Modeling and Development of Flow Duration Curves (FDC 1 Project)

Holistic Watershed Management for Existing and Future Land use Development Activities: Opportunities for Action for Local Decision Makers

Technical Steering Committee Mtg No 1
re: Task 4A Draft Project Scope / Approach

Prepared for

U.S. EPA Region 1

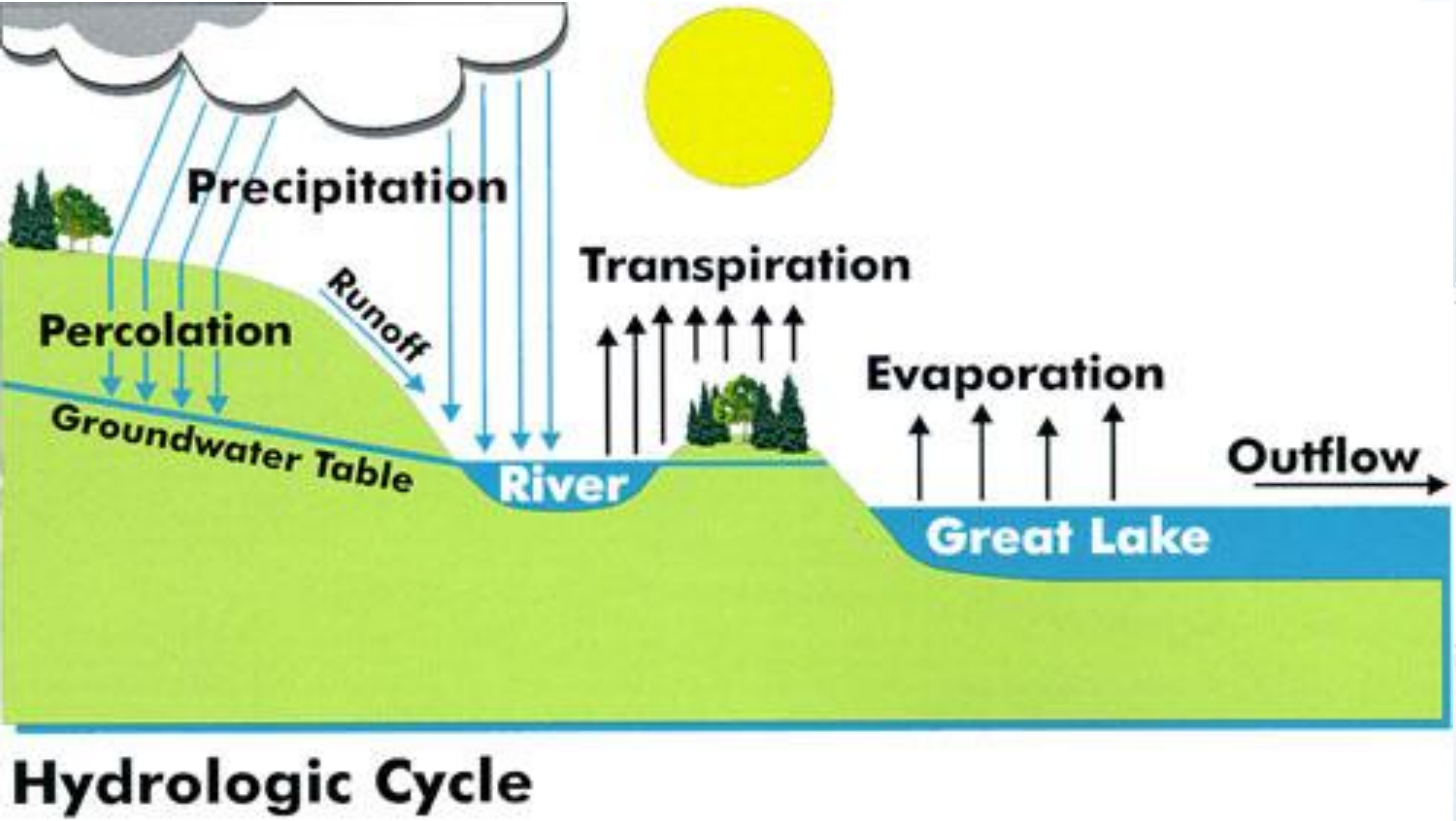
Prepared by:

Paradigm Environmental

Great Lakes Environmental Center

A Technical Direct Assistance Project funded by the
USEPA Southeast New England Program (SNEP)

Dec 18, 2020



Reference: NOAA, Great Lakes Environmental Research Laboratory (http://www.glerl.noaa.gov/pubs/brochures/lakelevels/lakelevels.html) citing U.S. Army Corps of Engineers, *Living with the Lakes*, 1999.

The Problem with Impervious Cover (IC)

They paved paradise
and put up a parking lot . ..

Joni Mitchell
"Big Yellow Taxi"
1968-69

Stormwater - Relationship between Impervious Cover (IC) and Surface Runoff

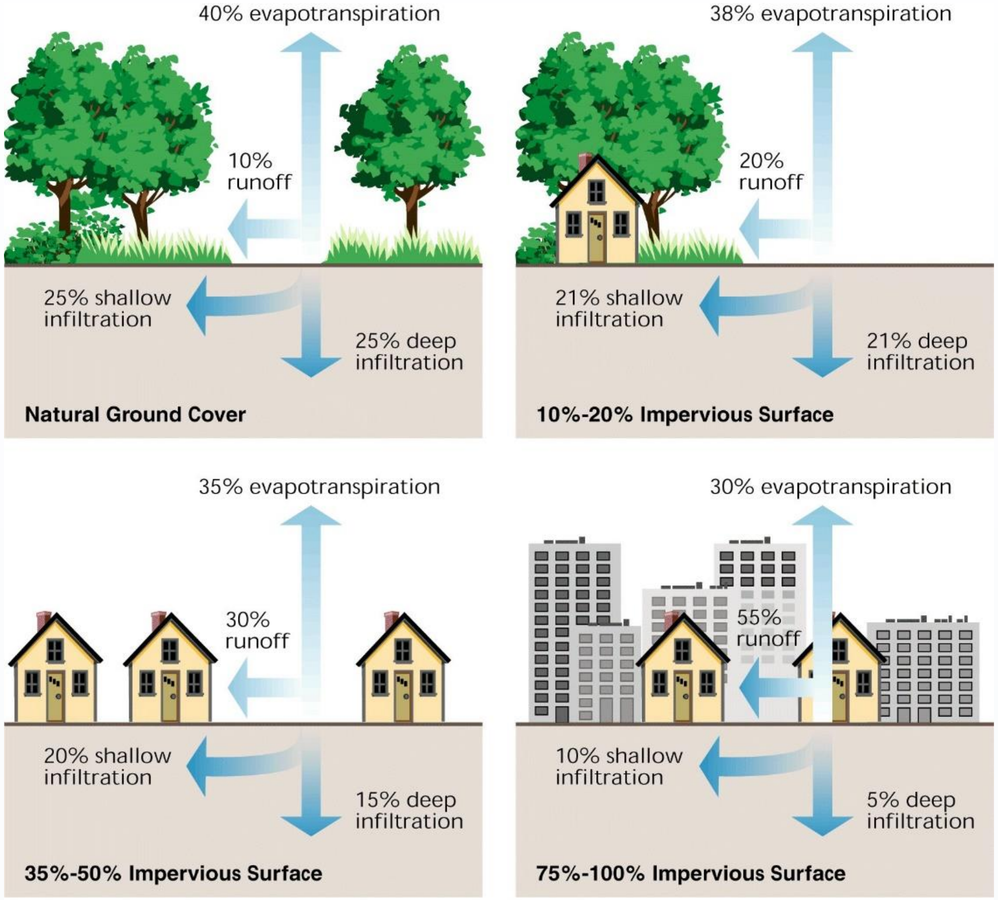
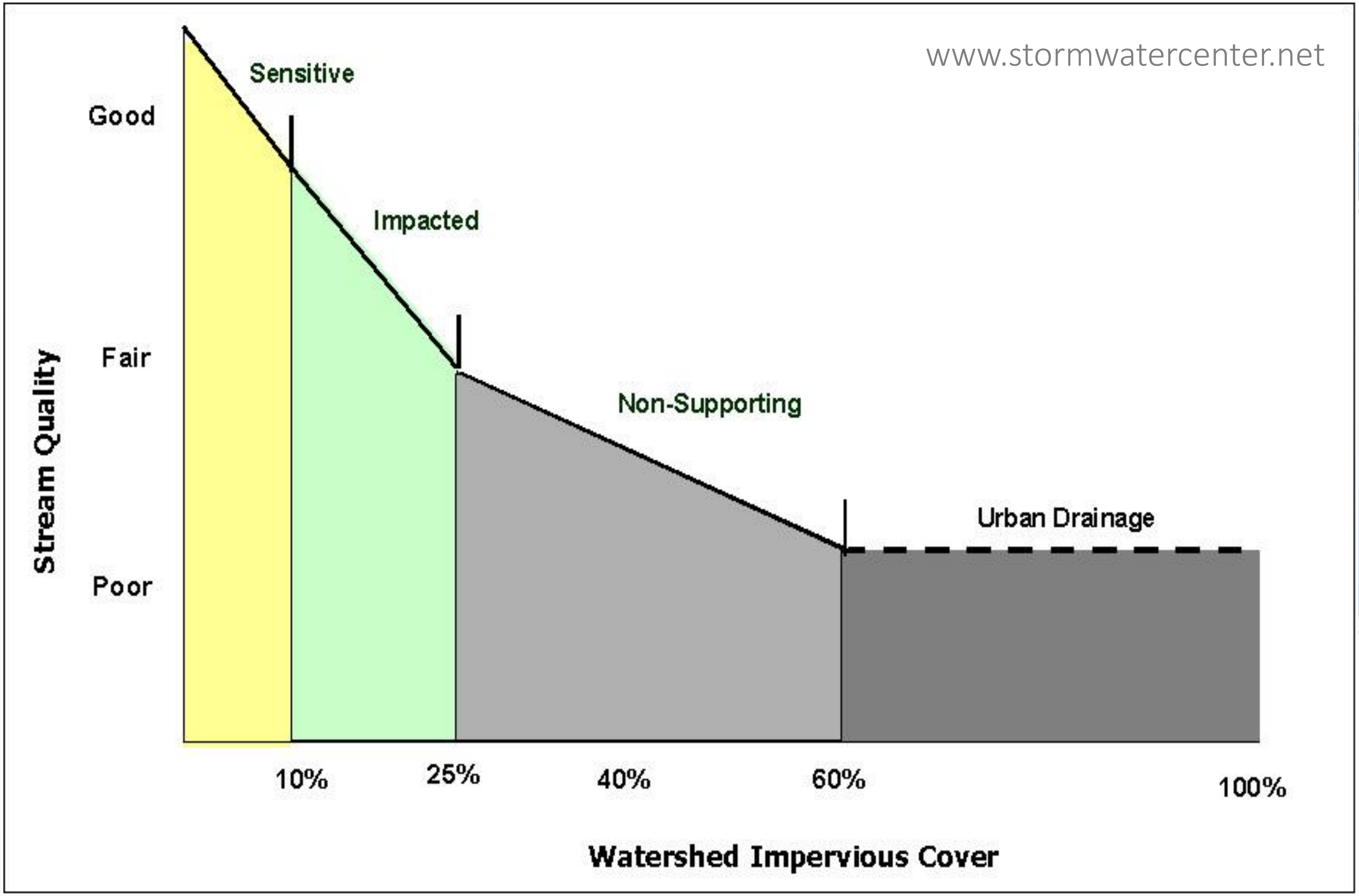


Fig. 3.21 -- Relationship between impervious cover and surface runoff. Impervious cover in a watershed results in increased surface runoff. As little as 10 percent impervious cover in a watershed can result in stream degradation.
In Stream Corridor Restoration: Principles, Processes, and Practices (10/98).
By the Federal Interagency Stream Restoration Working Group (FISRWG) (15 Federal agencies of the U.S.)

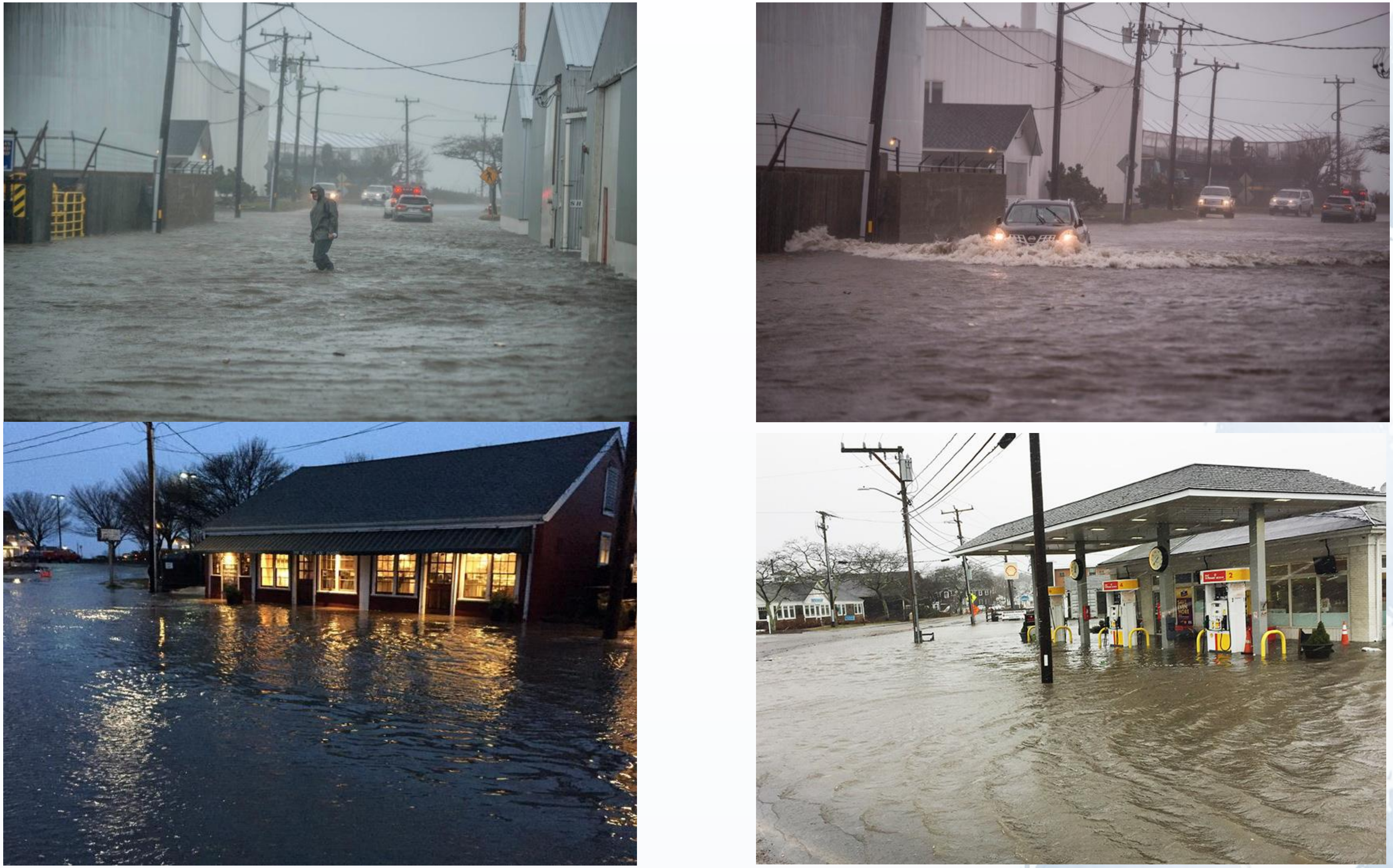
Reference: Federal Interagency Stream Corridor Restoration Working Group (FISRWG). 1998. Stream Corridor Restoration: Principles, Processes, and Practices. PB98-158348LUW.

Stormwater - Impact of Impervious Cover on Stream Quality



Nutrient Pollution (nitrogen, phosphorus)

Reference: Mystic River, BostonGlobe.com, July 30, 2017



Project in a Nutshell

Envisioning a new and different future
- shift in thinking about impervious cover (IC)

A foray or 'preface' for a larger 'textbook' on use and development of FDC for impervious cover-related watershed management approaches

Note on Applied v. Basic Research

Roles and Responsibilities:
- R. Cody: Contract and Policy
- M. Voorhees: Technical
- S. Burns (TNC): Technical and Policy; Municipal Liaison

Two Phases:
- Phase 1 – FDC Modeling
- Phase 2 – Direct Municipal Assistance: Development of FDC-related Tools and Approaches

Role of the TSC

- Provide guidance and critical feedback on key project milestones

- Advise on existing modeling and monitoring (physical, biological, chemical) to help inform which 3 Taunton River subwatersheds to explore

- Review and advise on modeling approach, climate baseline, and variables to explore integrating into the FDC-related efforts outputs (basic and/or applied research):

  - Flooding, drought, evapotranspiration (ET), landscape architecture, impervious cover disconnection, green infrastructure, critical threshold volumes, habitat, groundwater, hyporheic zone, fluvial geomorphology, other

- Guide and integrate research into applied methodology to advance the practice of watershed management.

Role of the TSC

Benefits:

- Collaboration with multi-disciplinary team of experts
- Cross fertilization of ideas / projects
- Multi-disciplinary projects, responses to grant solicitations
- Metrics for volumetric control of stormwater

Other:

- Constructive criticism of approach and assumptions employed for applied research outcomes

A Closer Look at the Impacts of IC Conversion on Natural Watershed Processes at the Site Scale

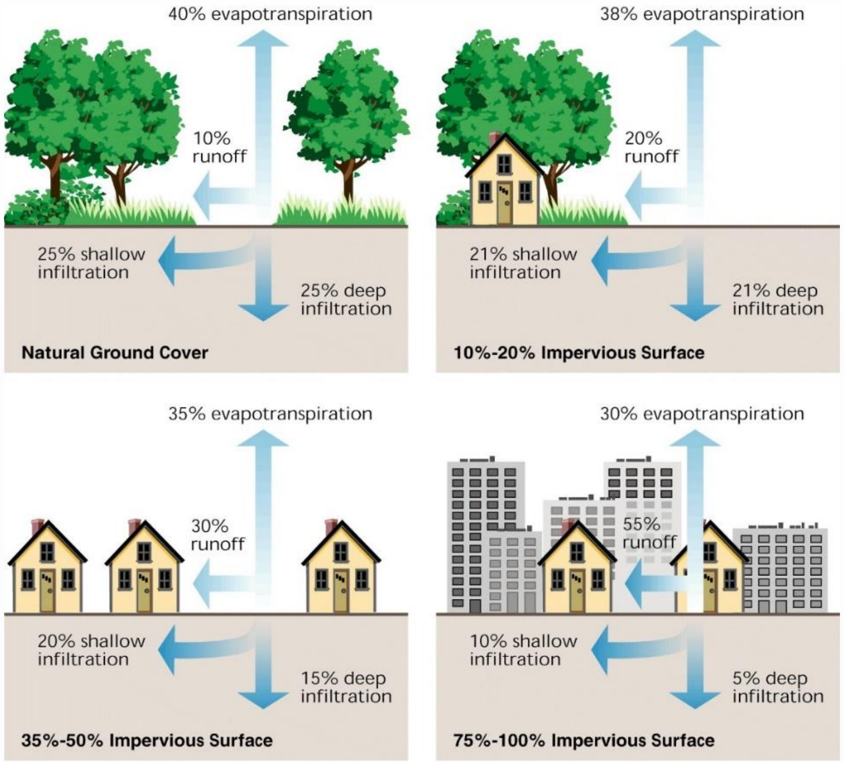


Fig. 3.21 -- Relationship between impervious cover and surface runoff. Impervious cover in a watershed results in increased surface runoff. As little as 10 percent impervious cover in a watershed can result in stream degradation.
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What Happens when vegetated permeable surfaces are converted to IC?

- Annual runoff volumes increase by 400% to 10,000%
- Runoff rates to receiving waters greatly increased
- Groundwater recharge is eliminated
- Evapotranspiration is eliminated and replaced with minimal evaporation
- Natural filtering capacity to attenuate pollutants of concern eliminated
- Natural cooling through evaporative heat exchange greatly diminished
- Carbon sequestration processes eliminated

Some preliminary calculations of IC conversion impacts based on Hydrologic Response Unit (HRU) Modelling

Hydrologic and Nutrient Export Consequences of Conversion of Natural Vegetated Areas to Impervious Cover (IC Conversion)

Land surface	Average Annual Precipitation, MG/acre/yr	Average Annual Runoff (SW) yield, MG/acre/yr	Average Annual GW Recharge Yield, MG/acre/yr	Average Annual SW Phosphorus Load Export, lbs P/acre/yr
Impervious cover	1.18	1.05	0.00	2.00
Grass/Forested HSG A (well drained)	1.18	0.01	0.58	0.03
Grass/Forested HSG B (moderately well drained)	1.18	0.06	0.53	0.14
Grass/Forested HSG C (less well drained)	1.18	0.12	0.47	0.31
Grass/Forested HSG D (poorly drained)	1.18	0.19	0.40	0.47

Relative Changes Due to IC Conversion without Controls

Land surface	Average Annual Precipitation, MG/yr/ac	Percent Change in Average Annual Runoff (SW) yield, MG/yr/acre	Percent Change in Average Annual GW Recharge Yield, MG/yr/ac	Percent Change in Average Annual SW Phosphorus Load Export, lbs/yr/ac
IC Conversion HSG A	No change	10050%	-100%	7654%
IC Conversion HSG B	No change	1747%	-100%	1311%
IC Conversion HSG C	No change	752%	-100%	551%
IC Conversion HSG D	No change	458%	-100%	326%

Change in Average Annual Runoff Yields, GW Recharge, and Nutrient Export from IC Conversion after applying a 1 inch recharge level of control for all HSGs, %

Land surface	Average Annual Precipitation, MG/yr/ac	Percent Change in Average Annual Runoff (SW) yield, MG/yr/acre	Percent Change in Average Annual GW Recharge Yield, MG/yr/ac	Percent Change in Average Annual SW Phosphorus Load Export, lbs/yr/ac
IC Conversion HSG A	No change	712%	66%	210%
IC Conversion HSG B	No change	103%	75%	-15%
IC Conversion HSG C	No change	53%	84%	-35%
IC Conversion HSG D	No change	73%	114%	-86%

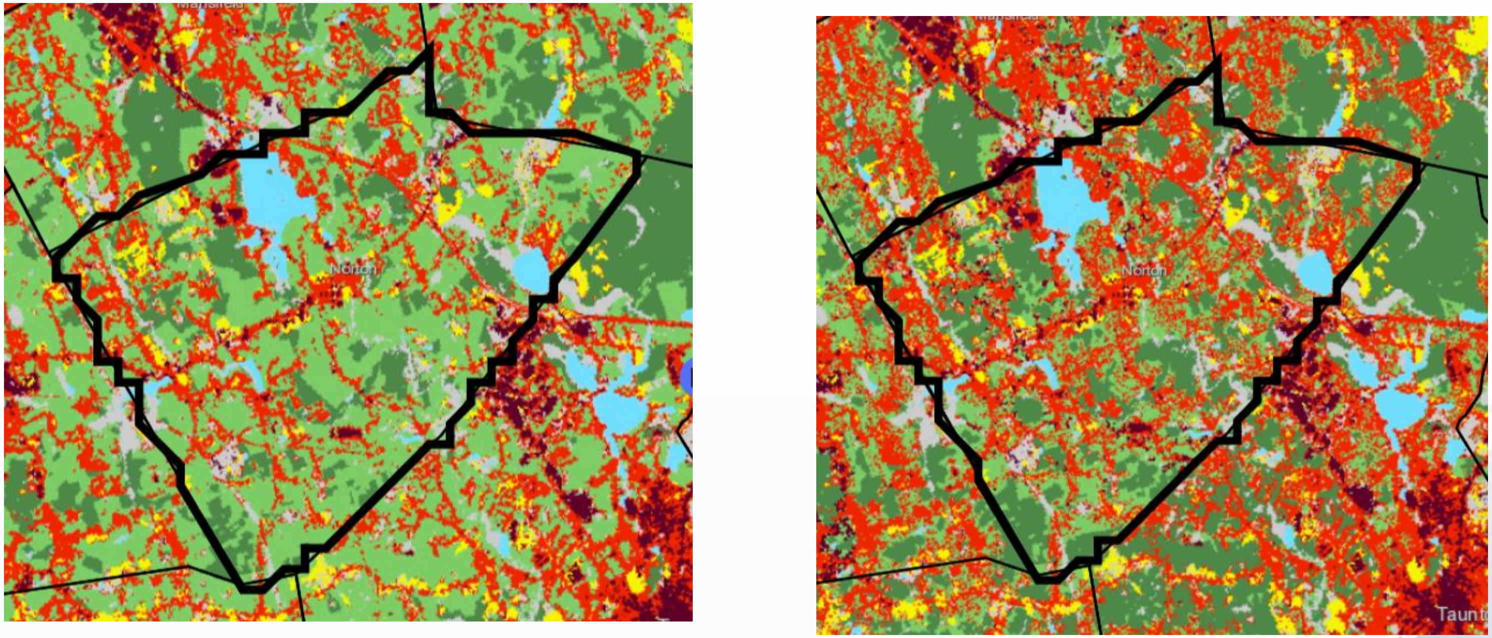
Notes: Runoff volumes from continuous simulation modeling using SWMM and P8 using hourly precip and daily temp data (Boston MA - 1998-2002), Assumed 50% Evapotranspiration, and applying MA SW Standard 3 (recharge standards = 0.6 in depth HSG A; 0.35 in depth HSG B; 0.25 in depth HSG C; and 0.1 in depth HSG D). SCM Infiltration performance curves were used to estimate average annual runoff volume reduction, recharge volumes and nutrient load reductions.

Examples of Challenges due to Existing IC

- Charles River:
  - **310 sq. mi. watershed w/ 61 sq. mi of IC (~39,000 IC acres)**
  - **Nutrient impaired**
  - **SW phosphorus load from IC primary source needing ~50% load reduction to attain Water Quality Standards (WQS) (Charles River P TMDLs 2007 and 2011)**
- Mystic River Watershed:
  - **63 sq. mi. watershed w/ 24 sq. mi. of IC (~15,000 IC acres)**
  - **Nutrient impaired**
  - **~ 60% SW P load reduction needed to attain WQS (Mystic River Alt TMDL 2020)**

Quantifying how management actions will address other SW-IC related impacts is needed to build support for action and select best management strategies.

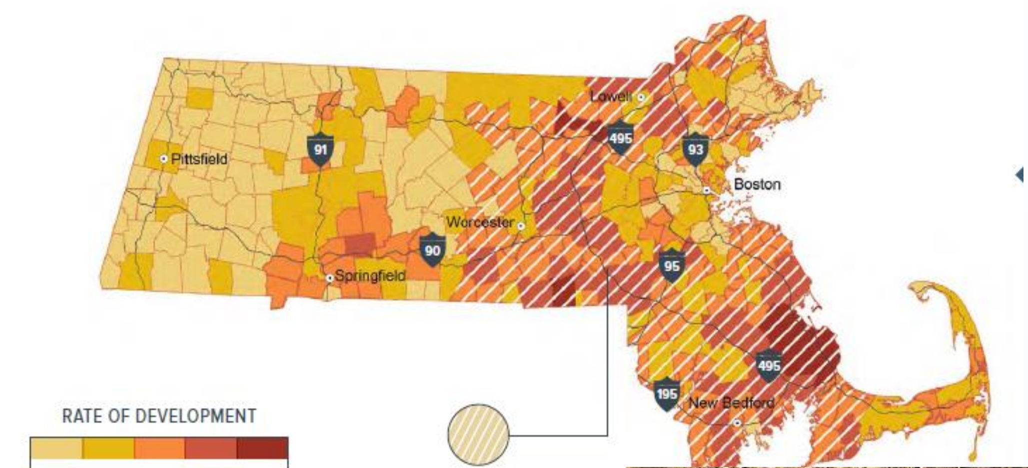
Preliminary Projection of Future Growth and Increased Development for Town of Norton, MA in Taunton Watershed



Estimated increases in developed land and impervious cover for Norton, MA from 2010 to 2060

Development Density	2010			2060			Increases to area and IC - 2010 to 2060	
	area, acre	IC acre	% IC	area acre	IC acre	% IC	area, acre	IC acre
High density development	380	222	58%	736	427	58%	355	205
Low density development	3857	661	17%	6210	1615	26%	2353	954
Totals	**4237**	**883**	**21%**	**6945**	**2041**	**29%**	**2708**	**1158**

Resilient Taunton Watershed Network (RTWN) http://srpedd.org/rtwn



Resilient Taunton Watershed Network (RTWN)

SRPEDD

manomet
Soaring Solutions. Grounded Science.

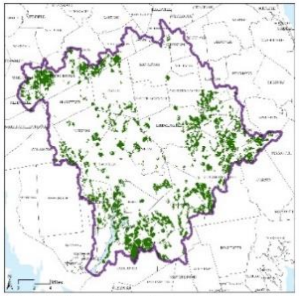
50 YEARS

The Nature Conservancy

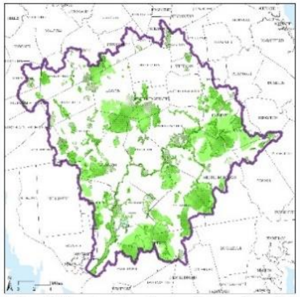
Mass Audubon

Shaping the Future of Your Community

Green Infrastructure Network Components…

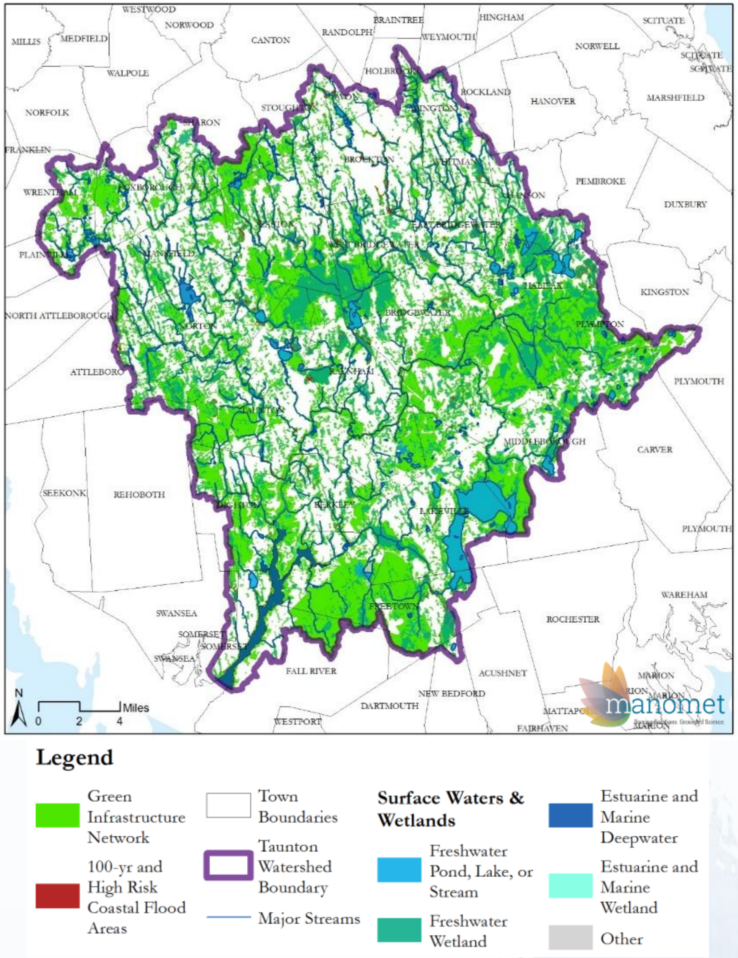


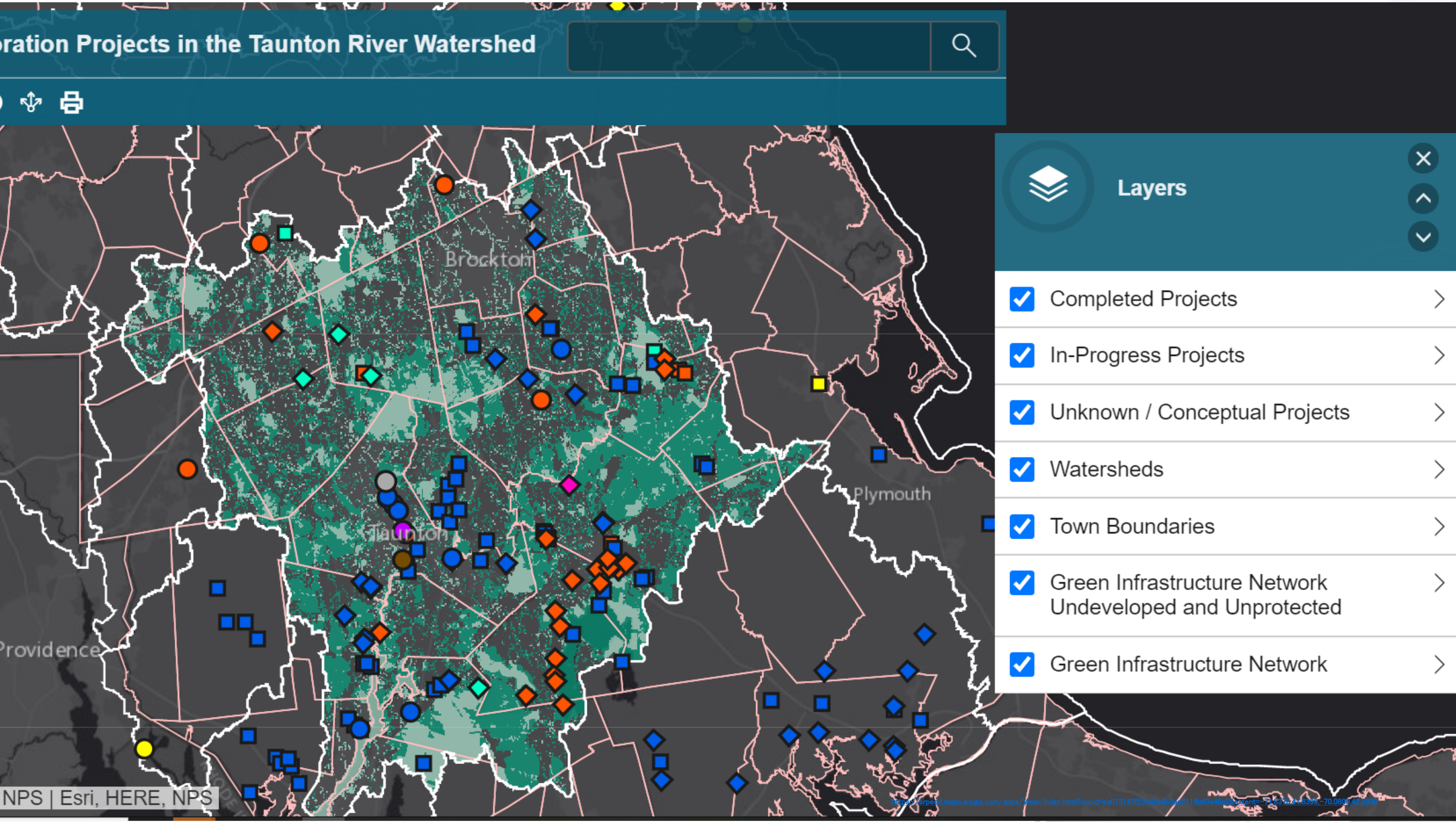
Areas of Above Average Resilience



BioMap2 Core & Critical Natural Landscape

Areas within 100ft of Surface Waters, Wetlands, and Flood Zones; Areas </= 4m elevation (vulnerable to sea level rise)





☑ Completed Projects

☑ In-Progress Projects

☑ Unknown / Conceptual Projects

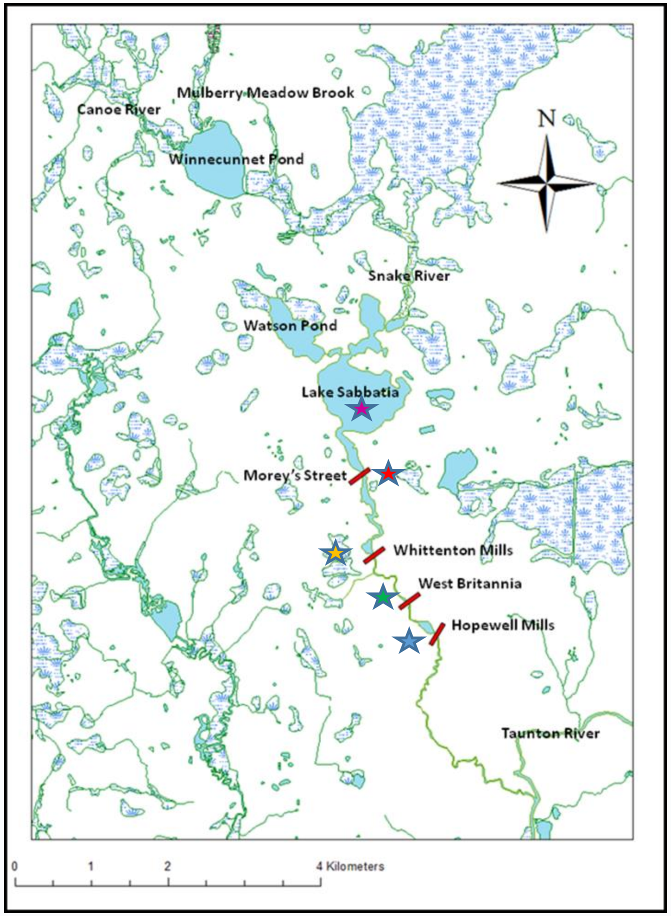
☑ Watersheds

☑ Town Boundaries

☑ Green Infrastructure Network Undeveloped and Unprotected

☑ Green Infrastructure Network

Mill River, Taunton




Hopewell ★ Dam, 2012


Whittenton ★ Dam, 2013


West Britannia ★ Dam, 2018


Fish Ladder at Morey's Street, 2013

River Herring in Lake Sabattia, 2018

Municipal Vulnerability Preparedness (MVP) and RTWN

1. Engage Community
2. Identify CC impacts and hazards
3. Complete assessment of vulnerabilities & strengths
4. Develop and prioritize actions
5. Take Action

State and local partnership to build resiliency to climate change

Lakeville
Middleborough
Freetown
Rochester
Easton
Mansfield
Norton

RTWN Current Projects

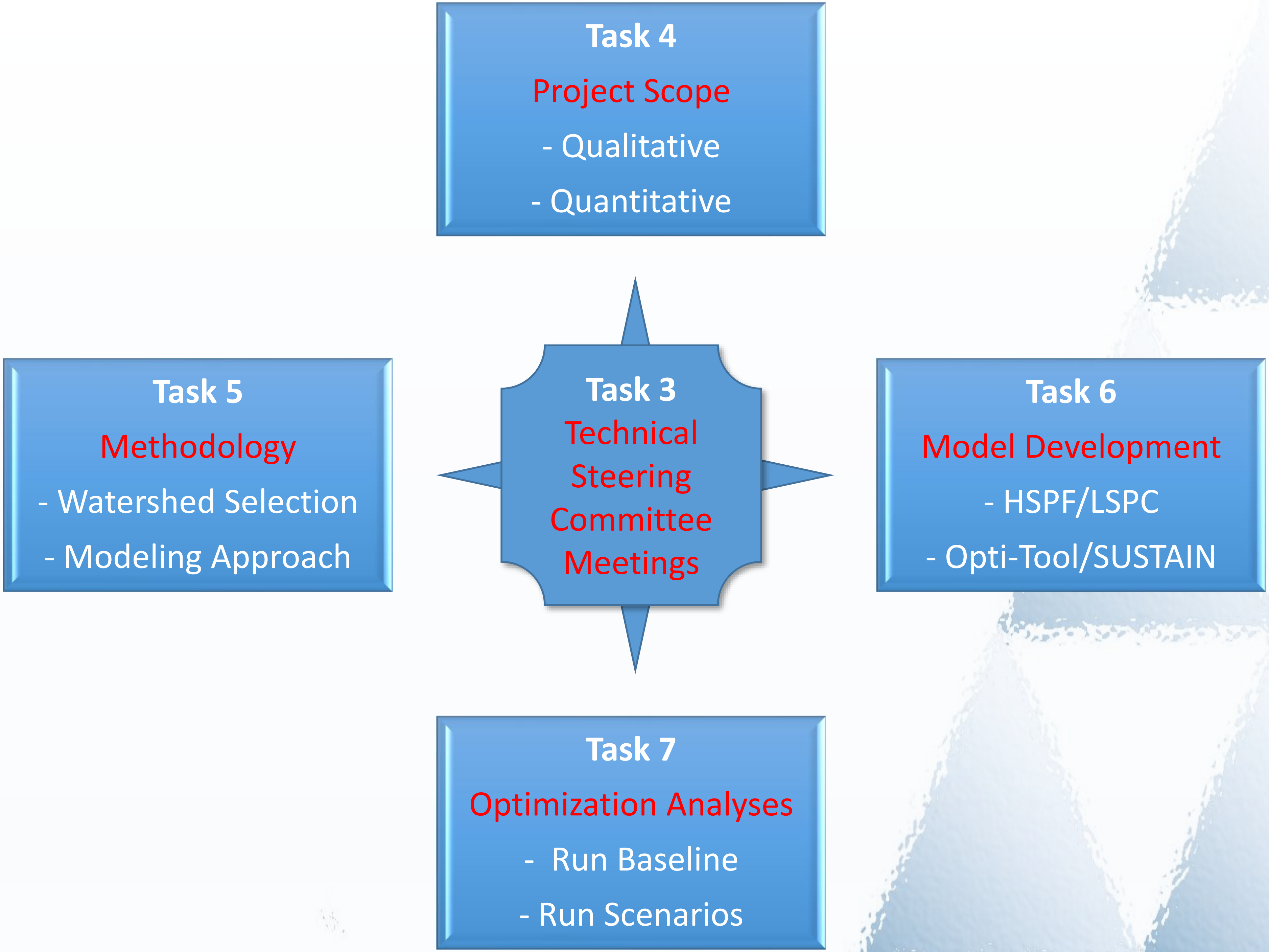
- Wetland Restoration and monitoring (including flow)– Easton, MA
- Canoe River Aquifer Protection Project – Planning and project design – Norton, Mansfield, Easton
- High St Dam Removal – Bridgewater
- Assawompsett Pond Complex – H&H study Upper Nemasket; WMOST modeling; Watershed Climate Resilience Plan
- Conservation of GI network – Plymouth

Project Elements/Sub-Tasks	Deliverables
Task 0: Work Plan, Budget, and Schedule	
Draft work plan, budget, and schedule	11/6/2020
Final work plan, budget, and schedule	11/20/2020
Task 1: Prepare Quality Assurance Project Plan	
Prepare draft QAPP	11/6/2020
Final QAPP	12/31/2020
Task 2: Project Management and Administration	
Kickoff call	11/9/2020*
Kickoff meeting and summary	11/13/2020
Monthly progress calls and summaries	Monthly
Task 3: Technical Steering Committee Meetings	
TSC Meeting 1: Completion of Subtask 4A - Draft Technical Scope Outline	12/17/2020*
TSC Meeting 2: Completion of draft Task 5 technical memorandum	4/22/2021*
TSC Meeting 3: Completion of draft Task 6 technical memorandum	6/24/2021*
TSC Meeting 4: Completion of draft Task 7 technical memorandum	9/23/2021*
Task 4. Coordinate with TSC to Finalize Phase 1 Project Approach	
4A: Draft Technical Scope Outline	
Draft technical approach outline	12/11/2020
4B: Final Technical Scope	
Final technical approach memo	12/31/2020
Task 5. Compile Available Data/Information for Taunton River Watershed Modeling Analyses	
5A: Data/Information Assessment	
5B: Past, Current, and Future Climate Data Analysis	
5C: Baseline Unit-Area Modeling Analysis	
5D: Develop Hydrologic/Streamflow and Water Management Modeling Approach for Taunton River Sub-watershed Analyses	
Draft technical memo and fact sheets	4/16/2021
Final technical memo and fact sheets	4/30/2021
Task 6. Phase 1 Hydrologic Streamflow Modeling Analyses	
6A: Adapt Models for Flow Duration Curve Analyses for Pilot Sub-watersheds	
6B: Adapt R1 Opti-Tool for Stormwater and FDC Management Analyses	
Draft technical memo	6/18/2021
Final technical memo	6/30/2021
Task 7. Phase 1 Stormwater/Hydrologic Management Optimization Analyses	
Draft project report and outreach materials	9/17/2021
Final project report and outreach materials	9/30/2021
Task 8. Phase 1 Project Webinar to SNEP Region	
Draft presentation slides	9/27/2021
Webinar presentation	9/30/2021*

*=tentative, to be finalized in consultation with EPA

As needed, 1 call each month

Completed



Task 4

Project Scope

- Qualitative
- Quantitative

Task 5

Methodology

- Watershed Selection
- Modeling Approach

Task 3

Technical Steering Committee Meetings

Task 6

Model Development

- HSPF/LSPC
- Opti-Tool/SUSTAIN

Task 7

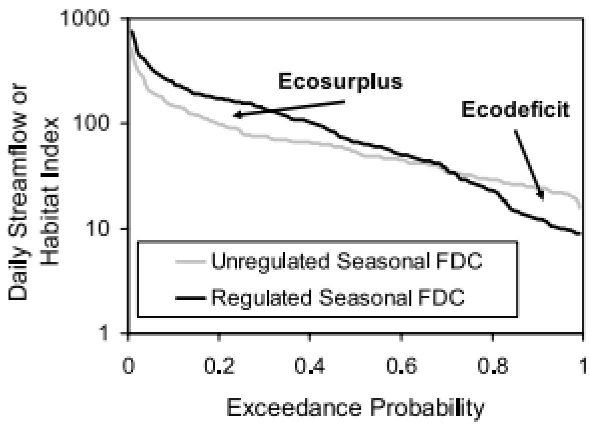
Optimization Analyses

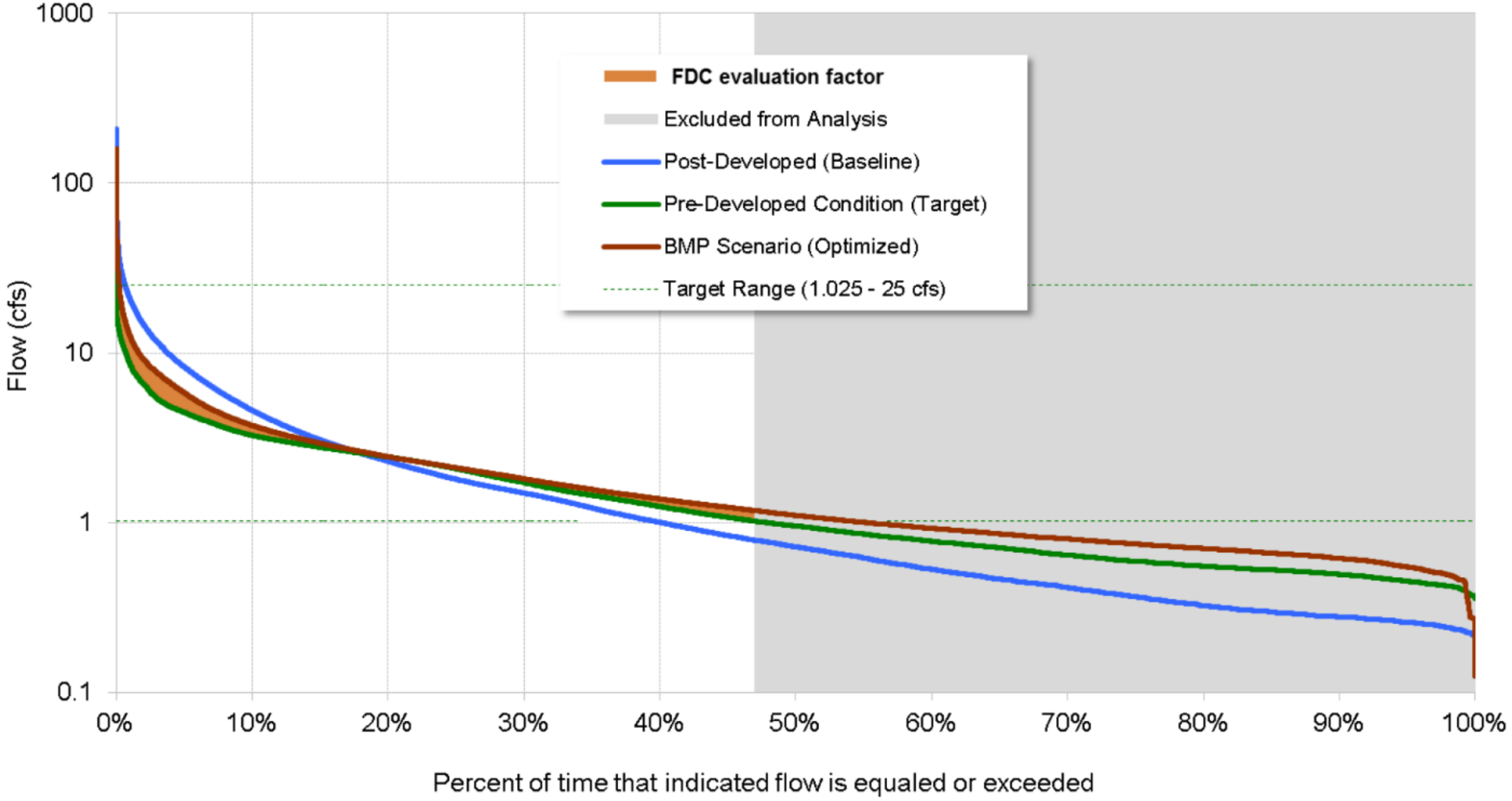
- Run Baseline
- Run Scenarios

Task 4. FDC Phase 1 Project Approach

- Phase 1 is “Proof of Concept” Demonstration
  - **Impacts of increase impervious cover (IC)**
  - **Impacts of climate change**
  - **Benefits of management actions (GI SCM)**
- Flow Duration Curve Development
  - **Frequency/Magnitude/Duration**
  - **Flooding/Channel destabilization/Aquatic life**
  - **Relationship between FDC and IC change**
- Phase 2 Roadmap
  - **Next generation municipal ordinance and bylaws**
    - Conservation development practices
    - Landscape architecture
    - Preserve pre-development hydrological condition
- Outcomes Transfer to SNEP Technical Assistance Network (STAN)

Flow Duration Curve

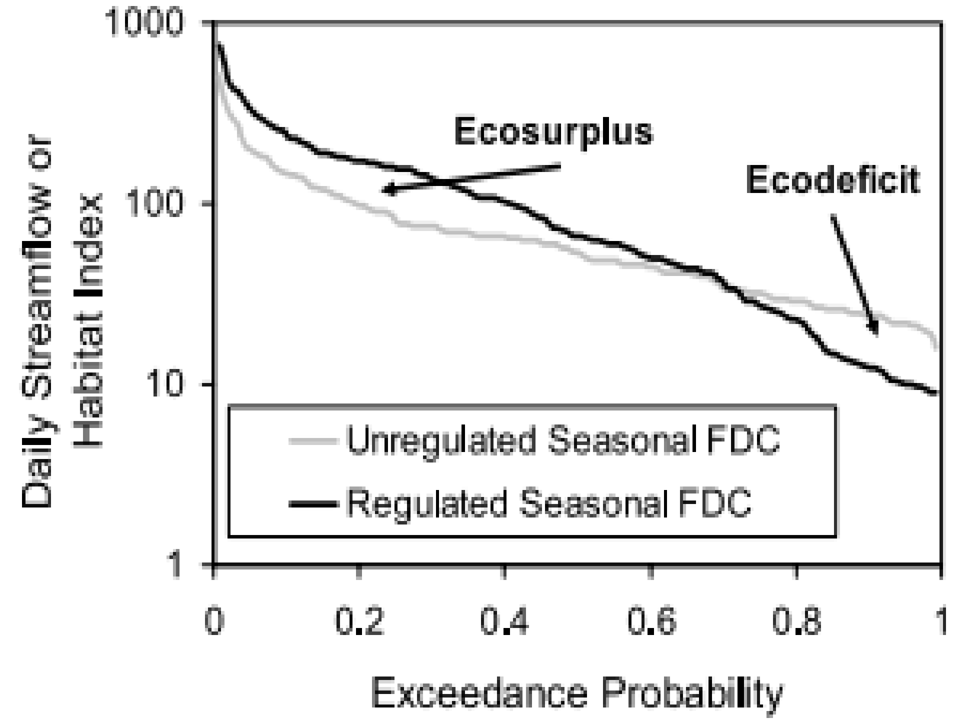




- Area between two FDCs – evaluation factor
- Additional measurements/metrics facilitate understanding

- Ecosurplus and Ecodeficit
  - **Percentage of excess water introduced to an ecosystem or percentage of water no longer available for ecosystem use**

- Indicators of Hydrologic Alteration (IHA)
  - **33 parameters relevant to ecological quality. Flow-based metrics**
  - **Range of Variability Approach (RVA) – establishes a range of expected variability in IHA in undeveloped conditions and used to identify the extent to which natural flow regimes have been altered**



Ecodeficit and ecosurplus regions between an unregulated (predevelopment) and regulated (post-development) FDC. Source: (Vogel et al., 2007).

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	

example

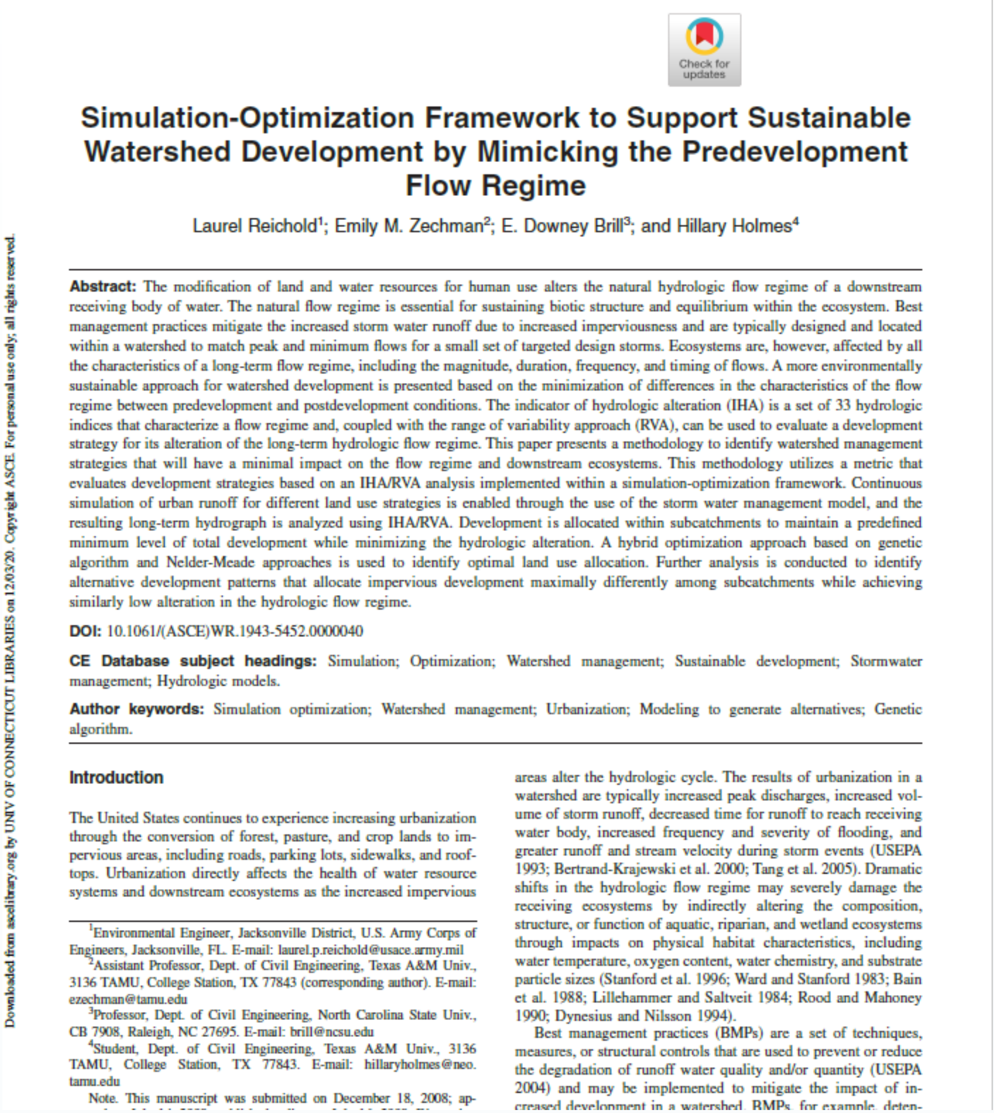
15-year simulation for undeveloped and developed conditions, same meteorology

IHA parameter: average annual one day minimum flow (1dayminflow)

	Low (<33%)	**Medium (34%-67%)**	**High (>67%)**
	<7 cfs	**7-12 cfs**	**>12 cfs**
Annual values, pre-developed	5	5	5

Hydrological alteration factor = $\frac{Observed\ frequency - expected\ frequency}{expected\ frequency}$

Negative value = frequency has decreased
Positive value = frequency has increased



Simulation-Optimization Framework to Support Sustainable Watershed Development by Mimicking the Predevelopment Flow Regime

Laurel Reichold[1]; Emily M. Zechman[2]; E. Downey Brill[3]; and Hillary Holmes[4]

Abstract: The modification of land and water resources for human use alters the natural hydrologic flow regime of a downstream receiving body of water. The natural flow regime is essential for sustaining biotic structure and equilibrium within the ecosystem. Best management practices mitigate the increased storm water runoff due to increased imperviousness and are typically designed and located within a watershed to match peak and minimum flows for a small set of targeted design storms. Ecosystems are, however, affected by all the characteristics of a long-term flow regime, including the magnitude, duration, frequency, and timing of flows. A more environmentally sustainable approach for watershed development is presented based on the minimization of differences in the characteristics of the flow regime between predevelopment and postdevelopment conditions. The indicator of hydrologic alteration (IHA) is a set of 33 hydrologic indices that characterize a flow regime and, coupled with the range of variability approach (RVA), can be used to evaluate a development strategy for its alteration of the long-term hydrologic flow regime. This paper presents a methodology to identify watershed management strategies that will have a minimal impact on the flow regime and downstream ecosystems. This methodology utilizes a metric that evaluates development strategies based on an IHA/RVA analysis implemented within a simulation-optimization framework. Continuous simulation of urban runoff for different land use strategies is enabled through the use of the storm water management model, and the resulting long-term hydrograph is analyzed using IHA/RVA. Development is allocated within subcatchments to maintain a predefined minimum level of total development while minimizing the hydrologic alteration. A hybrid optimization approach based on genetic algorithm and Nelder-Meade approaches is used to identify optimal land use allocation. Further analysis is conducted to identify alternative development patterns that allocate impervious development maximally differently among subcatchments while achieving similarly low alteration in the hydrologic flow regime.

DOI: 10.1061/(ASCE)WR.1943-5452.0000040

CE Database subject headings: Simulation; Optimization; Watershed management; Sustainable development; Stormwater management; Hydrologic models.

Author keywords: Simulation optimization; Watershed management; Urbanization; Modeling to generate alternatives; Genetic algorithm.

Introduction

The United States continues to experience increasing urbanization through the conversion of forest, pasture, and crop lands to impervious areas, including roads, parking lots, sidewalks, and rooftops. Urbanization directly affects the health of water resource systems and downstream ecosystems as the increased impervious areas alter the hydrologic cycle. The results of urbanization in a watershed are typically increased peak discharges, increased volume of storm runoff, decreased time for runoff to reach receiving water body, increased frequency and severity of flooding, and greater runoff and stream velocity during storm events (USEPA 1993; Bertrand-Krajewski et al. 2000; Tang et al. 2005). Dramatic shifts in the hydrologic flow regime may severely damage the receiving ecosystems by indirectly altering the composition, structure, or function of aquatic, riparian, and wetland ecosystems through impacts on physical habitat characteristics, including water temperature, oxygen content, water chemistry, and substrate particle sizes (Stanford et al. 1996; Ward and Stanford 1983; Bain et al. 1988; Lillehammer and Saltveit 1984; Rood and Mahoney 1990; Dynesius and Nilsson 1994).

Best management practices (BMPs) are a set of techniques, measures, or structural controls that are used to prevent or reduce the degradation of runoff water quality and/or quantity (USEPA 2004) and may be implemented to mitigate the impact of increased development in a watershed. BMPs, for example, deten-

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[2] Assistant Professor, Dept. of Civil Engineering, Texas A&M Univ., 3136 TAMU, College Station, TX 77843 (corresponding author). E-mail: ezechman@tamu.edu

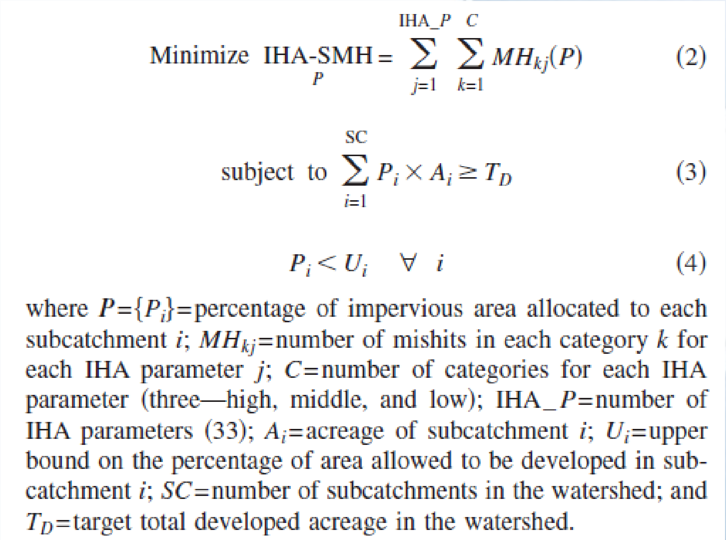
[3] Professor, Dept. of Civil Engineering, North Carolina State Univ., CB 7908, Raleigh, NC 27695. E-mail: brill@ncsu.edu

[4] Student, Dept. of Civil Engineering, Texas A&M Univ., 3136 TAMU, College Station, TX 77843. E-mail: hillaryholmes@neo.tamu.edu

Note. This manuscript was submitted on December 18, 2008; ap-

Uses number of mishits.

Synthesizes analysis of 33 IHA parameters and their three categories (low, medium, high) into a single metric



$$\text{Minimize } \underset{P}{\text{IHA-SMH}} = \sum_{j=1}^{\text{IHA}\_P} \sum_{k=1}^{C} MH_{kj}(P) \qquad (2)$$

$$\text{subject to } \sum_{i=1}^{SC} P_i \times A_i \geq T_D \qquad (3)$$

$$P_i < U_i \quad \forall \ i \qquad (4)$$

where $P=\{P_i\}$=percentage of impervious area allocated to each subcatchment i; MH_{kj}=number of mishits in each category k for each IHA parameter j; C=number of categories for each IHA parameter (three—high, middle, and low); IHA_P=number of IHA parameters (33); A_i=acreage of subcatchment i; U_i=upper bound on the percentage of area allowed to be developed in subcatchment i; SC=number of subcatchments in the watershed; and T_D=target total developed acreage in the watershed.

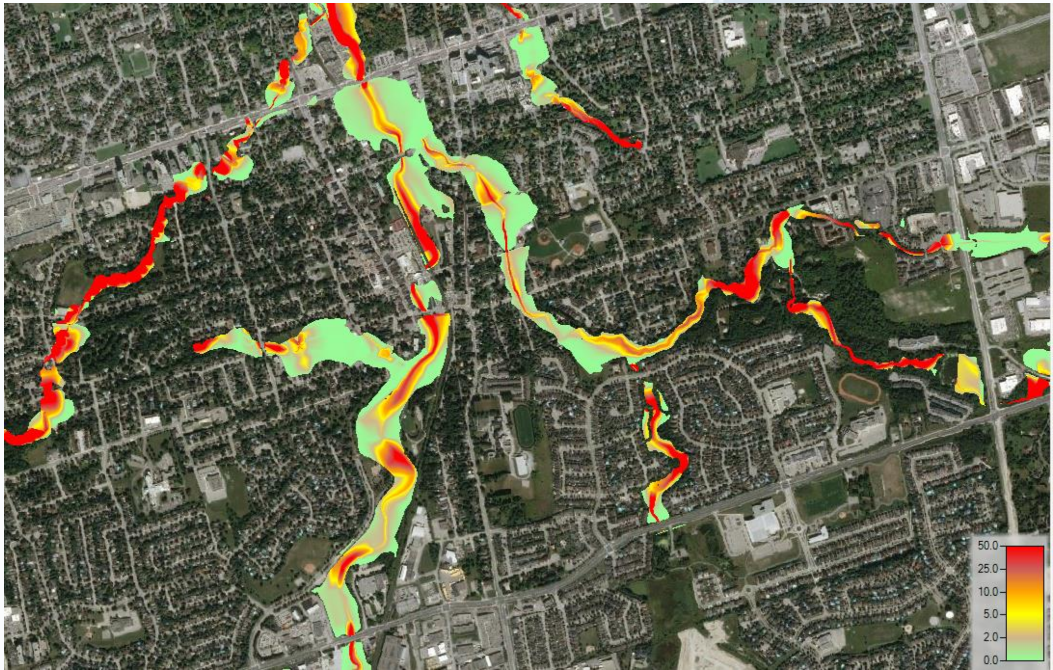
- While Reichold et al. used the single composite metric as the objective function, we would use it as an overall measurement of deviation between conditions.
  - **Can add additional metrics for number of expected times to achieve bankfull flows, critical shear stress flows, others.**

- Objective function for this project would be to reduce the area between FDCs.

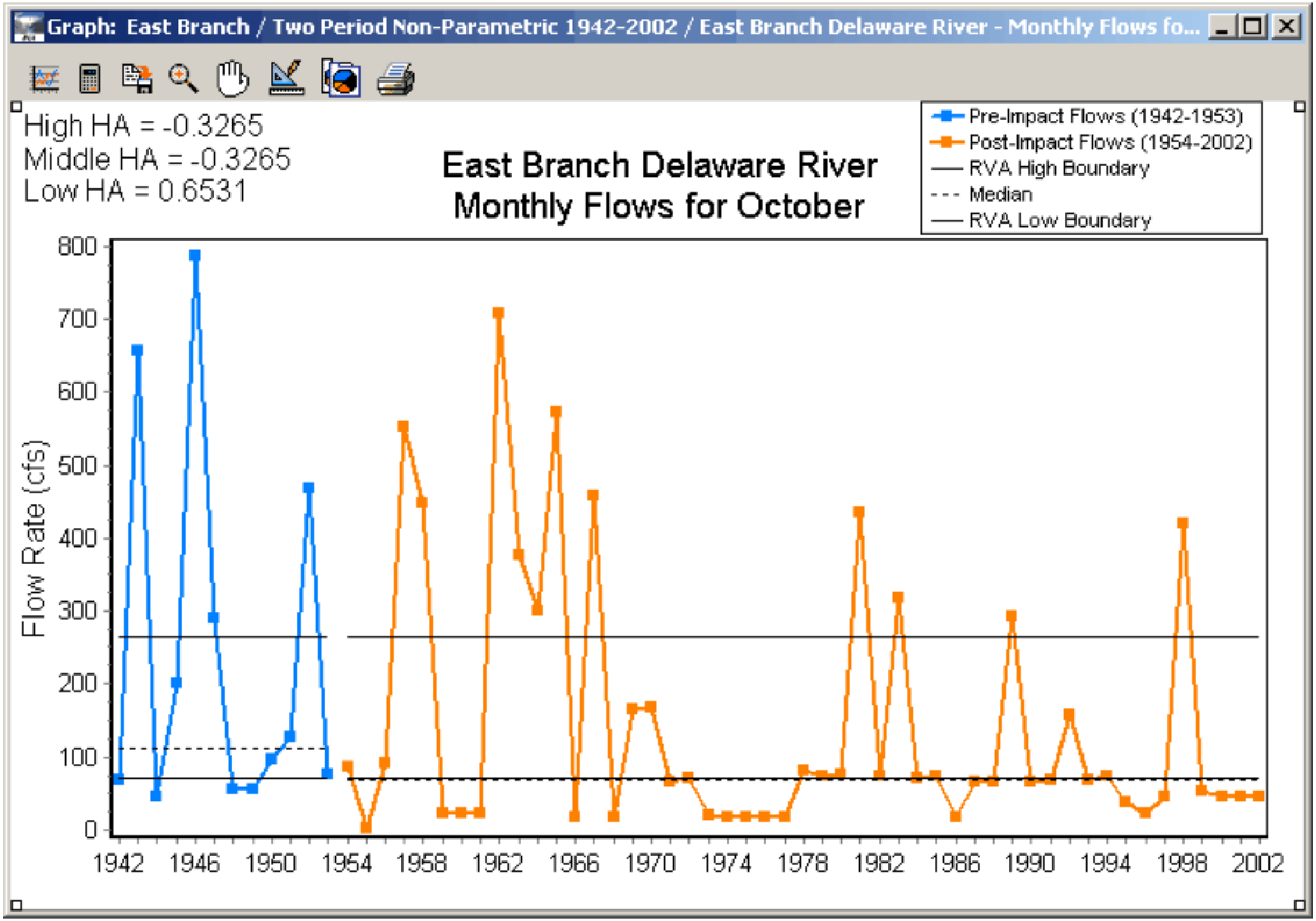
Evaluation Metric	Description	Units
Ecodeficit/Ecopsurplus	Flow Duration Curve	Dimensionless
IHA - Hydrological Alteration Factor	Flow Duration Curve	Dimensionless
IHA - Number of Mis-hits	Flow Duration Curve	Dimensionless
$Q_{Bankfull}$	Channel forming flows, flooding	CFS
Critical shear stress	Streambed mobility/stability	lb-force/ft^2
Evapotranspiration	Ecohydrology	mm day^{-1}
Laten heat flux	Ecohydrology	MJ m^{-2} day^{-1}
Carbon Sequestration	Ecohydrology	t C acre^{-1} yr^{-1}

Other opportunities for quantification of benefits

- Route LSPC peak flows or full hydrograph through an existing HEC-RAS model for the area.
  - **Identify floodplain inundation**
  - **Changes to stream power**



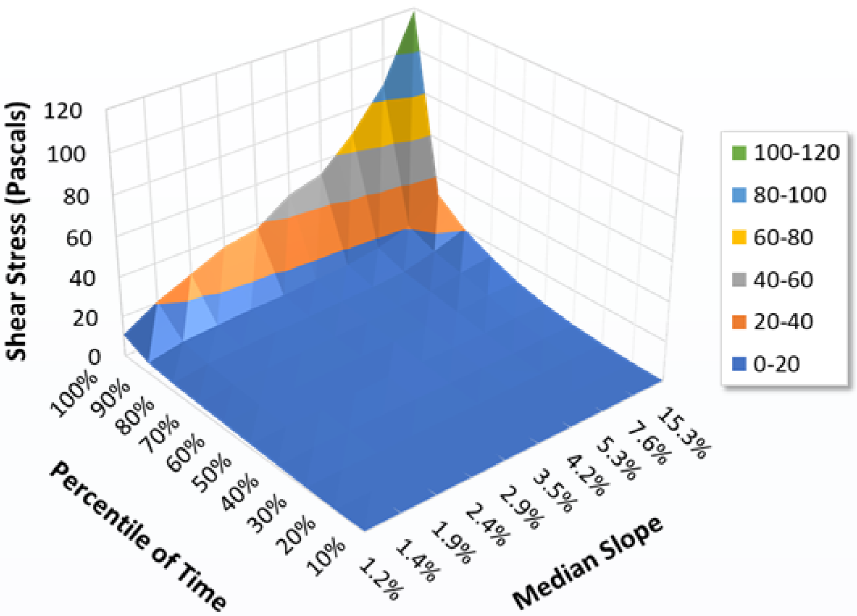
Velcome. Start by opening either a Hydro Data File or a Project

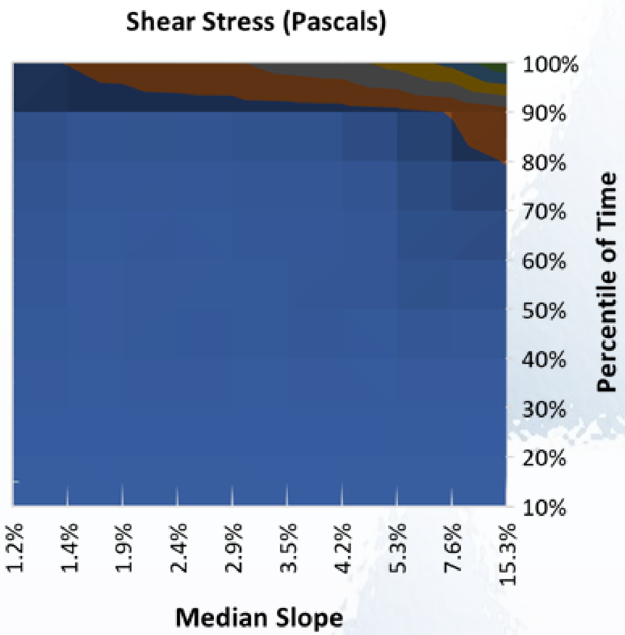


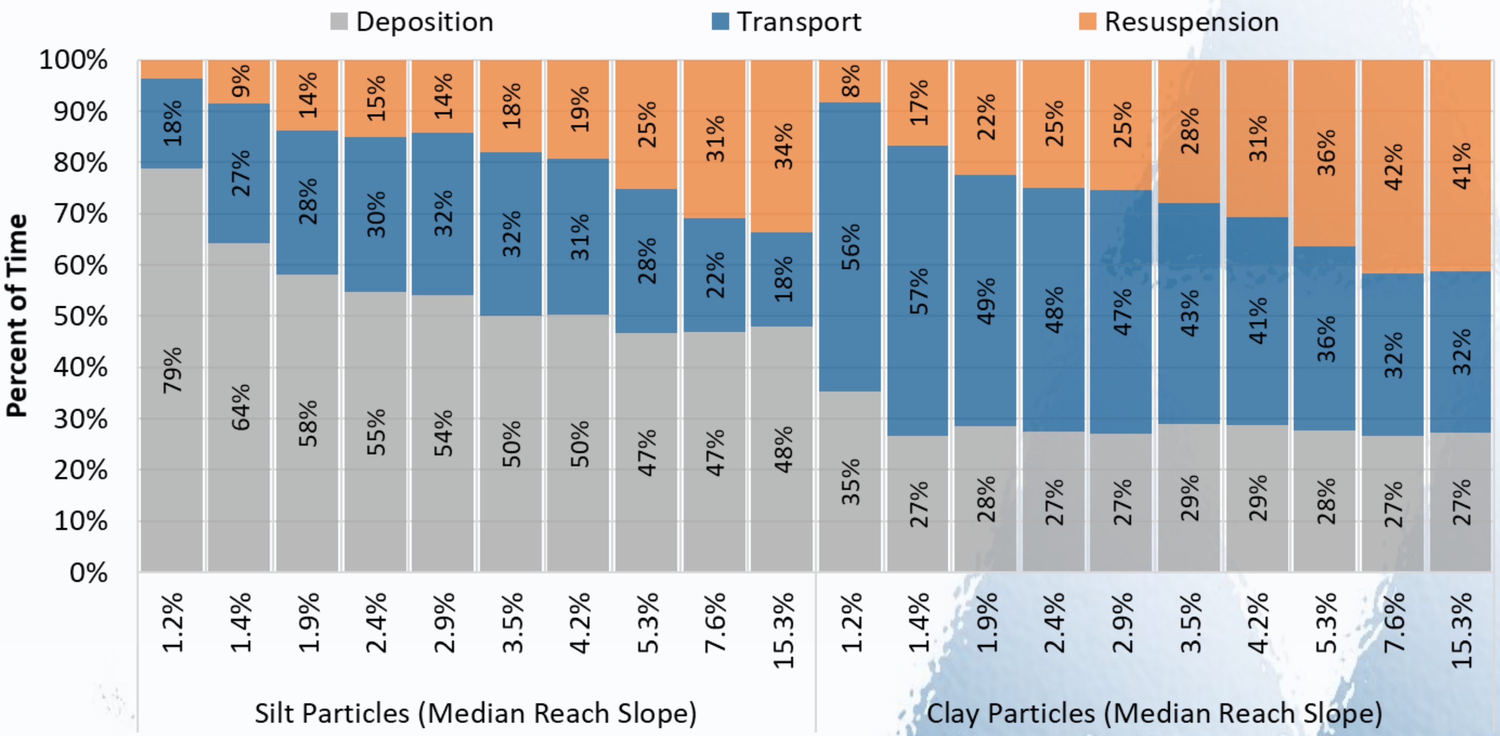
Graph: East Branch / Two Period Non-Parametric 1942-2002 / East Branch Delaware River - Monthly Flows fo...

High HA = -0.3265
Middle HA = -0.3265
Low HA = 0.6531

Instream Shear Stress







Quantifying ecohydrology benefits

- Carbon sequestration
- Heat exchange

Storrs, CT

Alexandria, VA

Some work has been done on carbon footprint of green infrastructure (Moore and Hunt, 2013)

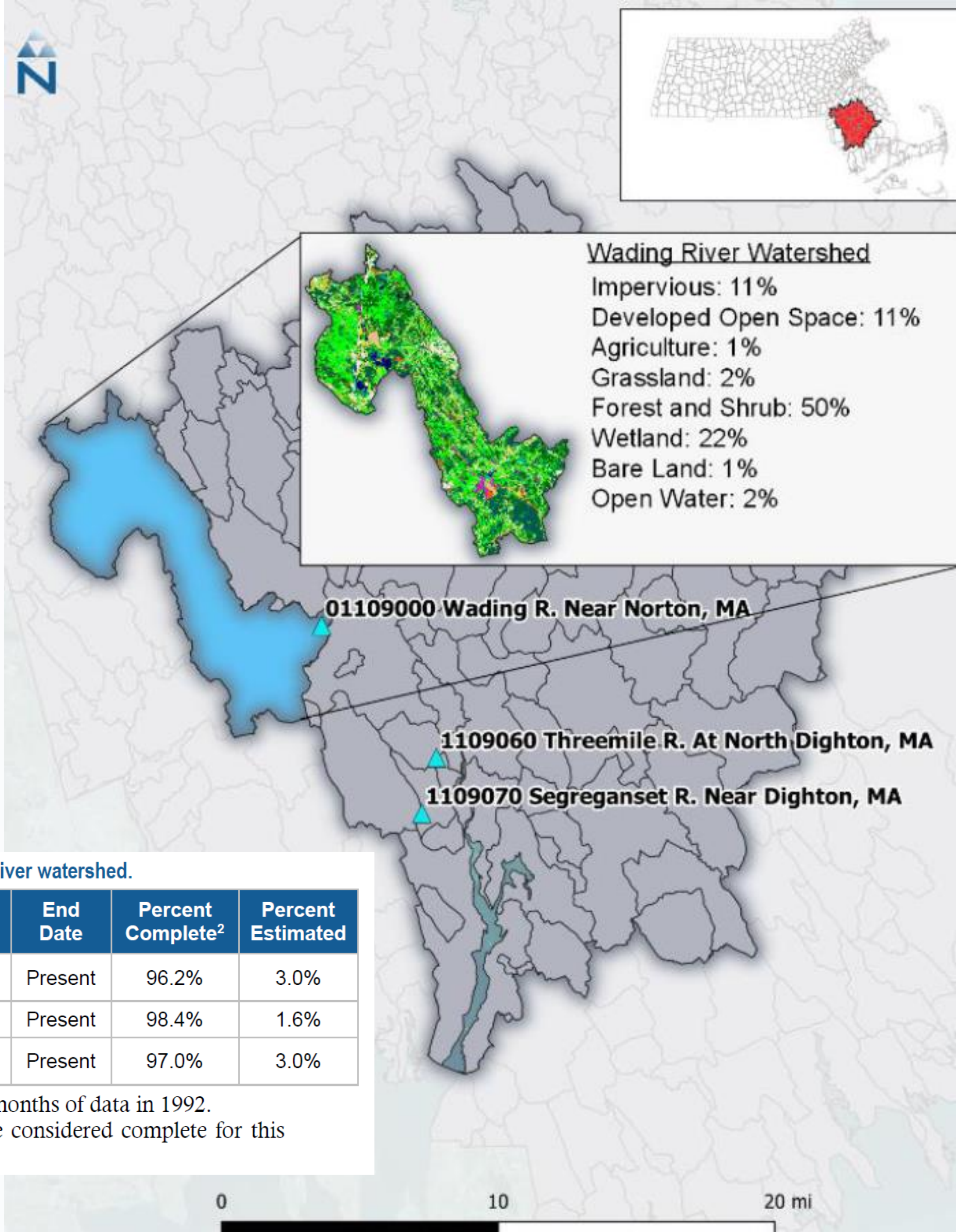
FDC Phase 1 Project Outcomes

- Updated Models
  - LSPC/HSPF model for selected subwatershed
  - Opti-Tool with groundwater recharge and FDC optimization options
- Final Report
  - Phase 1 outcome
  - Phase 2 linkage
- Outreach Materials
  - Factsheets
  - Graphics, summary tables
  - Key findings
- Webinar
  - Present phase 1 study results
  - Technical transfer to SNEP Technical Assistance Network (STAN)

Task 5. Methodology

- Data/Information Collection
  - Spatial data (landuse, impervious cover, soil, elevation, streams)
  - Temporal data (precipitation, temperature, stream flow, etc.)
  - Past, current, and future climate data (1980 to 2019)
- Literature Review
  - Critical flow regimes (flow metrics)
- Three Sub-watersheds Selection
  - 1st or 2nd or 3rd order stream drainage
  - <10%, 15%-25%, >30% impervious cover
- Modeling Approach
  - Watershed model (HSPF/LSPC)
  - Stormwater GI SCM model (Opti-Tool/SUSTAIN)
  - Model refinements and linkage
  - Stormwater/hydrologic management optimization approach

Task 5. Potential Study Area



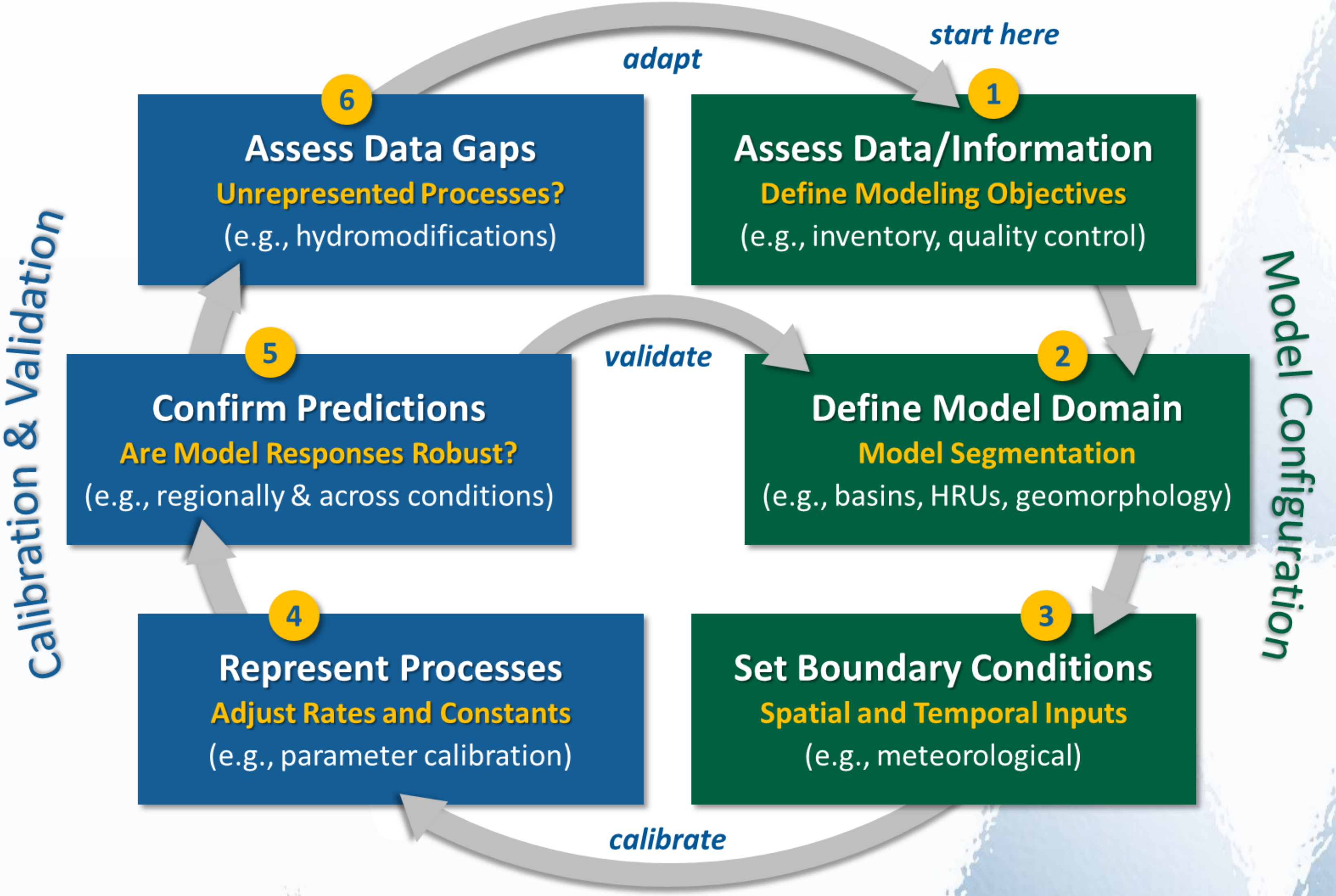
Wading River Watershed
Impervious: 11%
Developed Open Space: 11%
Agriculture: 1%
Grassland: 2%
Forest and Shrub: 50%
Wetland: 22%
Bare Land: 1%
Open Water: 2%

Table 1. Summary of active, long-term USGS gages located in the Taunton River watershed.

Location	USGS-ID	Drainage Area (mi^2)	Start Date	End Date	Percent Complete[2]	Percent Estimated
Segreganset River near Dighton, MA[1]	01109070	10.6	7/1/1966	Present	96.2%	3.0%
Wading River near Norton, MA	01109000	43.3	6/1/1925	Present	98.4%	1.6%
Threemile River at North Dighton, MA	01109060	84.3	7/1/1966	Present	97.0%	3.0%

1. The Segreganset River location is missing approximately five months of data in 1992.
2. Records flagged as provisional ("P") and revised ("A:R") are considered complete for this summary.

Conceptual Representation of the Model Development Cycle



1 **Assess Data/Information**
Define Modeling Objectives
(e.g., inventory, quality control)

2 **Define Model Domain**
Model Segmentation
(e.g., basins, HRUs, geomorphology)

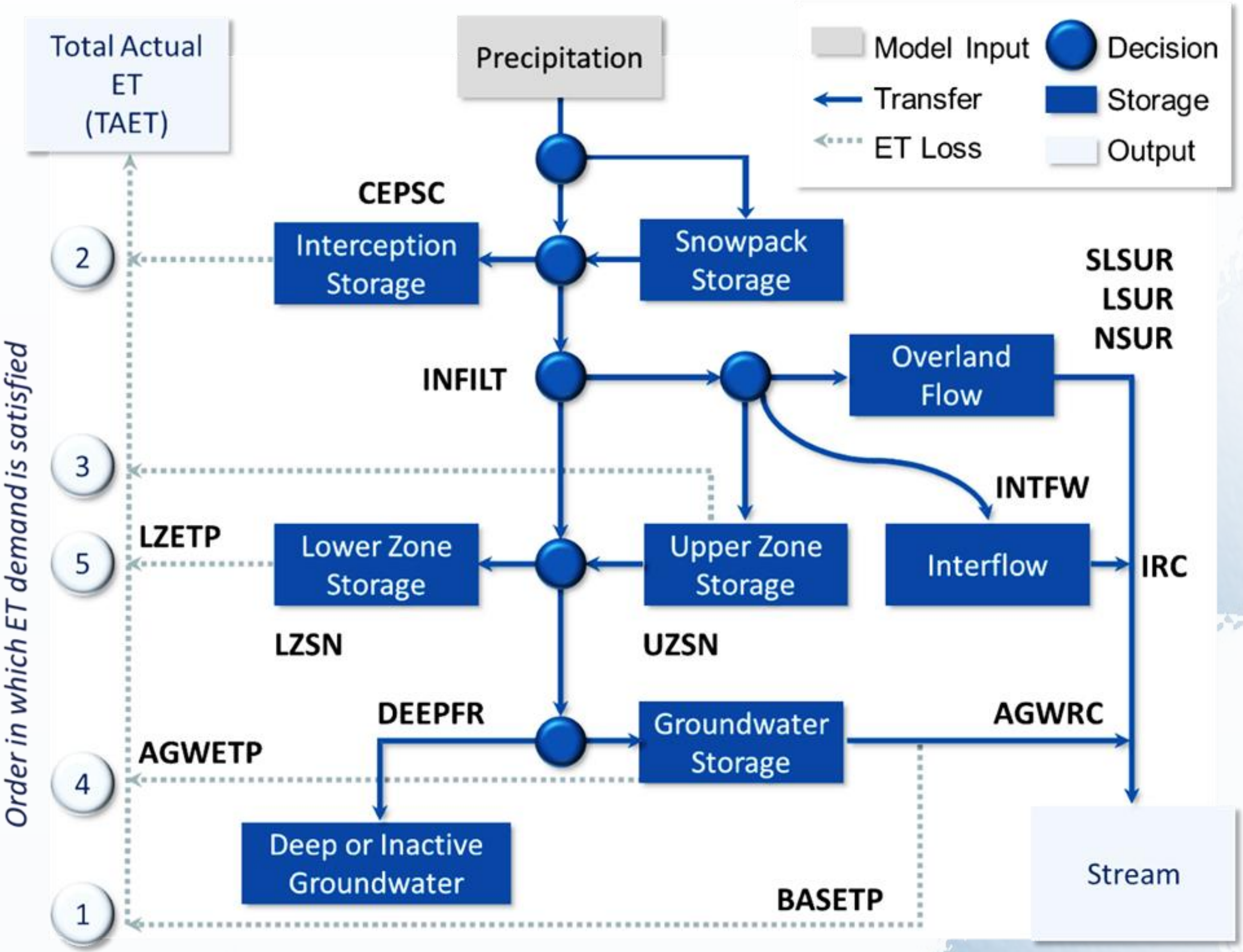
3 **Set Boundary Conditions**
Spatial and Temporal Inputs
(e.g., meteorological)

4 **Represent Processes**
Adjust Rates and Constants
(e.g., parameter calibration)

5 **Confirm Predictions**
Are Model Responses Robust?
(e.g., regionally & across conditions)

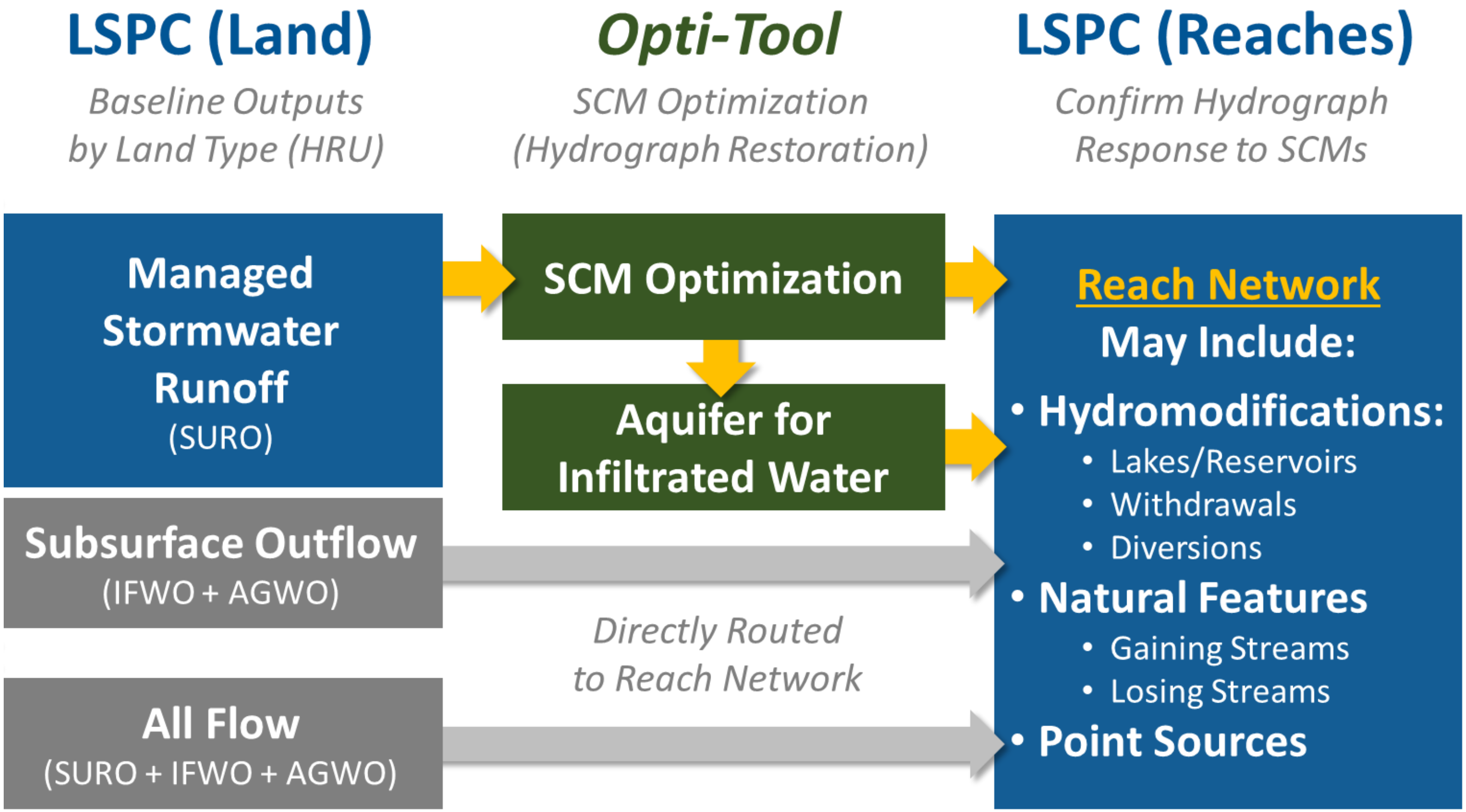
6 **Assess Data Gaps**
Unrepresented Processes?
(e.g., hydromodifications)

Hydrology Model Schematic for LSPC



Source: Stanford Watershed Model

LSPC and Opti-Tool Linkage



LSPC (Land)

Baseline Outputs by Land Type (HRU)

Opti-Tool

SCM Optimization (Hydrograph Restoration)

LSPC (Reaches)

Confirm Hydrograph Response to SCMs

Managed Stormwater Runoff
(SURO)

SCM Optimization

Aquifer for Infiltrated Water

Subsurface Outflow
(IFWO + AGWO)

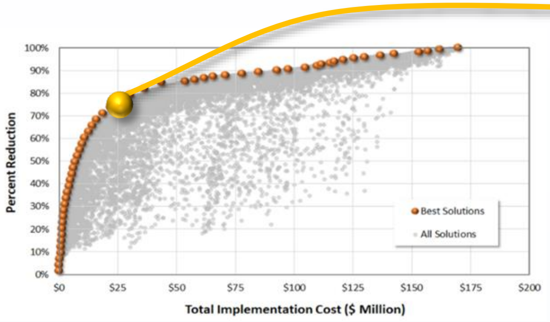
All Flow
(SURO + IFWO + AGWO)

Directly Routed to Reach Network

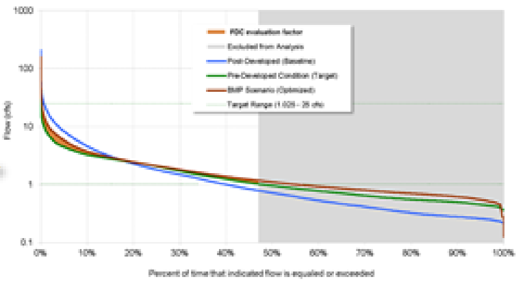
Reach Network May Include:

- **Hydromodifications:**
  - Lakes/Reservoirs
  - Withdrawals
  - Diversions
- **Natural Features**
  - Gaining Streams
  - Losing Streams
- **Point Sources**

Simulation Sequence



Each point on the curve has a unique FDC



FDC Simulation
(Hydrograph Restoration)

Step 1:

Opti-Tool

SCM Optimization
(Stormwater Infiltration)

Step 2:

Long-term Continuous Simulation
e.g., [25-years]

Step 3:

Validation

Identify Shorter Representative Time Period(s)
e.g., [Wet Year]

LSPC: SURO

Optimize SCMs: Derive Tier 1 CE-Curves

SUSTAIN

Cost-Optimal Sizes for SCM Network

Generate FDC and Compute Hydrograph IHA Metrics

FDC Validation

Evaluate FDC curves at a downstream assessment point to demonstrate that SCMs achieve long-term instream management objectives

Optimally sized SCM capacities from Tier 1 are locked down for the full FDC Simulation Run.

IFWO +AGWO + Infiltrated Stormwater are added back in here

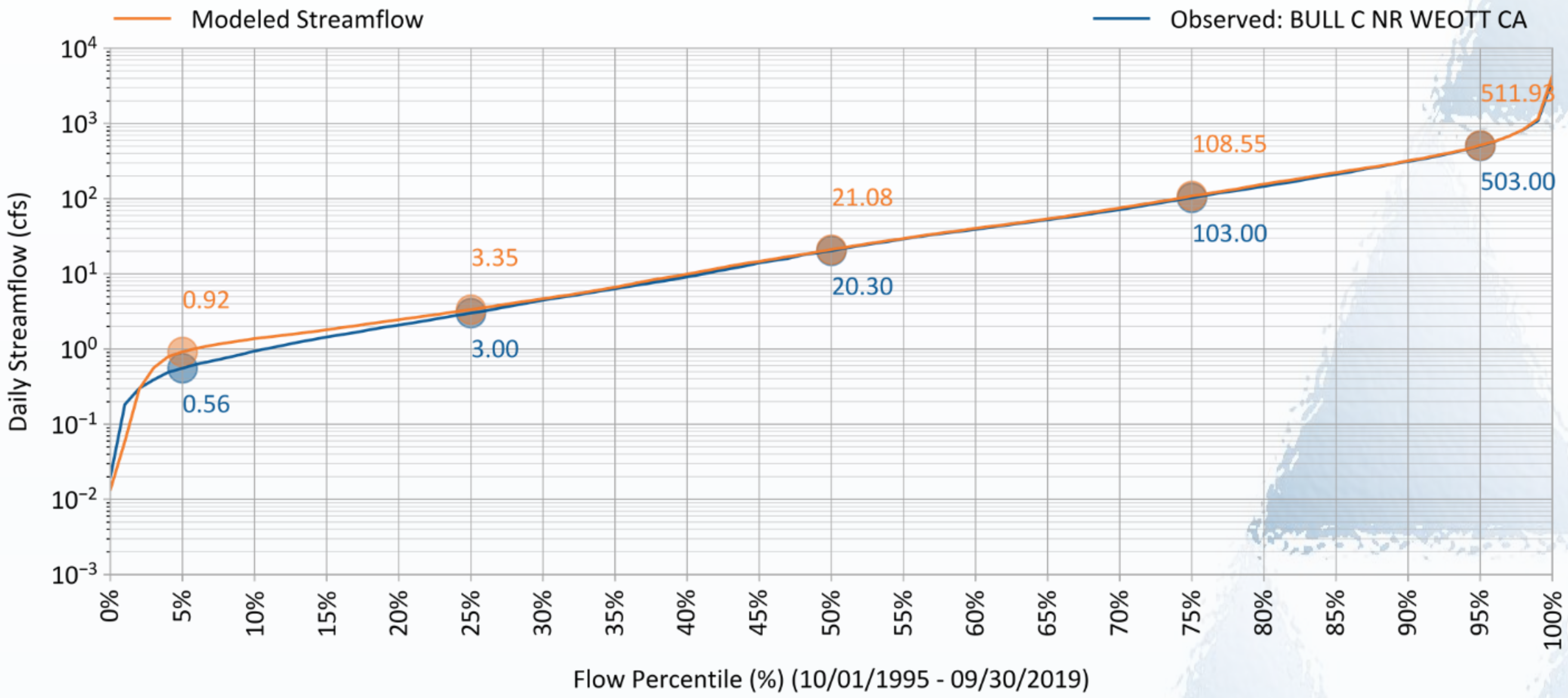
Task 6. Model Development

- Watershed Characterization
  - **Evaluate historical information to assess changes over time**
  - **Develop hydrologic response units (HRUs)**
- Model Refinements
  - **Convert HSPF to LSPC**
    - Adopt hydrology parameters from HSPF model
    - Adopt water quality parameters from Opti-Tool HRU-SWMM model
  - **Update Opti-Tool**
    - GI SCM groundwater recharge linkage to local surface water
    - FDC evaluation factors for GI SCM optimization
- Model Calibration/Validation
  - **Verify the model prediction at the instream gage using the long-term observed continuous flow data**

Performance Metrics 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						

Example Calibration: Modeled vs. Observed FDC Comparison



Task 6. Model Results

- FDC for Baseline (3 Sub-watersheds)
  - Pre-development
  - Historic development (if available)
  - Existing development conditions
- FDC for Future Climatic Condition (3 Sub-watersheds)
  - Pre-development
  - Historic development (if available)
  - Existing development conditions
- Quantify Impacts of IC Conversion
  - Critical streamflow regimes / metrics (e.g., flooding, channel scouring, baseflow depletion, etc.)
  - Stormwater runoff pollutant load export
  - Groundwater recharge
  - Evapotranspiration
  - Carbon sequestration and heat loss exchange

Task 7. Optimization Analyses

- Potential GI SCM Opportunities
  - **GIS based screening**
  - **Identify potential footprints and treated impervious areas**
- Management Scenarios
  - **Optimize GI SCM opportunities**
    - Evaluation factor: FDC critical regimes
    - Pre-development, historic development, and existing development conditions
    - Baseline and future climatic conditions
    - Three selected sub-watersheds
- Results
  - **FDC for each management scenario**
  - **Quantify benefits for critical streamflow regime/metrics**
  - **Evaluate water quality long-term cumulative benefits**
  - **Assess benefits for carbon sequestration and heat loss exchange**

Group Discussion

- Feedback
- Action Items