upon GW sources.

Generalized metrics for evaluating differences between two FDCs, such as FDCs representing predevelopment and post-development conditions, include ecodeficits and ecosurpluses (Figure 4). An ecodeficit and ecosurplus calculate alterations to an FDC as a percentage of water no longer available for ecosystem use or the percentage of excess water introduced to an ecosystem (Vogel et al., 2007). More complex approaches include indicators of hydrologic alteration (IHA) and the range of variability approach (RVA) (Reichold et al., 2010). The IHA uses 33 parameters (Table 1) based on their relevance to ecological quality to provide a set of quantitative metrics representing various characteristics of a natural flow regime. The RVA was developed to establish a range of natural variability about a measure of central tendency and can be used as a measure of acceptable variability over the long-term flow regime. A combined IHA/RVA approach can be used to assess a change in the natural flow regime due to watershed development. Reichold et al., (2010) synthesized the IHA/RVA approach into a single metric to serve as a practical objective function for the optimization of watershed development plans. The authors called the metric the IHA sum of mishits (IHA-SMH), although a simpler term may be Composite IHA. The discrepancy between two FDCs is identified as the number of data points that fall outside of their expected category. Importantly, Reichold et al., (2010) used the Composite IHA as the objective function for optimization, while the FDC1 Project proposes to update the Opti-Tool with the existing SUSTAIN FDC objective function (which minimizes area between curves). However, the composite IHA or its components may still be used to quantify the changes that result from optimization. The IHA and RVA approaches that were further synthesized and developed by Reichold et al., (2010), are available as a software package (The Nature Conservancy, 2007).

The application of IHA and other metrics, when applied to (1) existing condition hydrology, (2) pre-developed condition hydrology, and (3) managed post-development hydrology, can provide a meaningful computational framework for evaluating impacts and benefits. These metrics include those that evaluate the overall FDC, as well as metrics specific to flooding, erosion, pollutant load export, and ecohydrological processes (Table 2). Boundary shear stress, which is a function of hydrology and hydraulics, is also an indicator of erosion potential. Figure 5 presented post-processed LSPC outputs for stream bed shear stress for existing condition hydrology. The optimized output from Opti-Tool can be linked back to the LSPC model. The resulting analysis and associated graphics may provide valuable information that can be disseminated as part of the project.

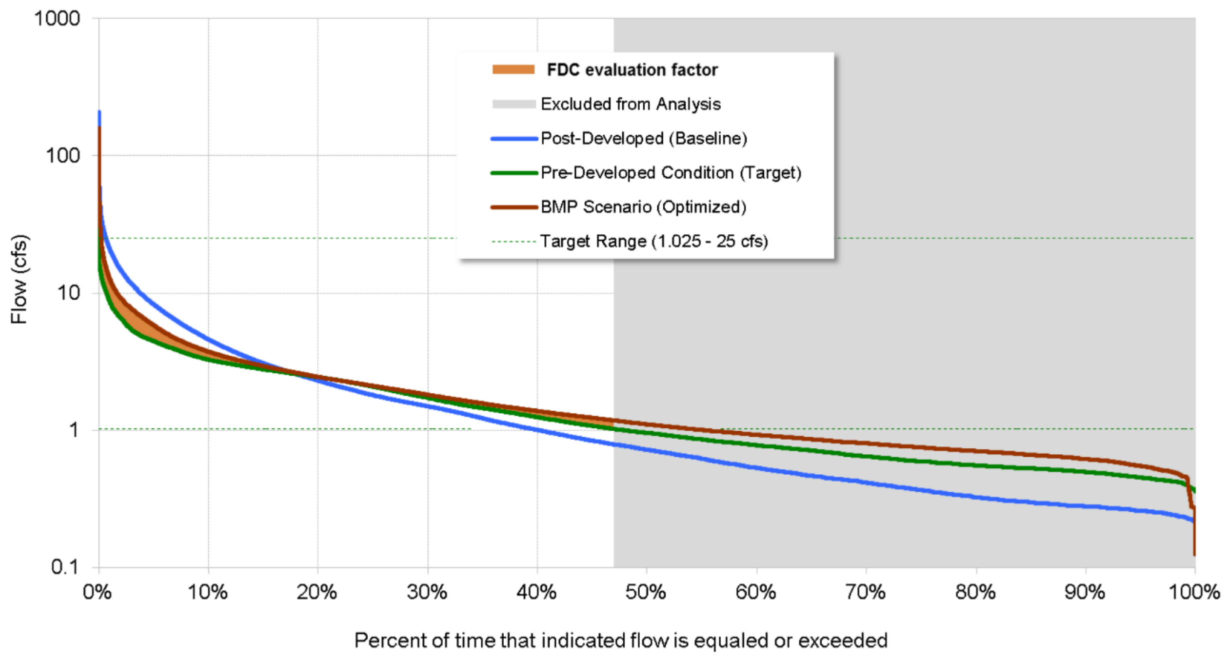

Figure 3. Flow duration curve evaluation factor in EPA SUSTAIN (version 1.2).

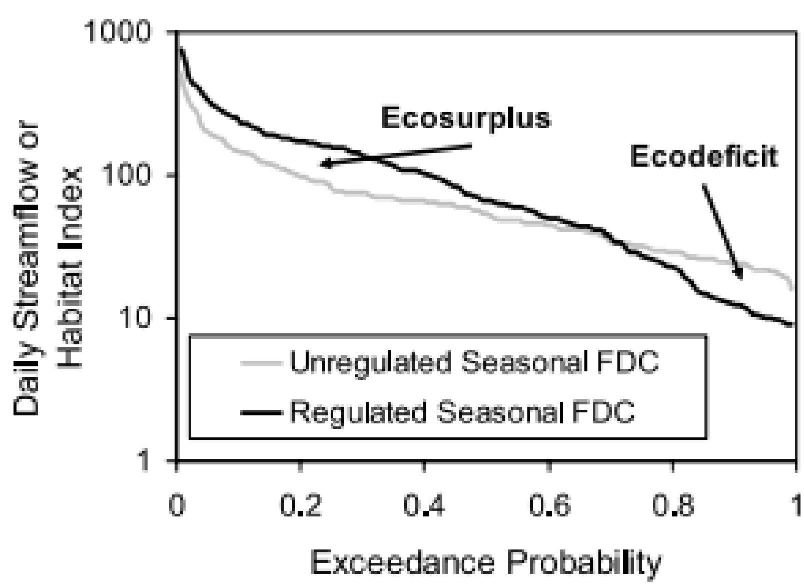

Figure 4. Definition of ecodeficit and ecosurplus regions between an unregulated (predevelopment) and regulated (post-development) FDC. Source: (Vogel et al., 2007).

Table 1. IHA Parameter Grouping (Reichold et al., 2010)

Group	IHA parameter	Examples of Ecosystem Impact
Group 1—magnitude and timing (12 parameters)	Average monthly flow (1 value for each of the 12 months)	Increased flow variations may lead to wash out or stranding of sensitive species
Group 2—magnitude and duration (12 parameters)	Average annual 1-day minimum flow	Prolonged low flows, prolonged base flow spikes, and altered inundation period may lead to a change in the concentration of aquatic organisms, reduction or elimination of plant cover, diminished plant species diversity, and loss of floating eggs
	Average annual 3-day minimum flow	
	Average annual 7-day minimum flow	
	Average annual 30-day minimum flow	
	Average annual 90-day minimum flow	
	Average annual 1-day maximum flow	
	Average annual 3-day maximum flow	
	Average annual 7-day maximum flow	
	Average annual 30-day maximum flow	
	Average annual 90-day maximum flow	
	Number of days per year with zero flow	
	7-day minimum flow divided by mean flow	
Group 3—timing (2 parameters)	Julian date of the minimum flow	Loss of seasonal flow peaks may disrupt cues for spawning, egg hatching, and migration and lead to loss of fish access to Julian date of the maximum flow wetlands or backwaters
	Julian date of the maximum flow	
Group 4—frequency and duration (4 parameters)	Number of low pulses	Flow stabilization may lead to invasion of exotic species and reduced water and nutrients to floodplain plant species
	Average duration of low pulse	
	Number of high pulses	
	Average duration of high pulses	
Group 5—rate of change and frequency (3 parameters)	Rise rate (mean of all positive differences)	Rapid changes in river stage and accelerated flood recession may cause wash out and stranding of aquatic species, failure of seedling establishment
	Fall rate (mean of all negative differences)	
	Number of flow reversals	

Table 2. Potential Metrics for Evaluating impacts and benefits from changes in land cover

Evaluation Metric	Description	Unit
Annual Nutrient (P&N) load export (excluding channel processes)	Pollutant load Export rates	lbs/acres/year
Annual surface runoff volume	Runoff yields	inches/year
Annual Groundwater recharge		inches/year
Ecodeficit/Ecosurplus	Flow Duration Curve	Dimensionless
Composite IHA	Flow Duration Curve	Dimensionless
$Q_{Bankfull}$	Flooding	cfs
$\frac{Stream\ depth}{Bank\ Height}$	Flooding when value >1	Dimensionless
Richard-Baker Flashiness index	Quicker routing of storm flows to streams and rivers relative to natural conditions	Dimensionless
Critical Shear Stress (mobilization of particles)	Streambed Mobility/Stability	$lb\text{-}force/ft^2$
Evapotranspiration rate	Ecohydrology	$mm\ day^{-1}$
Latent heat flux	Ecohydrology	$MJ\ m^{-2}\ day^{-1}$

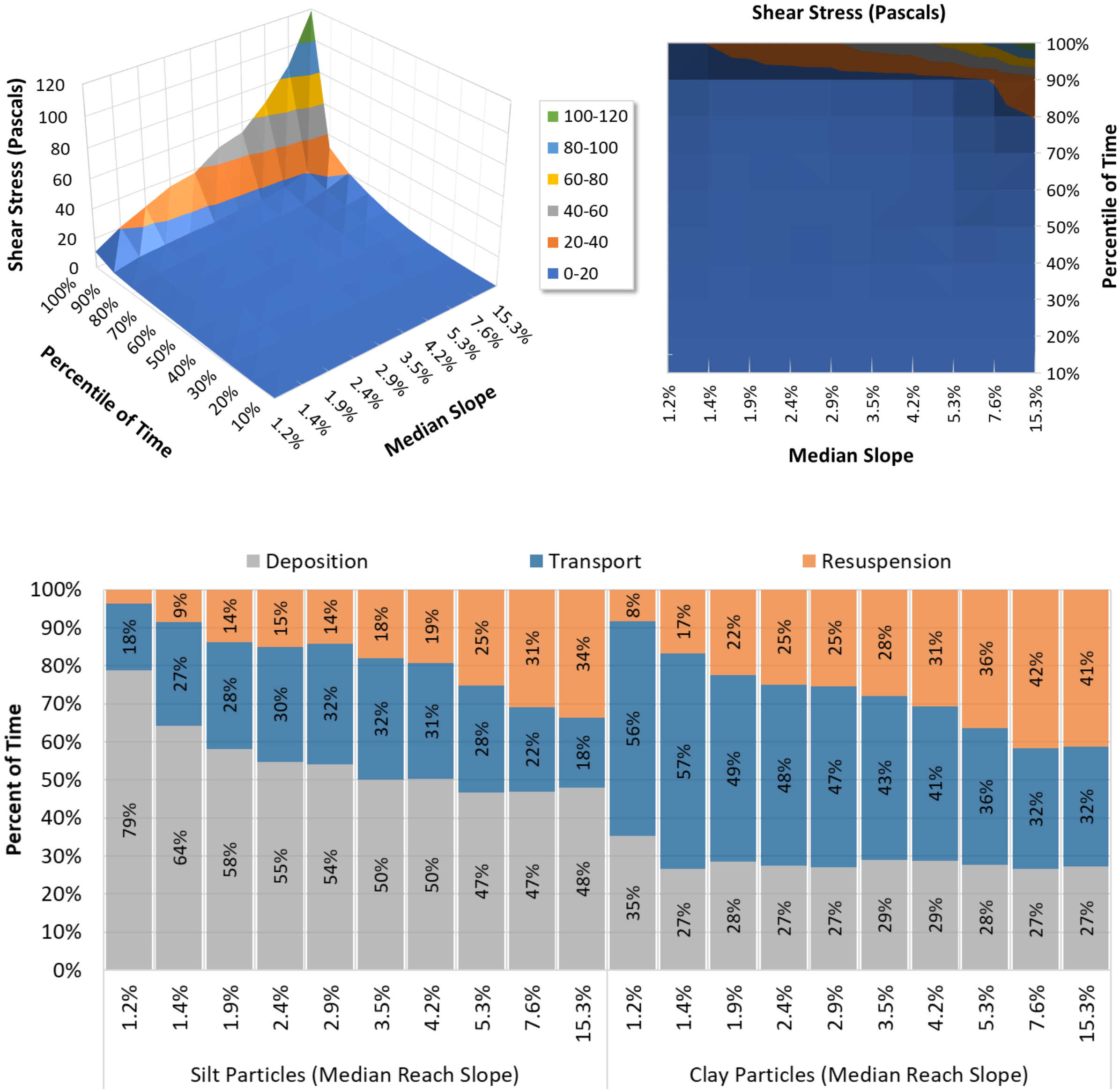

Figure 5. Post-processed shear stress output from LSPC. Top: Surface of stream bed boundary shear stress vs. slope and percent of the time (all modeled reaches). Bottom: Percent of time that silt and clay particles spend in the deposition, transport, and resuspension in model reach segments, as estimated from critical shear stress values.

1.4.2 Ecohydrology Metrics

The FDC1 project will develop methods to quantify average annual unit-area-based changes in heat exchange and carbon sequestration resulting from land use change/IC conversion. A satisfactory approach to estimating heat exchange and carbon sequestration can leverage model estimates of evapotranspiration (ET) and data embedded within the hydrologic response units (HRU) such as land cover and soil type. Van Buren et al. (2000) documented the thermal enhancement of stormwater runoff by paved surfaces. Moore & Hunt (2013) assessed several BMP types and predicted that only stormwater wetlands and grass swales would store more carbon than what is released through their construction and maintenance. The inclusion of these metrics will further illustrate the impacts associated with IC conversion and further assess the benefits of management strategies.

1.5 Limitations

While the project focuses on land-based management strategies, flow regimes can also be altered by in-stream structures like culverts and dams. Mass Audobon and TRWA (2017) provide an overview of stream continuity in the Taunton watershed. Additionally, there may be some intractable relationships that impact the study. One example is regarding bank full flows/flows that cause flooding. While impervious surfaces may cause changes to the FDC that could be expected to result in increased flooding, the changes may also cause stream incision, resulting in larger-than-expected flows being confined to the altered channel and therefore overtopping of banks occurring less frequently. Additionally, it may be difficult to isolate the effect of changes in historical and current observed FDCs due to land use change given co-occurring changes to climate and the construction/removal of in-stream structures. For example, the Wading River is regulated to some extent by Lake Mirimichi and other lakes and reservoirs upstream. Upstream of the USGS gage is a diversion for municipal supply for Attleboro, MA, as well as small diversions to and from the basin for other municipal supplies.

2.0 OUTCOMES

Project outcomes are anticipated in two phases: Phase I – Proof of concept application of updated Opti-Tool to Taunton River Watershed, and Phase II – Future-state application and Regulatory Guidance. These phases are outlined below.

2.1 Phase I – Proof of concept application of updated Opti-Tool to Taunton River Watershed

2.1.1 Updated hydrologic models for stream FDC development – predeveloped, historic, existing conditions

A model using the Loading Simulation Program in C++ (LSPC), a hydrologic model based on HSPF algorithms, will be developed for the selected three sub-watersheds in the Taunton River Watershed. The FDCs will be developed for the selected sub-watersheds for predevelopment, historic development (if available), and existing development conditions for baseline and future climatic conditions to estimate changes/impacts related to stream channel stability, aquatic life and habitat health, and flooding associated with watershed development and to guide the development of management solutions. The generic relationships will be identified between FDCs and watershed development patterns. Also, an assessment and refinement of approaches will be explored to quantify pollutant load export, carbon sequestration, and heat loss exchange for various development conditions.

2.1.2 Updated Opti-Tool

The Opti-Tool user-interface and VBA source codes will be updated to adopt the functionality of groundwater/aquifer and FDC evaluation factor from the EPA SUSTAIN version 1.2 model. Currently, Opti-Tool is designed to optimize the treatment of overland flow, it does not include groundwater components comparable to those found in the EPA SUSTAIN model. Water that infiltrates to 'active groundwater storage' can move laterally and contribute to baseflow, percolate to the deeper groundwater or leave the groundwater through plant uptake. Adding the functionality of a SUSTAIN aquifer unit into the Opti-Tool is necessary for tracking groundwater recharge and baseflow for the instream linkage to a hydrologic watershed model (e.g., LSPC).

2.1.3 Optimized Stormwater Management Strategies – existing conditions

The updated Opti-Tool will be used to simulate watershed management opportunities to address existing impacts. This modeling sets the stage for Phase 2 which will address mitigating impacts under future development. In Phase I, Opti-Tool will be used to identify optimal strategies to address impacts to critical flow regimes/metrics.

2.1.4 Final Report

A project report will be prepared that documents all work performed during Phase 1 of this project. The final project report will also describe how the work conducted under Phase 1 will be applied to accomplish the objectives of Phase 2 work to develop informed water resource management strategies for future watershed development activities.

2.1.5 Outreach Materials

Outreach materials will be developed to effectively communicate key findings including discussion of relationships between watershed function, land use development, and water resource impacts in low-order stream systems. The modeling results will be presented in a tabular and graphical format to facilitate understanding, education, and outreach. A primary set of graphics will compare FDCs for predevelopment, historical, and existing land use as well as existing land use with optimized SCM implementation.

2.1.6 SNEP Region Webinar

A technical webinar will be conducted to present the Phase 1 study results and key findings to the SNEP Region.

2.2 Phase II – Future-state application and Regulatory Guidance

2.2.1 Stormwater/Hydrologic Management Optimization – future conditions

Phase I will directly inform Phase II of the project. Phase II will evaluate a wide range of potential management measures including GI SCMs, removal of existing IC, and potential future CD practices that can be reasonably simulated in the hydrologic modeling. Future land use management strategies will be identified which protect water resources from future watershed development activities. These strategies will inform the development of next-generation municipal ordinances and bylaws that incorporate next-generation nD/rD practices, or "Conservation Development" (CD) practices, that include among other things, a de-emphasis on use and application of impervious cover (IC), an increasing role of landscape architecture to achieve enhanced evapotranspiration (ET) and better geospatial distribution of nD/rD site runoff, preservation of naturally vegetated areas and incorporation of architecture for increased sustainability and resilience and which preserves the predevelopment hydrological condition.

2.2.2 Model ordinances/bylaws to incorporate next-generation nD/rD practices

Model ordinances and bylaws provide language for municipalities to incorporate and adapt to public regulatory laws. Phase II of this project will include the drafting of model bylaws intended to be disseminated to communities to guide development and protect water resources.

Phase II may include the drafting of companion outreach material associated with the model bylaws, these may include figures, schematics, and text that provide a plain-language explanation of the model bylaws to be used in outreach to town planning and select boards as well as the public.

Phase II may also include recommendations for successful dissemination and adoption of bylaws. Adoption of bylaws that impact development in a community can be encouraged through incentives. An example of such an incentive is that provided to Vermont communities to adopt River Corridor and Flood Hazard (RC/FH) Protections. Municipalities that adopt approved bylaws that meet RC/FH protections are eligible to receive the maximum 17.5% Vermont Emergency Relief and Assistance Fund (ERAF) cost share of non-federal match requirements for FEMA Public Assistance Grants. To receive the maximum match, municipalities have two options; (1) Enroll in the National Flood Insurance Program Community Rating System and adopt a bylaw that prohibits new structures in the Flood Hazard Area, or (2) Adopt River Corridor protection standards that meet Agency of Natural Resources (ANR) criteria (State of Vermont, 2018).

Similar to model ordinances that guide floodplain development and can require hydraulic modeling to demonstrate compliance (Vermont Agency of Natural Resources, 2018), the Phase II model ordinances may define metrics and objectives that can be supported by Opti-Tool results to demonstrate that nD/rD results in No Adverse Impact (NAI) to the FDC.

2.2.3 Technical Support Documents

Technical Support Documents (TSDs) will be developed to disseminate the technical transfer of the project, potential documents include:

- Guidance for next-generation stormwater optimization – builds upon Task 5 Technical Support Document (TSD): Next Generation Stormwater Management (Paradigm Enviornmental et al., 2020. Task 5)
- Opti-Tool guidance for FDC optimization - including a case study example.

2.2.4 SNEP Region Webinar

A technical webinar will be conducted to present the Phase 2 project results and key findings to the SNEP Region.

3.0 TECHNICAL TASKS TO BE COMPLETED

The following are the technical tasks to be completed to deliver the outcomes outlined above for Phase 1 of the project. For a detailed discussion of each task, please refer to the Project Work Plan.

3.1 Compile Available Data/Information for Taunton River Watershed Modeling Analysis (Task 5A of Work Plan)

Collect, review, and assess all readily available data and information including previous hydrologic modeling analyses related to the Taunton River Watershed. Efforts will include, but not be limited to, the following:

- Land Use and Land Cover
- Existing models for the area, such has HSPF and HEC-RAS
- Identifying Candidate Sub-Watershed Drainage Areas
- Identifying Useful Streamflow Gauging Station Data
- Sub-Watershed Prioritization
- Literature Reviews
- Monitoring Data

3.2 Analyze Historical, Current, and Future Climate Data (Task 5B of Work Plan)

Efforts will include, but not be limited to, the following:

- Evaluate approximately 40 years of meteorological data (1980-2019).
  - Perform trend analysis for precipitation and temperature
  - Perform interdecadal comparisons of storm distribution, rainfall intensity, and daily maximum temperatures.
- Develop meteorological boundary conditions based on projected future climate change.

3.3 Perform Baseline Unit-Area Modeling Analysis (Task 5C of Work Plan)

Efforts will include, but not be limited to, the following:

- Establish a baseline and future climate conditions
- Configure the LSPC model for unit-area time-series
  - Reclassify land uses into 9 major land uses used in Opti-Tool
  - Reclassify soil info into hydrological soil groups (HSGs)
  - Reclassify slope into low, medium, and high categories
  - Develop HRU categories to be consistent with the Opti-Tool
  - Estimate effective impervious areas (EIA) using Sutherland's equations (Southerland, 2000).
  - Develop an HRU spatial raster layer showing modeled EIA footprint using the peppering technique in the GIS platform.
- Evaluate changes in unit area annual water/mass balance (runoff, recharge, ET, pollutant export) due to IC conversion.
- Evaluate changes in unit area heat exchange and carbon sequestration due to IC conversion
- Develop fact sheets with figures and tables to highlight results

3.4 Develop Hydrologic/Streamflow and Water Management Modeling Approach for Taunton River Sub-watershed Analyses (Task 5D of Work Plan)

The following steps outlined the approach for the development of the hydrologic watershed model.

1. **Assess Available Data**: Data for source characterization, trends analysis, and defining modeling objectives.
2. **Delineate Project Extent**: Model segmentation and discretization needed to simulate streamflows at temporal and reach scales appropriate for developing flow duration curves at specific sites.
3. **Set Boundary Conditions**: Spatial and temporal model inputs defining the appropriate hydrologic inputs and outputs.
4. **Model Calibration**: Adjustment of model rates and constants to mimic observed physical processes of the natural system.
5. **Model Validation**: Model Testing with data not included in the calibration to assess predictive ability and robustness.
6. **Assess Data Gaps**: Sometimes the nature of modeled responses can indicate the influence of unrepresented physical processes in the modeled system. A well-designed model can be adapted for future applications as new information about the system becomes available. Depending on the study objectives, data gaps sometimes provide a sound basis for further data collection efforts to refine the model, which cycles back to Step 1.

3.5 Adapt Models for Flow Duration Curve Analyses for Pilot Sub-watersheds (Task 6A of Work Plan)

Efforts will include, but not be limited to, the following:

- Conduct a GIS-based Watershed Characterization
- Conduct Model Refinement
    - Review existing HSPF models for the study area.
        - Map HSPF land segments to Opti-Tool HRU classification.
        - Review land/stream parameters
        - Review point source representation in the model
        - Identify data gaps
    - Develop LSPC models for the selected sub-watersheds
        - Configure the delineated sub-watersheds with land (HRUs) and stream segments
        - Assign existing HSPF land/stream parameters to the LSPC model
        - Assign Opti-Tool's SWMM-HRU water quality parameters to the LSPC model
        - Assign weather boundary condition
- Calibrate hydrology to proposed observed gage (e.g., USGS 01109000 flow gage)
- Develop FDCs
    - Predevelopment, historical (if possible), and existing land use
    - Baseline and Future climate condition
- Present Results

Perform modeling and assess performance based on both statistical and visual approaches. Based on literature sources, performance targets for simulation of the water balance components are summarized in Table 3. The coefficient of determination (r-Squared) describes the degree of collinearity between simulated and measured data. The correlation coefficient is an index that is used to investigate the degree of a linear relationship between observed and simulated data. r-Squared describes the proportion of the variance in observed data that is explained by a model. Values for r-Squared range from 0 to 1, with 1 indicating a perfect fit. The percent bias (PBIAS) quantifies systematic overprediction or underprediction of observations. A bias towards underestimation is reflected in positive values of PBIAS while a bias towards overestimation is reflected in negative values. Low magnitude values of PBIAS indicate a better fit, with a value of 0 being optimal. The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. Values for NSE can range between $-\infty$ and 1, with NSE = 1 indicating a perfect fit.

Table 3. Summary of performance metrics used to evaluate hydrology calibration

Performance Metric	Hydrologic Condition	Comparison Type	Performance Thresholds for Hydrology Simulation				Reference
			Very Good	Good	Satisfactory	Unsatisfactory	
R-squared (R^2)	All Flows	Compare All Observed vs Simulated Daily Flow Rates that Occur During Selected Season-Condition	> 0.85	0.75 - 0.85	0.60 - 0.75	≤ 0.60	Based on Moriasi et al. (2015)
	Seasonal Flows		> 0.75	0.60 - 0.75	0.60 - 0.50	≤ 0.50	
	Highest 10% of Flows						
	Lowest 50% of Flows						
	Storm Flows						
	Baseflows						
Nash-Sutcliffe Efficiency (E)	All Flows		> 0.80	0.70 - 0.80	0.50 - 0.70	≤ 0.50	
	Seasonal Flows		> 0.70	0.50 - 0.70	0.40 - 0.50	≤ 0.40	
	Highest 10% of Flows						
	Lowest 50% of Flows						
	Storm Flows						
	Baseflows						
Percent bias (PBIAS, %)	All Flows		+/- 5	5 - 10	10 - 15	> 15	
	Seasonal Flows		> 10	10 - 15	15 - 25	> 25	
	Highest 10% of Flows						
	Lowest 50% of Flows						
	Storm Flows						
	Baseflows						

Comparison of modeled vs. observed time series can be generated on daily or monthly timesteps, summarized seasonally as box plots, statistical metrics such as the 7Q10, and flow duration curve comparison presented in Figure 6 as an example.

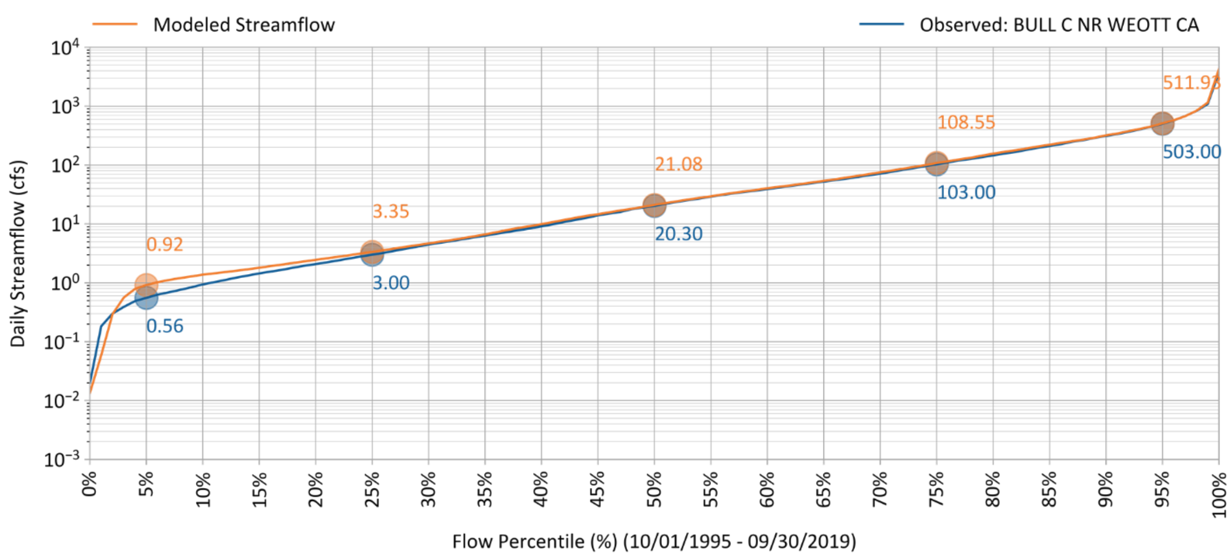

Figure 6. Example calibration modeled vs. observed flow duration curve comparison.

3.6 Adapt EPA R1 Opti–Tool for Stormwater and FDC Management Analyses (Task 6B of Work Plan)

Efforts will include, but not be limited to, the following:

- Review the functionality of GI SCM groundwater recharge linkage to local surface waters in SUSTAIN version 1.2 developed for EPA Region 10.
- Review the GI SCM interfaces and VBA source codes for the current version of Opti-Tool developed for EPA Region 1.

- Design user interfaces to incorporate the EPA SUSTAIN's Aquifer module into the Opti-Tool spreadsheet.
- Develop VBA source codes to integrate the groundwater/aquifer component for tracking baseflow and infiltrated water from GI SCM controls in Opti-Tool.

3.7 Phase 1 Stormwater/Hydrologic Management Optimization Analyses (Task 7 of Work Plan)

Efforts will include, but not be limited to, the following:

- Perform SCM screening in the selected three sub-watersheds.
- Configure the updated Opti-Tool with HRU boundary conditions for the three sub-watersheds
- Identify optimal combinations of SCM types and sizes based on the FDC objective.
- Link Opti-Tool results to LSPC to incorporate stream routing and compare FDCs before and after SCM implementation.

4.0 TECHNICAL STEERING COMMITTEE'S FEEDBACK

A virtual meeting with the Technical Steering Committee members was held on Dec 18, 2020, and the project approach was discussed with the participants. The focus of the meeting was on developing in-stream (1st order and/or 2nd order) FDCs and identifying potential FDC metrics to compare the pre-development and post-development conditions and minimizing the gap between those two curves through optimizing the strategic locations and sizes of the structural GI SCM controls on the landscape to capture and treat surface runoff. Participants supplied feedback and questions verbally and through the online chat. Several participants also sent emails with questions, comments, and suggested scientific papers and reports that are relevant to the project.

The following are key discussion points from the meeting:

- The distinction between Total Imperviousness and Directly Connected Imperviousness
- Evaluation metrics, such as the Richard-Baker Flashiness Index, and identifying ones that can be easily conveyed to the public
- Goodness-of-fit for model calibration
- Water travel time
- FDC's low and high flow extreme ends
- BMP site suitability and screening
- Stream restoration and channel evolution processes
- Comparison between business as usual and next-generation SCM guidance
- Additional specific literature references

The participants' comments and questions on these topics are presented and addressed in the Section 6.0 Appendix.

5.0 REFERENCES

Archfield, S.A., Vogel, R.M., Steeves, P.A., Brandt, S.L., Weiskel, P.K., Garabedian, S.P., 2010. The Massachusetts Sustainable-Yield Estimator: A Decision-support Tool to Assess Water Availability at Ungaged Stream Locations in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2009–5227, 41p.

Barbaro, J.R., Sorenson, J.R., 2013. Nutrient and sediment concentrations, yields, and loads in impaired streams and rivers in the Taunton River Basin, Massachusetts, 1997–2008: U.S. Geological Survey Scientific Investigations Report 2012–5277.

Donigian, A. Jr., J. Imhoff, B. Bicknell, and J. Kittle. 1984. Application Guide for Hydrological Simulation Program - Fortran (HSPF). Prepared for U.S. EPA, EPA-600/3-84-065, Environmental Research Laboratory, Athens, GA.

Donigian, A. Jr. 2000. HSPF Training Workshop Handbook. Lecture #15. Watershed Model Calibration and Verification: Issues and Procedures. Prepared for U.S. Environmental Protection Agency, Office of Water, Office of Science and Technology, Washington, DC.

Fan, C., Li, J., 2004. A Modelling Analysis of Urban Stormwater Flow Regimes and their Implication for Stream Erosion. Water Qual. Res. J. 39, 356–361. https://doi.org/10.2166/wqrj.2004.048

Gao, Y., Vogel, R.M., Kroll, C.N., Poff, N.L., Olden, J.D., 2009. Development of representative indicators of hydrologic alteration. J. Hydrol. 374, 136–147.

Homa, E., Casey Brown, Kevin McGarigal, Bradley W. Compton, Scott D. Jackson. 2013. Estimating hydrologic alteration from basin characteristics in Massachusetts. Journal of Hydrology. 503, 196–208.

Lumb, A., R. McCammon, J. Kittle Jr. 1994. User's Manual for an Expert System (HSPEXP) for Calibration of the Hydrological Simulation Program–FORTRAN. Water-Resources Investigations Report 94-4168. U.S. Geological Survey, Reston, VA.

Mass Audobon, TWRA, 2017. No TitleStream Continuity Assessment in the Taunton Watershed.

Moore, T.L.C., Hunt, W.F., 2013. Predicting the carbon footprint of urban stormwater infrastructure. Ecol. Eng. 58, 44–51. https://doi.org/10.1016/j.ecoleng.2013.06.021

Moriasi, D.N., Gitau, M.W., Pai, N., Daggupati, P., 2015. Hydrologic and water quality models: Performance measures and evaluation criteria. Trans. ASABE 58, 1763–1785. https://doi.org/10.13031/trans.58.10715

Naito, K., Parker, G., 2019. Can Bankfull Discharge and Bankfull Channel Characteristics of an Alluvial Meandering River be Cospecified From a Flow Duration Curve? J. Geophys. Res. Earth Surf. 124, 2381–2401. https://doi.org/10.1029/2018JF004971

Northwest Hydraulic Consultants, 2017. Little Bear Creek Basin Plan, A Final Watershed-Scale Stormwater Plan Prepared in Fulfillment of Special Condition S5.C.5.c.vi of the Phase I Municipal Stormwater Permit. Prepared for Snohomish County.

Paradigm Environmental, Great Lakes Environmental Center, 2020. Task 0 Work Plan. Holistic Watershed Management For Existing And Future Land Use Development Activities: Opportunities For Action For Local Decision Makers: Phase 1 – Modeling And Development Of Flow Duration Curves (FDC 1 Project) Prepared for U.S. EPA Region 1.

Paradigm Environmental, University of New Hampshire Stormwater Center, Great Lakes Environmental Center, 2020. Task 5 Technical Support Document (TSD): Next Generation Stormwater Management. Prepared for U.S. EPA Region 1.

Price, K., 2011. Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review. Prog. Phys. Geogr. 35, 465–492.

Reichold, L., Zechman, E.M., Brill, E.D., Holmes, H., 2010. Simulation-Optimization Framework to Support Sustainable Watershed Development by Mimicking the Predevelopment Flow Regime. J. Water Resour. Plan. Manag. 136, 366–375. https://doi.org/10.1061/(asce)wr.1943-5452.0000040

Searcy, J., 1959. Flow-Duration Curves. Manual of Hydrology: Part 2. Low-Flow Techniques. Washington, DC.

State of Vermont, 2018. Emergency Relief & Assistance Fund Eligibility Criteria – 17.5% State Share.

Sutherland, R, 2000. Methods for Estimating the Effective Impervious Area of Urban Watersheds. In: The

Practice of Watershed Protection (Edited by T. R. Schueler and H. K. Holland). Technical Note #58. Center for Watershed Protection, Ellicott City, MD: 193-195.

The Nature Conservancy, 2007. IHA Software Download [WWW Document]. URL https://www.conservationgateway.org/ConservationPractices/Freshwater/EnvironmentalFlows/MethodsandTools/IndicatorsofHydrologicAlteration/Pages/IHA-Software-Download.aspx

Van Buren, M.A., Watt, W.E., Marsalek, J., Anderson, B.C., 2000. Thermal enhancement of stormwater runoff by paved surfaces. Water Res. 34, 1359–1371. https://doi.org/10.1016/S0043-1354(99)00244-4

Vermont Agency of Natural Resources, 2018. Vermont Model Flood Hazard Bylaws. Montpelier, VT.

Vogel, R.M., Sieber, J., Archfield, S.A., Smith, M.P., Apse, C.D., Huber-Lee, A., 2007. Relations among storage, yield, and instream flow. Water Resour. Res. 43, 1–12. https://doi.org/10.1029/2006WR005226

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., Ii, R.P.M., Ii, R.A.P.M.O., 2015. The urban stream syndrome : current knowledge and the search for a cure The urban stream syndrome : current knowledge and 24, 706–723. https://doi.org/10.1899/04-028.1

Wandle, S.W.J., Keezer, G.R., 1984. Gazetteer of Hydrologic Characteristics of Streams in Masachusetts - Taunton and Ten Mile River Basins and Coastal River Basins of Mount Hope Bay, Narragansett Bay, and Rhode Island Sound: U.S. Geological Survey Water-Resources Investigations Report 84-42.

Zarriello, P.J., Barbaro, J.R., 2014. Hydraulic Assessment of Existing and Alternative Stream Crossings Providing Fish and Wildlife Passage at Seven Sites in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2014–5146.

6.0 APPENDIX. RESPONSE TO TSC COMMENTS

This section responds to the comments received on the project technical scope at the technical steering committee meeting 1 held virtually on Dec 18, 2020. The responses are shown in red font color.

6.1 TSC Meeting Comments

1. David Boutt: I would like to see water travel time distributions, residence times, and other travel time characteristics (for groundwater inflows and surface waters) included in these metrics.

   We have previously estimated overland travel time for model sub-watersheds ranging in size between 1 and 4 km^2. A 15-min timestep works well when sub-watersheds are about 1 km^2, but an hourly timestep can work for sub-watersheds between 3-4 km^2. Slower moving interflow and groundwater outflow recession rates are derived during model calibration, with the average peak of baseflows sometimes occurring several days or weeks after the peak of precipitation or surface runoff. When snowfall/snowmelt is simulated the lag time between peak precipitation, runoff, and baseflow is longer. Travel time metrics can be calculated on modeled hydrograph time-series as a post-process.

   As Jeff Barbaro noted, HSPF handles groundwater very empirically. The model calibration can give us a good match at the streamflow calibration site, but the Hydrologic Response Unit (HRU) distribution is the mechanism available for varying baseflow in the drainage area. Coupling with MODFLOW adds flexibility for baseflow simulation but also increases the level of effort and data requirements for model configuration. The project includes updating Opti-Tool with aquifer functionality like that of HSPF/LSPC/SUSTAIN, however, a sophisticated groundwater model linkage is not envisioned.

2. Margherita Pryor: Having more public-friendly indicators from the hydrology information would be great. Bankfull flow seems like it could be one. Are there any habitat or other ecological aspects we could adopt?

   Agree, have included bankfull flow as a metric, also considering metrics indicating sediment mobilization/erosion. Grouping a set of metrics as ‘channel destabilizing flows’ or something similar. We can also quantify the relative change in scouring flow periods. Additionally, we will include pollutant export parameters. The IHA parameters are also associated with ecological impacts. We may want to consider visuals that relay these.

3. Kimberly Groff: I was thinking the same thing as Margherita, we should think about how the metrics will translate to visuals that are easily understood by the public.

   Agree. Noted.

4. Ray Cody: Agreed. The real challenge I think is going to be translating this work into meaningful and readily communicated results. The good news is we have some time to think about this as this first phase of modeling work is being conducted. Your ideas in this regard will be much appreciated!

   Agree.

5. James Houle: But that is different than what you are proposing. If results that will address the drastic contrast between these restoration efforts, you are going to model with the business as usual approach Mark outlined is such a significant threat to the future then that needs consideration in this phase.

One of the main objectives is to illustrate the impact of impervious cover (IC) on watershed health, then look at land-based interventions to improve conditions to better mimic natural conditions from the perspective of the stream. Moving from predevelopment conditions to existing to restoration should demonstrate both impacts and solutions.

It is anticipated to keep the priority evaluation metrics to just a few that are easily understandable (e.g., high pollutant export flows, scouring flows, and bank full flows) and then evaluating how secondary metrics are improved. The optimization target can be set to minimizing the difference between predevelopment and post for the flow rates that carry the bulk of the load and cause channel destabilization.

Also, it could be a powerful comparison to show the effects of implementation based on 'next-generation' SCM guidance versus the business-as-usual approach.

There can be two ways to do this: one is to use the observed, current-condition FDCs as an indication about how 'business as usual' is impacting the streams. Homa *et al.* (2013), studied FDCs in Massachusetts. Their results suggest that business as usual has tended to decrease the variability in daily streamflows.

The second may be to model 'business as usual' versus next-generation approaches. This might be more appropriate in Phase II where we can simulate future land use change with more impervious surfaces and the business-as-usual way of dealing with treating their runoff, based on existing stormwater management regulations, versus next-generation approaches.

6. Naomi Detenbeck: There is already a calibrated HSPF model for the Taunton watershed. Why are you redoing this?

   This effort builds upon the existing HSPF modeling efforts in the Taunton watershed. USGS (including Jeff Barbaro and Kim Groff) has also published a model for the basin based on impairments and water quality. For the calibration effort, we may want to consider adding water use stresses for the Wading River that USGS did not consider in the previous modeling efforts. However, for FDC analysis the focus of this study is on small subwatersheds (1st order and/or 2nd order streams) that minimize the impact of hydromodifications in the stream channel.

7. Laura Schifman, MassDEP: What is the assumption on soil conditions for scenarios for the reduction in the impervious cover? Post-development soils are often very different from the predevelopment ones (texture, C content, K, etc.) and change how/how much runoff is generated. Across a watershed with a 10% reduction in IC that may make a big difference in the FDC.

   Agreed. HRU development provides an opportunity to characterize the combined impact of physical characteristics like the land cover, soil type/composition, and slope. Certain land management activities can be represented as a change in HRU distribution. In the absence of soil information for the developed areas, a relatively less permeable soil type C will be assumed to represent the post-development condition.

8. Blaine Hastings: I would argue that if the goal is restoration, the driving factors should be the correlation between the metrics and in-stream conditions reflective of healthy function, e.g., biology, sedimentation, WQ, erosion, etc. Data showing the connection between targets and outcomes is invaluable

   The restoration goal of this study is to quantify the impacts of impervious cover change on the instream hydrograph and estimate the costs and benefits of restoring the instream hydrograph through impervious cover disconnection using green infrastructure and stormwater control measures. Indicators of Hydrologic Alteration (IHA) and other secondary benefits will be assessed as a post-process to estimate or infer changes in the resulting hydrological and stream conditions. Water quality benefits will also be included in the results, the default buildup and washoff functions associated with the Opti-Tool package will be used to simulate water quality (sediment and nutrients).

9. Jeff Barbaro, USGS: Will you be making a distinction between total imperviousness and directly connected (or effective) imperviousness?

   Yes. The watershed model simulates individual land units in parallel—there is no land-to-land flow simulated. However, the Sutherland (2000) equations provide an empirical way of adjusting the mapped impervious area to a directly connected impervious area (DCIA). Certain land management activities can be represented as a change in HRU distribution (e.g., depaving or additional disconnected imperviousness). DCIA may be adjusted during calibration if the comparison between observed and predicted flows indicates the watershed has a different amount of effective impervious surfaces. Such a change would be made after exhausting other reasonable calibration parameter adjustments and identification of other flow sources.

10. Scott Jackson: How will you account for changes in hydrology due to climate change? Ecosurpluses and ecodeficits will change due to climate change even without changes in land use. How will the effects of climate change be separated from changes in land use/use of BMPs?

    In phase I, we will evaluate the impact of a future climate scenario by changing the precipitation but keeping the land use the same. In phase II, when the impacts of future land use change are evaluated, we will use the same meteorological forcing for different land use scenarios.

11. James Houle: The modeling process will provide learning opportunities [only] if the assumptions are open and transparent. For instance, we could discuss DCIA and how to treat it for 4 hours and still not satisfy everyone!

    Agree.

12. Blaine Hastings: Richard-Baker Flashiness index is another metric that is often used in this sphere. One reason is that it is helpful over short periods as it is normalized by total flow during the period and so has some degree of control for interannual climate variability.

    Thank you, the index seems like a good metric that is relatively easy to relay to the public. We will investigate this further.

13. Scott Jackson: Will your model be able to evaluate non-stormwater BMPs, such as restoring channel sinuosity, reconnecting streams with their floodplains, wetland creation/restoration, and adding wood to headwater stream channels?

    While we recognize the value, importance, and effectiveness, in-stream, and riparian restoration measures are beyond the project scope and will not be addressed. The model does not change the geometry of the channel and the Opti-Tool optimization will be constrained to land-based BMPs intended to capture and treat overland flow.

14. Blaine Hastings: Well said, John. I would heavily weight smaller watersheds for that very reason of driving on the ground decision making for BMPs. The majority of benefits will be for sub-daily flow characteristics and at the highly local scale. Weight, as in the selection of observed streamflow data to build the model(s).

Agree, we are focusing on small watersheds (i.e., 1st order and/or 2nd order streams).

15. Allison Roy: Yes, while the smaller scale makes sense given the scale of the restorations themselves, the biotic and habitat metrics that people are most interested in connecting to are measured at larger scales… a perpetual challenge!

    Agree.

16. James Houle: How do you calibrate decreases in IC from improved analytical GIS methods with the reductions that the Sutherland equation imparts?

    We have generally relied on applying the Sutherland equations to the mapped total impervious area as they provide a concise, consistent, and widely used approach. In our experience, we have found that higher-resolution land cover, impervious cover (LiDAR-derived as available), soil data, and slope data add more granularity to the derived HRU and IC estimates, improving the robustness of the Sutherland equation estimates. We are open to GIS approaches; do you have a recommended one? It may be worth some time spent reviewing literature that compares techniques.

6.2 Email Comments from Individuals

6.2.1 Mike Kline

1. Is there an effect of historic land clearing and agricultural drainage systems in the flow records? Have stream flows changed due to reforestation. Are FDCs in target and reference streams influenced by historic alterations? Picking a land use condition at a specific point in time (i.e., that looks better than a probable future condition) and calling it the "reference" has been problematic in the creation of environmental and flood mitigation standards.

   Excellent point. We will be constrained by the historical flow records which are certainly impacted by the land use at the time of observation. However, the calibration will include a range of Hydrological Response Units, including those that are completely forested. The initial HRU parameters will be based on the existing HSPF model and supplemented with the literature and model guidance and adjusted as necessary during calibration. While we will be calibrating to a larger watershed that represents a mix of land uses, we will be able to look at model predictions in headwater, forested streams.

2. Will the study consider the geomorphic condition and channel evolution processes underway in the stormwater impacted and reference streams, the suite of stressors that caused these conditions, and the wholistic set of practices necessary to achieve the physical, chemical, and biological integrity of the stream? I think I heard that channel geometry will be held constant in the modeling. Since this does not happen in real life, will the study explain how stormwater management toward a reference FDC will be impacted, positively or negatively, by channel evolution and consequences of the many channel management activities that typically occur in the urban setting?

   The restoration goal of this study is to quantify the impacts of impervious cover change on the instream hydrograph and pollutant export and estimate the costs and benefits of restoring the instream hydrograph through impervious cover disconnection using green infrastructure and stormwater control measures. IHA and other secondary benefits will be assessed as a post-process to estimate or infer changes in the resulting hydrological and stream conditions.

3. In developing optimal sets of site-specific stormwater treatment practices, will the modeling exercises include the siting of those practices, and, if so, is there or will there be a protected corridor established along the streams to accommodate the stream erosion and depositional processes and channel evolution. (We cannot continue to make the cure worse than the disease.)

   Yes, there will be a GIS analysis to identify suitable areas for BMPs. We apply criteria to remove areas from consideration, proximity to streams and floodplains will be included.

4. In achieving the stated goal of creating a more wholistic and integrated approach to watershed management, I hope there will be a concerted effort to recognize the role of natural storage and infiltration, i.e., naturally functioning riparian wetlands and floodplains. Developers and stormwater managers need financial and regulatory incentives to restore and protect natural storage as a key mechanism for reducing eco-surpluses and eco-deficits. Can we figure out a way to give credit to those systems that not only treat their regulated "discharges" but restore and protect lands that provide storage and infiltration benefits over the range of high flow events?

   For existing wetlands, we could define those as a separate HRU category with increased storage but the limitation is that HRUs are all parallel to the stream, so no other HRU would flow into the wetland. For large wetlands, we could delineate drainage areas and model them as part of the baseline condition.

   While the focus of this effort is on LID benefits, representing additional management strategies depend on how such management activities are configured. It is possible to simulate regional facilities that provide benefits for a larger drainage area.

5. I am encouraged that parameters like critical shear stress will also be modeled. In Vermont, we are currently looking at the specific stream power signatures (site-scale, in-channel [Specific Stream Power (SSP)] values over the range of flood returns (2yr to 500yr)) and at what flood frequency stage do we see an exceedance of the entrainment thresholds for the course sediments that maintain vertical channel stability and critical cover habitats (and why). If the SENE region is like the NWNE region, many small streams are incised and lack floodplain access. Since a goal [of] stormwater management is channel protection, the FDC study might successfully show how cost-effective it is to achieve equilibrium conditions if the evolution of the entire channel-floodplain geometry (with both passive and active interventions) is factored into the stability of channel boundaries over the range of flood flows. I think this will be critical, both economically and ecologically, as we look forward to the full impacts of climate change.

   Agree. Noted.

6.2.2 Tom Ballestero

I had to leave the meeting a little early. The following are my comments.

1. Little information was presented on modeling components. Are they physically based or simple transform functions? This hits at the heart of the calibration parameters: is calibration a common physical variable (like hydraulic conductivity), or a simple abstract parameter? How is ET modeled? In contrast to something that Mark said, I believe that evaporation in highly urbanized environments is very large in the summer months. For example, look how fast things dry-out after a thunderstorm. This underscores the urban heat island effect.

   Meteorological boundary conditions include precipitation, temperature, wind speed, dewpoint, and solar radiation. Evaporation is computed as a function of temperature, wind speed, dewpoint, and solar radiation. A "cover" coefficient is then used to calculate potential evapotranspiration (PEVT) from pan evaporation which is then scaled with vegetation type/density. Impervious areas will have PEVT values that are closer to pan evaporation. The runoff boundary conditions from the watershed model will implicitly reflect those nuances. Depending on the BMP type, additional PEVT may occur in Opti-Tool for ponded/stored water.

2. The FDC is a probability distribution. While using IHA metrics are standard and widely used, I wonder if employing fitted distributions and their parameters might be more quantitative, although not necessarily easily translatable in public meetings. Interestingly, [Green Stormwater Infrastructure (GSI)] is to be implemented to address the FDC. Our experiments demonstrate that on large watersheds, GSI has little impact on flooding at the watershed scale, and this is because GSI is typically designed for storms of 1-inch or less. Higher flows are designed to quickly bypass GSI. So is there another management option for this end of the FDC?

   Agree that the project is conducive to investigating the ability of different distributions to describe the observed and simulated data, and also that the results are probably not as easily translatable to the public. EPA and its consultants are willing to share data and collaborate on additional analyses that use the project data, but an extensive statistical analysis is likely to be outside the scope of the project. While the focus of this effort in phase 1 is green infrastructure stormwater control measures to mitigate hydrologic impacts to small order streams and reduce pollutant load export associated with IC and possible channel destabilization, it may be possible to evaluate other management opportunities for addressing the higher flow portion of the FDC. Representing the benefits of additional management depends on how management activities are configured. It is possible to simulate regional facilities that provide benefits for a larger drainage area. While this study will focus on a smaller scale, LID-type control measures, future work can incorporate larger, regional facilities as part of the analyses. It may be that we can better address this issue when we evaluate future climate change and in Phase 2 for future build-out by proposing important potential conservation areas that provide watershed flood attenuation benefits.

3. Along the lines of more stochastic analysis of results, maybe looking at stochastic descriptors. Since the modeled scenarios fundamentally result in a long-term hydrograph, I think that time series analyses might be appropriate. For example, crossing levels, correlation, etc.

   Time series analysis can certainly elucidate important characteristics of the hydrologic data (e.g. trend, persistence, homogeneity, stationarity), and it may especially be useful to analyze the observed historical flow data to identify trends and shifts in the time series that may impact calibration.

   We may make use of limited time series analysis, such as detecting trends in IHA parameters over time, and how BMP implementation may impact those trends but are cognizant of the ease at which such analyses can become studies unto themselves. However, we do recognize that the long-term, continuous time series that this project will produce can be a valuable source of information for various research questions. EPA and its consultants are willing to share data and collaborate on additional analyses that use the project data, but extensive statistical analysis of time-series characteristics may be outside the scope of the project.

4. At the high flow end of the FDC, things like bankfull flow, stream power, and critical shear stress were mentioned, however, the real issue is the total annual volumes of sediment transport. With this in mind, you might consider taking a few of the riffle cross-sections, creating sediment rating curves from bar samples nearby and riffle hydraulics, then for each hydrograph scenario, computing total sediment flux (may need to assume that the system is not sediment limited).

The model will produce estimates of land-side sediment flux using Opti-Tool buildup washoff functions calibrated for New England. The LSPC model can simulate sediment scour and deposition processes in the channel. Rating curve data would be valuable information to help further calibrate the sediment processes; however, collecting such data is beyond the current scope. Therefore, the project intends to rely on the previously calibrated parameters; no additional water quality calibration is planned as part of this project.

5. The low flow end of the FDC is dominated by groundwater baseflow. All the more important that the hydrologic model be capable of adequately describing the entire water cycle. There are so many calibration parameters that there is a real problem of non-unique answers in the final calibrated model. The dilemma is that parameters are calibrated to adequately predict the majority of observed data, and then we use the model to focus on extremes, and this is where the model performs the poorest.

   Calibration involves graphical and quantitative numerical statistics, evaluated across the full range of hydrological conditions. Numerical performance metrics from various literature sources will be used to evaluate the model performance (Donigian et al. 1984, Lumb et al. 1994, Donigian 2000, and Moriasi et al. 2015), with the goodness of fit of existing condition modeled vs. observed FDC as a priority consideration. In practice, model sensitivity analyses can be used to test and quantify the implications of model assumptions at the FDC extremes and model uncertainty. Findings will be used to qualify conclusions and recommendations.

6. It is not really clear how a GSI system is incorporated and modeled. We know that SWMM does a poor job on infiltration and cannot generate time series information for a LID component. What is the calibration data for GSI systems and system hydraulic and water quality performance?

   The Opti-Tool user's guide contains information on GI SCM/BMP configuration. The default design specifications for Opti-Tool GI SCMs are based on BMP monitoring data collected by UNHSC. The GI SCMs parameters will not be further calibrated. Model calibration will focus on watershed characteristics and use observed streamflow data. Like SWMM, the GI SCMs in Opti-Tool only simulate vertical infiltration, while lateral infiltration can also be an important factor for how a real-world GI SCM performs. It is possible to provide results over a low-medium-high range of simulated vertical infiltration rates to attempt to quantify uncertainty. Other thoughts or recommendations are welcomed.

7. Although calibration was mentioned, it was not really exposed. What are the measures used for goodness-of-fit and why?

   As is generally done for HSPF/LSPC modeling efforts, numerical performance metrics from various literature sources will be used to evaluate the model performance (Donigian et al. 1984, Lumb et al. 1994, Donigian 2000, and Moriasi et al. 2015), with the goodness of fit of existing condition modeled vs. observed FDC as a priority consideration.

8. There needs to be a demonstrated sensitivity analysis on the cost model for the reality of real constraints on meeting the optimal state. This is simply because when a model says to put a bioretention system somewhere, it does not mean that it is a realistic outcome due to property ownership or other reasons.

   The model is a tool and relies on the user inputs based on the best information available at the time of its development. The suitability and feasibility of different GI SCM opportunities are part of the screening process. Under this project, a GIS screening will be performed to identify the suitable locations and types of GI SCM opportunities at the watershed scale. There will be no ground investigation performed under this study.

6.2.3 James Houle

I would also echo Dr. Ballestero's comment on real constraints. In the Tisbury project, we provided real examples of what could be done and showed concept designs in areas that were identified by the end-users needing attention. Is there a similar ground truthing of this approach with end-users?

- Theoretically, this is a great project. It underscores a lot of what we are seeing in our continued monitoring of urban watersheds and urban restoration benefits; at a watershed scale, the hydrology or more specifically altered urban hydrology dominates watershed health and resilience.

- The contrast is that our regulatory approach, largely how we mitigate for increases in impervious cover, is half a century behind. It was mention[ed] that looking forward over the next 50 years[,] IC is the largest threat. Yet every cut, every development, exacerbates the problem in a less than wholistic way.

1. So how are these products going to specifically inform new development and redevelopment regulations?

   This project is attempting to open the doon on providing planning level information for better understanding what level of control is needed for new development and what levels of restoration could be achieved through optimizing retrofit management strategies that could be realized through redevelopment standards. The Little Bear Creek Basin Plan in Snohomish County, WA provides a useful precedent for the proposed analytical approach. The plan showed that future build-out under the current code would result in temperature, bacteria, and aquatic health impairments; however, when implemented with a strategic plan focused on site-scale and regional stormwater management, development impacts were offset. The study used a coupled HSPF-SUSTAIN model to evaluate the costs and benefits of impervious cover management focused on hydrograph restoration. The plan included stormwater management practices that targeted both extremes of the hydrograph, and the modeling analysis highlighted priority locations and stormwater management strategies that provided the highest chance of success.

2. How will FDC change the current approach?

   At this point, we envision that the FDC will be used as an information tool to illustrate multiple impacts associated with IC and multiple potential benefits associated with watershed-wide management solutions. FDC will provide insight into the full spectrum of flow regimes. Stormwater runoff is the main driver for urban hydrology alteration and water quality degradation. It is anticipated that comparing the long-term flow duration curves for pre-development and post-development conditions will help to identify the trends and patterns in the flow regimes caused by the impervious cover change in the watershed. One of the objectives of this study is to develop relationships between FDC and IC change that can demonstrate the watershed health impacted by the increased development in simple terms that can be applied to other watersheds. It will also guide in developing the next generation municipal ordinances and bylaws. The illustrative power of the FDC for assessing multiple impacts and benefits can be used to inform the selection of levels of controls needed for new and redevelopment for existing and future growth scenarios.

3. At some point, this information and its underlying approach contrast with event-based sizing and event-based hydrology matching currently being engineered and implemented. They cannot both exist. Or, more to the point, engineers cannot design to meet both. One approach focuses on large

volume retention and outlet controls, the other focuses on small systems, land conservation, and wetland restoration efforts. The same could be said of historical TMDL approaches that focus not on the restoration of the flow regime, but reductions in pollutant load. These processes are likely fundamentally linked in the natural environment but are not well linked in our models that often govern restoration activities.

This project is focused on tools to better demonstrate how land use based decisions involving development and stormwater management impact water resource health and to identify potential management strategies for both retrofitting existing development to improve conditions and for conducting new development to protect water resources. This study will result in proposed management approaches focused on impervious cover disconnection using small-scale green infrastructure stormwater control measures; however, it is recognized that a wholistic approach involves actions at both small and large spatial scales. Although certain instream strategies such as streambank stabilization, wetland restoration, and channel reconnection will ultimately be important components of an overall stormwater management strategy, they will not be modeled as part of this study. However, this study will help to better define hydrograph restoration targets. It is anticipated that as part of an overall adaptive management strategy, opportunities for instream strategies would be identified and engineered to supplement instream restoration goals, providing management equivalence to offset some of the structural management actions identified through this effort.

4. UNH has proven this approach works through our published efforts in the Berry Brook watershed, not simply in models but empirically through hydrological and water chemistry modeling including latent temperature impacts.

   Noted.

5. So, the objectives here seem to need some rethinking. If you are out to prove that with sophisticated modeling you can link more innovative urban restoration efforts that focus on restoring altered hydrology you will certainly be able to show that. The novelty here, or more strategic objective, is to develop tools to change and augment traditional management regulations and guidelines. I understand this is a component of phase II, however, phase I has the potential to steal the thunder of your funded effort and I fear that the phase II outputs will not be given the broadband they deserve. This was illustrated by one of the presenters from Paradigm during the meeting when asked about selecting the area or unit of the HRU. He mentioned that the scale of the unit area selected should be commensurate with your modeling objectives. This is not an exact science. Understanding what is needed to shift the current approach should be part know the upfront as it may be important to shape some of the modeling assumptions.

   Yes, the ultimate goal is to develop the tools and guidance that can shape future development in a way to have a minimum impact on watershed health and augment traditional management regulations and guidelines. Phase 1 of the project is to lay out the foundation and perform proof-of-concept modeling to investigate the relationship between the impervious cover change and its impact on the instream hydrograph. This project is not a specific watershed case study but rather focused on developing generic relationships and tools that can be applied to other watersheds. It is anticipated that the outcome of Phase 1 will provide a clear pathway to developing such tools under phase 2 of the project.

6.3 Suggested Literature for Review

Margherita Pryor provided two references for review and consideration:

- It Is Not Easy Being Green: Recognizing Unintended Consequences of Green Stormwater Infrastructure.
- Indicators-HydrologicAlternation this was part of TNC's nature-based solutions presentation

Scott Jackson provided another reference: Estimating hydrologic alteration from basin characteristics in Massachusetts.

Dave Boutt provided a paper: Debates—The future of hydrological sciences: A (common) path forward? A call to action aimed at understanding velocities, celerities, and residence time distributions of the headwater hydrograph.

These references were reviewed and summarized below.

6.3.1 It Is Not Easy Being Green: Recognizing Unintended Consequences of Green Stormwater Infrastructure (2020)

Vinicius J. Taguchi, Peter T. Weiss, John S. Gulliver, Mira R. Klein, Raymond M. Hozalski, Lawrence A. Baker, Jacques C. Finlay, Bonnie L. Keeler, and John L. Nieber

Summary

Taguchi et al (2020) discuss how green stormwater infrastructure (GSI) practices are intended to function and how they could malfunction, and discusses improvements to their design, construction, monitoring, and maintenance to ensure GSI projects are effective and cost-efficient. One example the authors discuss is the complex socio-economic consequences that may occur because of tree-planting. Planting trees can increase property values, which becomes a challenge for lower-income residents in rental housing without rent-stabilization programs. Affordable housing programs may need to be established before tree plantings to help mitigate gentrification. Residents may also be resistant to tree-planting efforts because of past experiences dealing with poorly maintained or neglected urban forests. Resident surveys conducted in Detroit found that low-income neighborhoods had negative perceptions of tree-planting campaigns, in part because communities had to shoulder the maintenance costs of Detroit's past tree-planting efforts when budget cuts reduced the maintenance budget of the program.

Additionally, the authors discuss how performance expectations and modeling assumptions can lead to the perception of a failed implementation. A model may assume a 50% phosphorus reduction for stormwater ponds, which is applied to all scenarios and left unchanged throughout the life of the GSI practice. However, a more robust analysis may consider best-case and worst-case scenarios to account for variable site conditions and changes over time.

Applicability to project

The paper rightfully points out that there are extensive historical examples of unintended negative consequences resulting from large, ambitious infrastructure projects. Both Phase I and II of the project should be candid about this and recognize that there is some uncertainty about the unintended socio-economic impacts of a draft model ordinance aimed at mitigating the impacts of impervious cover.

The authors propose that for the stormwater benefits of trees to be fully realized, the organic matter and nutrients from falling leaves and other debris must also be considered in tree placement strategies and street sweeping plans. This should be considered in Phase II of the project when future land use conditions are simulated. It may be pertinent to incorporate additional street sweeping, including its costs, into areas that have had impervious cover turned to pervious areas with trees.

While the Taunton FDC project does not include changing the removal effectiveness of SCMs during a simulation, best and worst-case uptake scenarios may be beneficial to include. As an example, a low uptake scenario may include only 30% of the total identified opportunity area to be considered for optimization while a high scenario could include 100% of the identified area. Note that just because the high solution may include 100% of the available opportunity area, the optimization would still likely result in a smaller subset of opportunities.

6.3.2 Indicators of Hydrologic Alteration (2002)

Steve Swanson

Summary

This paper presents the 33 Indicators of Hydrologic Alteration (IHA). These parameters have been discussed in detail in the Task 4 draft memo and at the first TSC meeting. The paper is highly relevant to the project.

6.3.3 Estimating hydrologic alteration from basin characteristics in Massachusetts (2013)

Elizabeth S. Homa, Casey Brown, Kevin McGarigal, Bradley W. Compton, Scott D. Jackson

Summary

The paper focuses on developing a method of evaluating the relative impacts of both point and non-point source anthropogenic basin modifications on streamflow and estimating the degree of hydrologic alteration at any site. The authors rely on statistical relationships, rather than physically-based models. The authors cite Gao et al. (2009) who found that annual ecodeficit and ecosurplus statistics best summarized the variability represented in the Indices of Hydrologic Alteration (IHA). Therefore, the authors use ecosurplus and ecodeficit to summarize the effect of basin alterations instead of the more extensive set of IHA statistics.

The paper found that anthropogenic alterations tended to decrease the variability in daily streamflows. Watersheds with impervious surfaces had decreased high flows and increased low flows, a finding which more and more studies also support (Price 2011). The result could be due to stormwater storage systems which occur more frequently in areas with higher impervious cover.

Applicability to project

The paper is highly pertinent given its focus on predicting and interpreting FDCs in Massachusetts. The study had larger errors associated with lower flows (higher exceedance probabilities), consistent with other efforts to model low flows. Therefore, it may be expected that the Taunton project may also have similar difficulties with accurately simulating low flows. The finding of increased low flows and decreased high flows may be an important consideration when comparing results for the Taunton FDC project.

The paper provides additional valuable data sources, including:

Water use database developed for the Massachusetts Sustainable Yield Estimate

This database (Archfield et al., 2010) includes 6581 georeferenced points with groundwater (GW) and surface water (SW) withdrawal and/or discharge rates regulated by the MA Department of Environmental Protection and the U.S. Environmental Protection Agency (EPA). The points covered by the regulations included GW and SW public water supply withdrawals greater than 100,000 gals/day, pollutant discharges greater than 10,000 gals/day, and National Pollutant Discharge Elimination System (NPDES) regulated SW discharges. The database requires the 32-bit version of Access to operating.

GAGES II – USGS Geospatial Attributes of Gages for Evaluating Streamflow version II. Stream gages across the nation.

This dataset includes over 200 basin characteristics for each gage from a variety of primary sources. Daily streamflow data for at least 20 years is available from the USGS for each gage included in the dataset. The geospatial data includes both physical and climate data (soil, topology, temperature, precipitation, etc.) and anthropogenic basin characteristics (population, impervious surface, water use, dam density/storage).

6.3.4 The future of hydrological sciences: A (common) path forward? A call to action aimed at understanding velocities, celerities, and residence time distributions of the headwater hydrograph.

Jeffrey McDonnell and Keith Beven

Summary

The authors argue that a fundamental issue to improving our understanding of hydrological processes and our capability to model them is the explicit and routine use of celerities and velocities in model development and testing. The authors note the interesting and at times confusing issues about velocity-celerity in natural, preferential flow-dominated headwater catchments. Particularly, the processes by which 'old' water is delivered to a stream after a storm still need further investigation. The authors call for the routine use of tracers in monitoring studies and the development of more complex hydrological models that have additional, albeit unspecified parameters to allow for the additional mixing volume needed to predict water residence times relative to predicting the hydrograph.

Applicability to project

Figure 7 represents an example LSPC water balance in the form of un-routed aggregated edge-of-stream flows as a proportion of total precipitation across all modeled subwatersheds. LSPC hydrology is calibrated by comparing the simulated routed response against stream gage data where observed groundwater recession is estimated through hydrograph separation.

LSPC uses the groundwater recession constant (AGWRC) and interflow recession constant (IRC) to calibrate to observed hydrographs. The AGWRC is a ratio of current groundwater discharge to that from 24 hours earlier. The IRC affects the rate at which interflow is discharged from storage, it also affects the falling limb of the hydrograph between peak flow and baseflow. The AGWRC and IRC are the parameters that facilitate the investigation of residence time dynamics within watersheds.

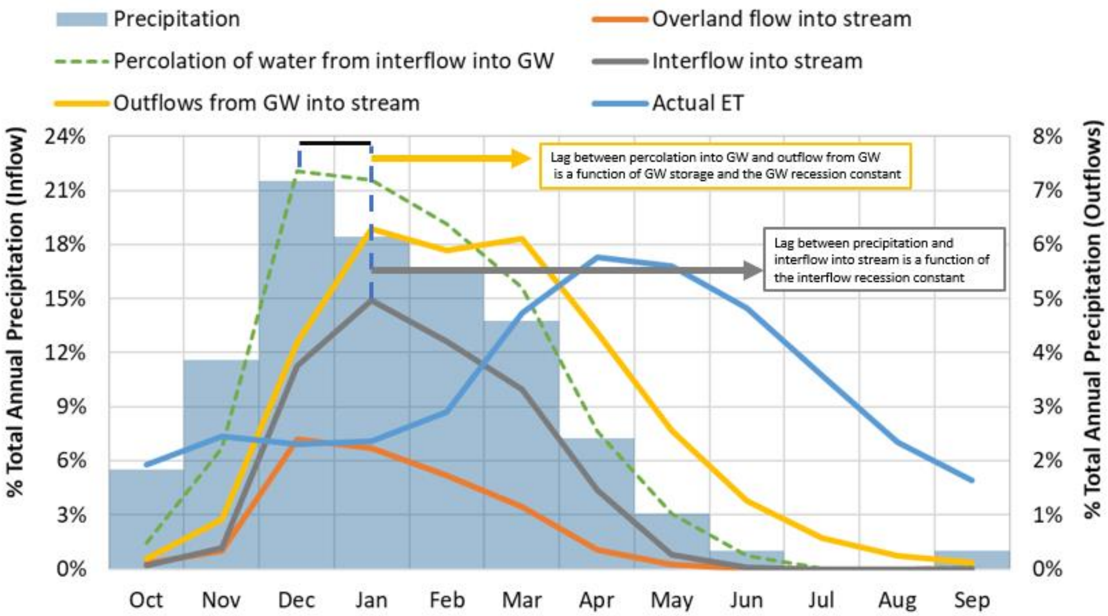

Figure 7. Example LSPC water balance.

Limitations: While LSPC can track water and pollutants within a channel from one watershed to another, the model is limited in its capabilities in tracking water within a subcatchment. A robust assessment of celerity would likely require the ability to track a molecule of water spatially and temporally as it fell as precipitation, infiltrated into the subsurface, and eventually reemerged in stream flow. This robust assessment would also require observed tracer data for study subwatersheds to facilitate calibration and validation.

Possible solution to calibrating to both velocity and celerity in the study watershed: Besides the typical calibration metrics, velocity and celerity may be addressed. Velocity and celerity quantify the movement of water through soil media. Velocities are controlled by the characteristics of the saturated water storage; celerities are controlled by the storage deficit that must be satisfied or remain as the saturated zone rises and falls. Velocity is generally understood to be the Darcian flux, a volume of water per cross-sectional area of soil. Velocity is calibrated by adjusting the saturated hydraulic conductivity of soil media. LSPC does not directly simulate Darcian flux but instead relies on coefficients to drive the movement of interflow and groundwater into streams. Celerity can also be calculated using saturated hydraulic conductivity.

Since no tracer studies are likely to have occurred in the study watershed, velocity and celerity can be calculated based on published hydraulic conductivity values for the soils within the subwatershed. The AGRWC and IRC may then be adjusted to replicate observed hydrographs but also result in fluxes (LT^{-1}) that would be expected from the calculated values of velocity and celerity.