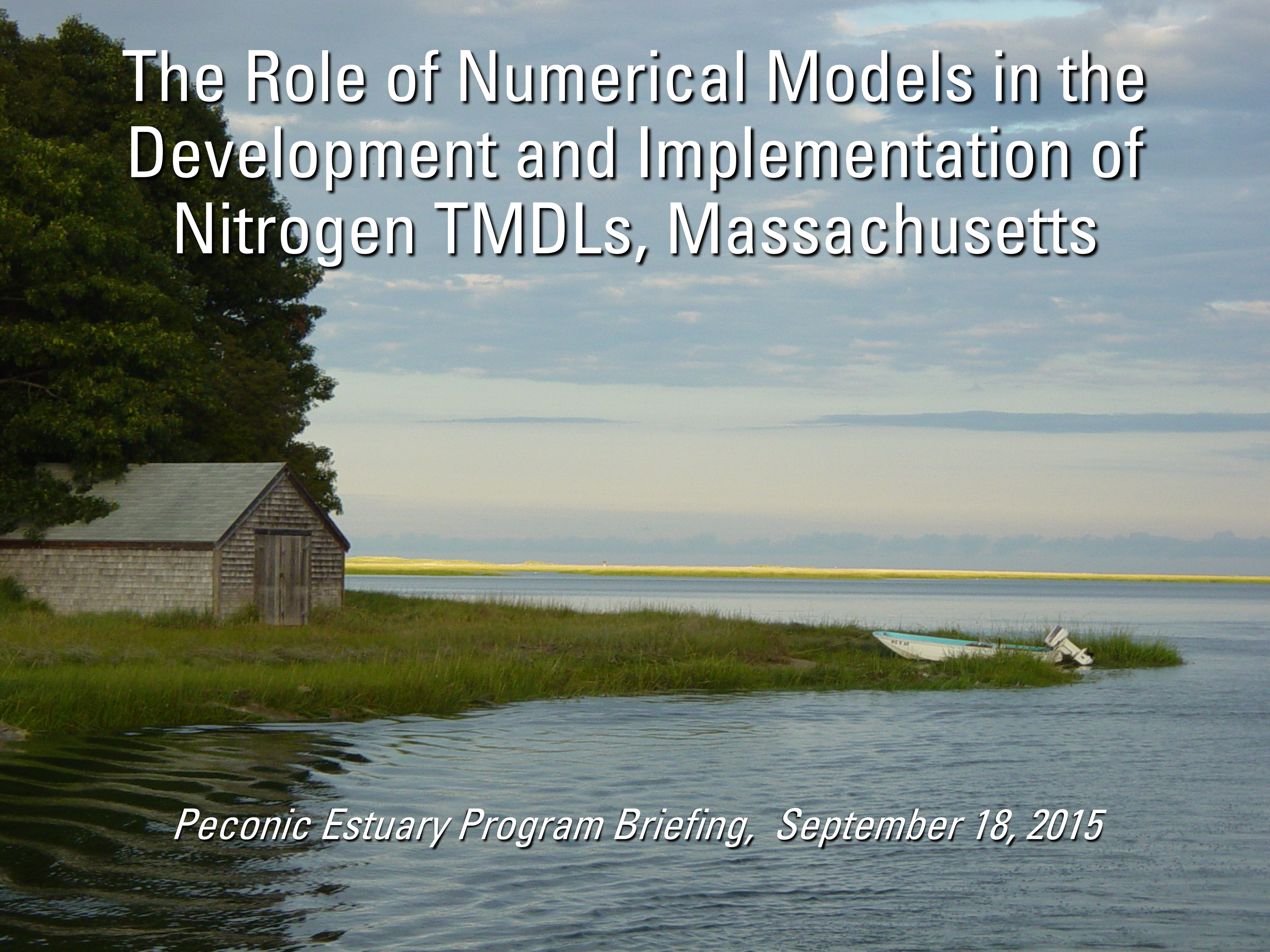
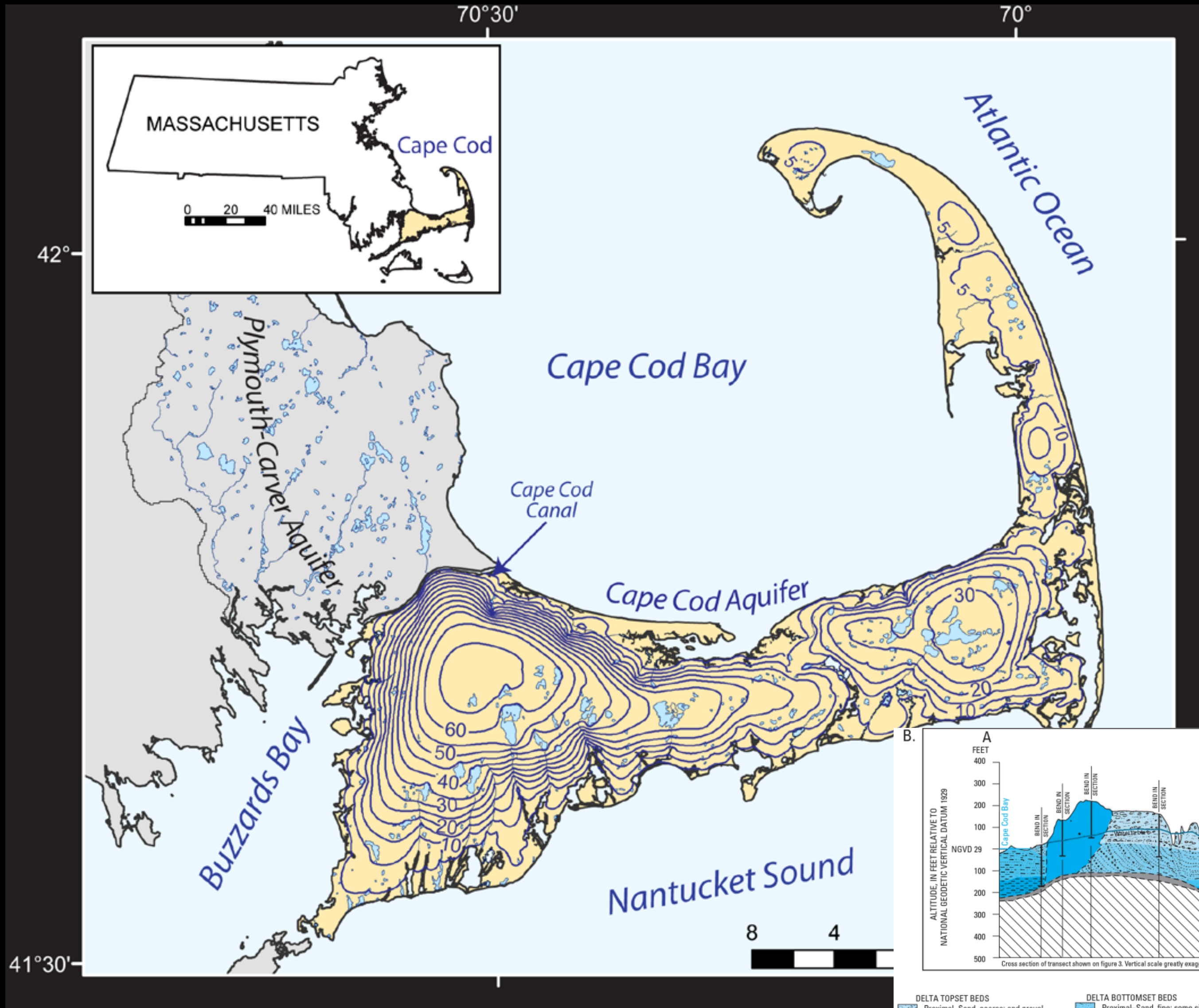
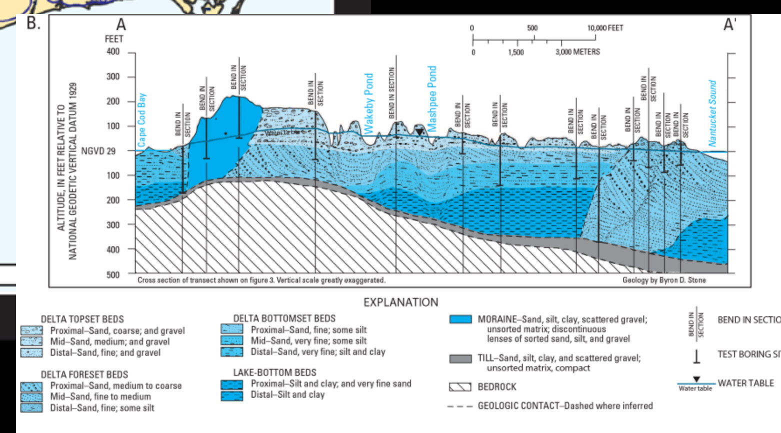
The Role of Numerical Models in the Development and Implementation of Nitrogen TMDLs, Massachusetts



Peconic Estuary Program Briefing, September 18, 2015

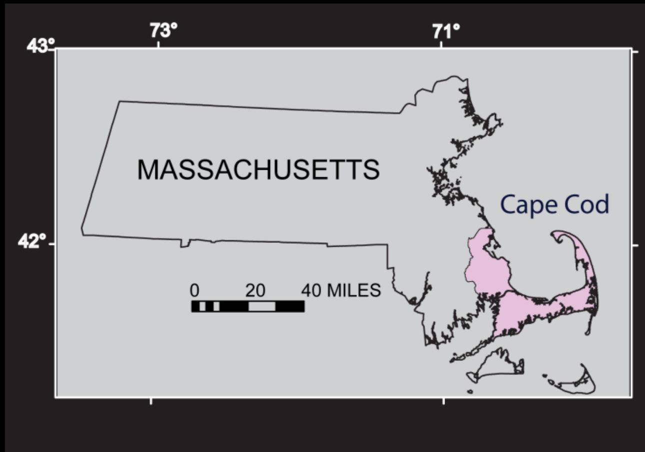
Location and Hydrography of Cape Cod, Massachusetts



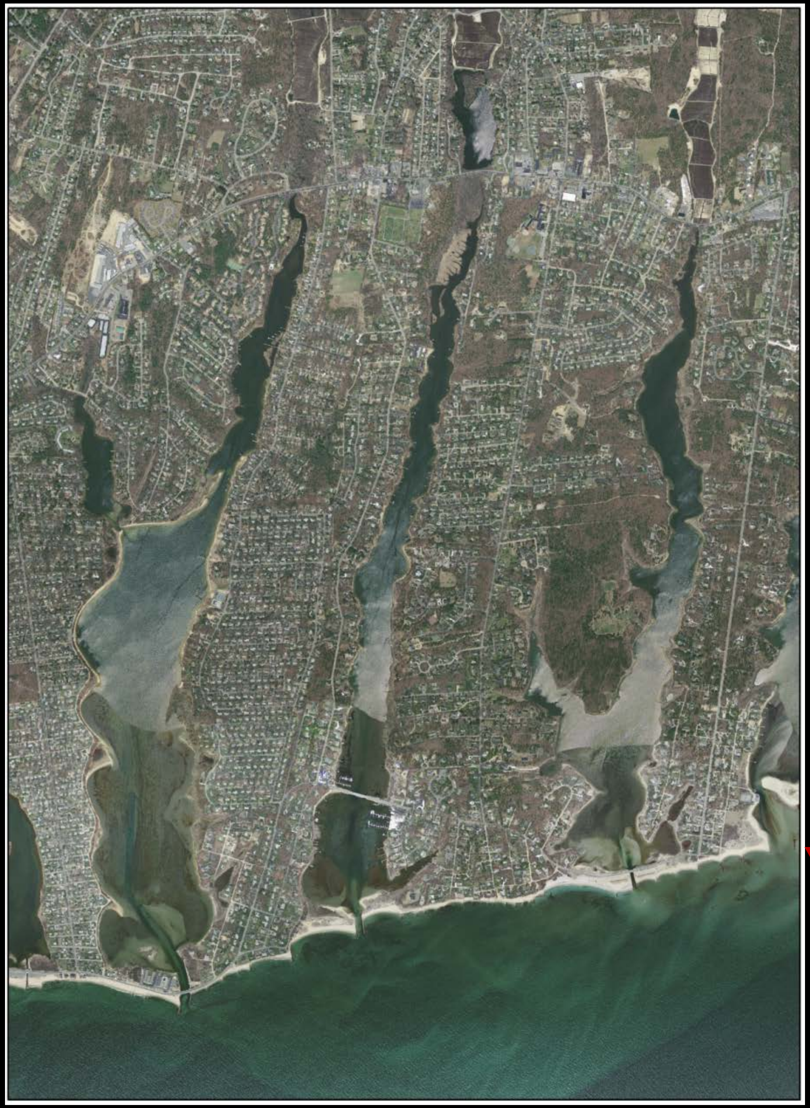


Massachusetts Estuaries and Coastal Waters

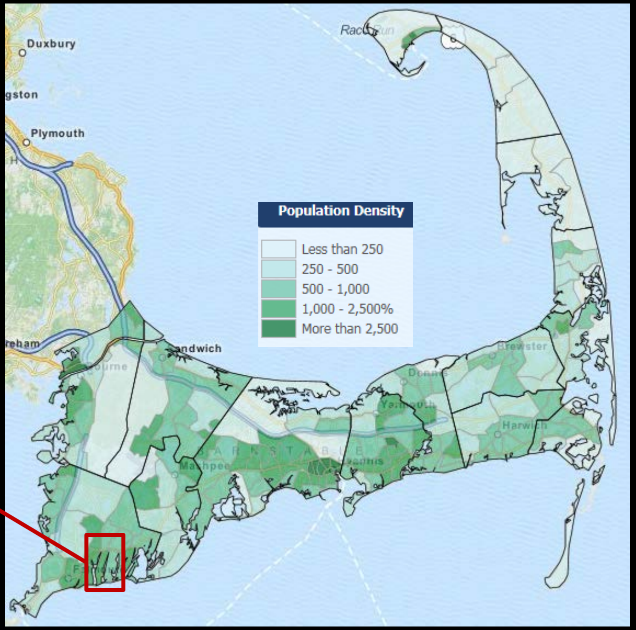
- Coastal estuaries are important recreational and economic resources
- Eel grass habitats support shellfish populations and are nurseries for juvenile fish
- Healthy estuaries are important for tourism and commercial fishing



Wastewater on Cape Cod



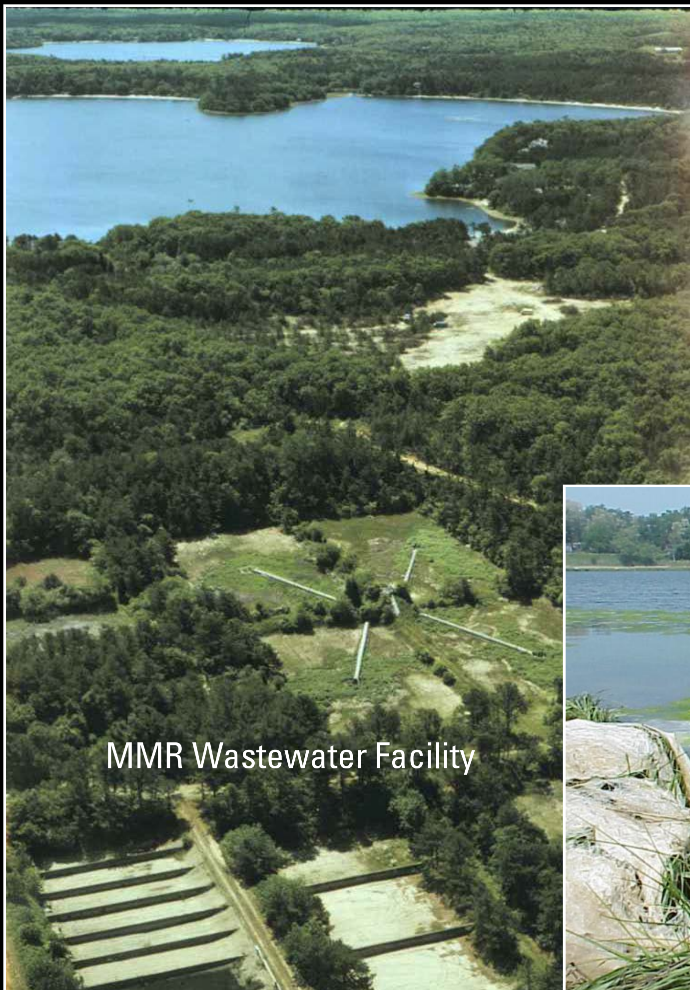
- Population :(2000) 222,230
- Housing Units: 160,281
- About 85 percent have on-site disposal
- On-site systems produce an average of 8 to 10 pounds of nitrogen annually



Source: http://www.capecodcommission.org/resources/

Massachusetts Estuaries and Coastal Waters

- Coastal waters are susceptible to eutrophication caused by excess nitrogen derived from terrestrial sources
- Effects of eutrophication include poor water quality and clarity, algal blooms, and loss of eel grass habitat
- Terrestrial nitrogen primarily from residential and municipal wastewater

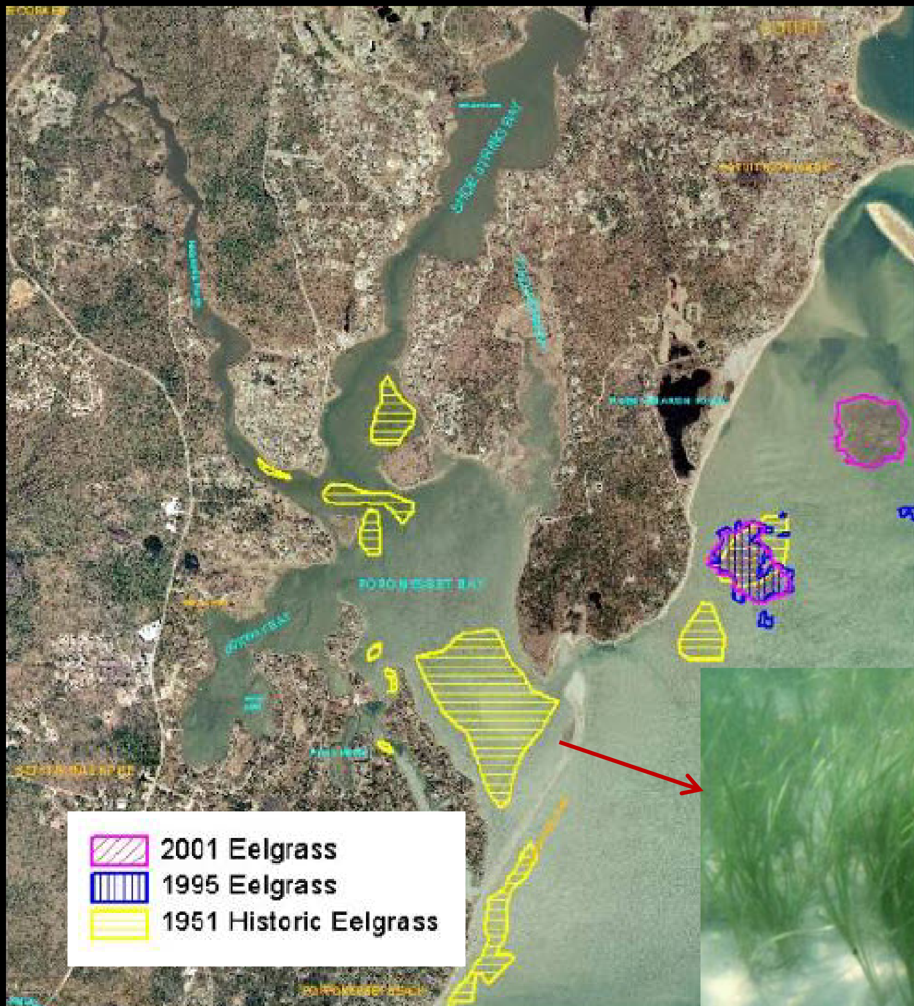


MMR Wastewater Facility

Algal Bloom, Salt Pond

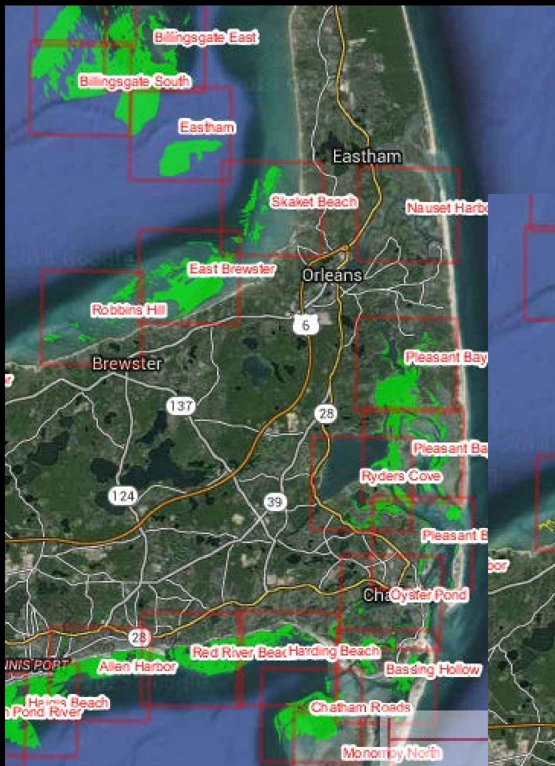
Wastewater on Cape Cod

- Population (2000): 222,230, Housing Units: 160,281
- About 85 percent have on-site disposal, 15 percent are sewered
- On-site systems produce an average of 8 to 10 pounds of nitrogen annually

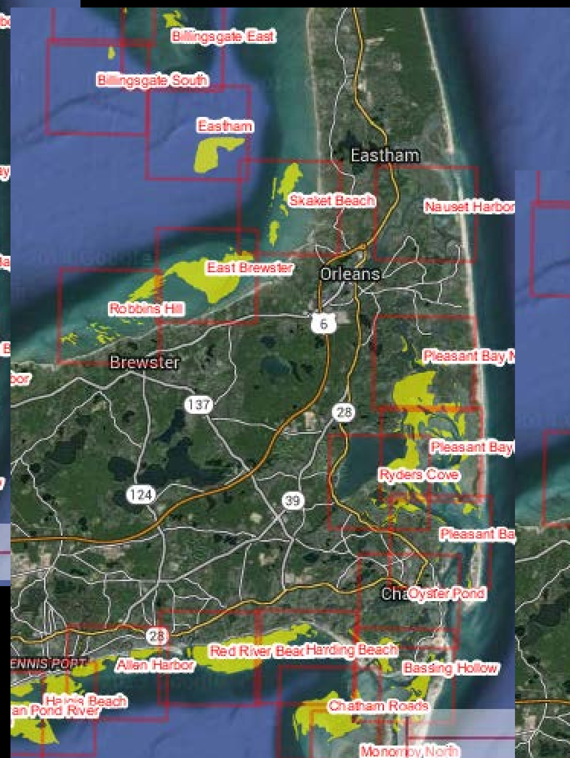


MassDEP Eel Grass Mapping Project

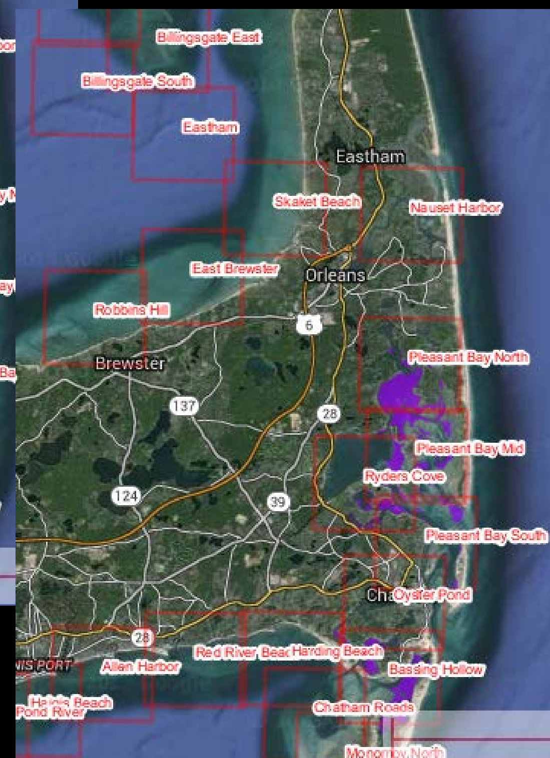
- Mapping extent of Zostera marina since 1994
- Assays in 1995, 2001, 2006, and 2010-13



1995



2001

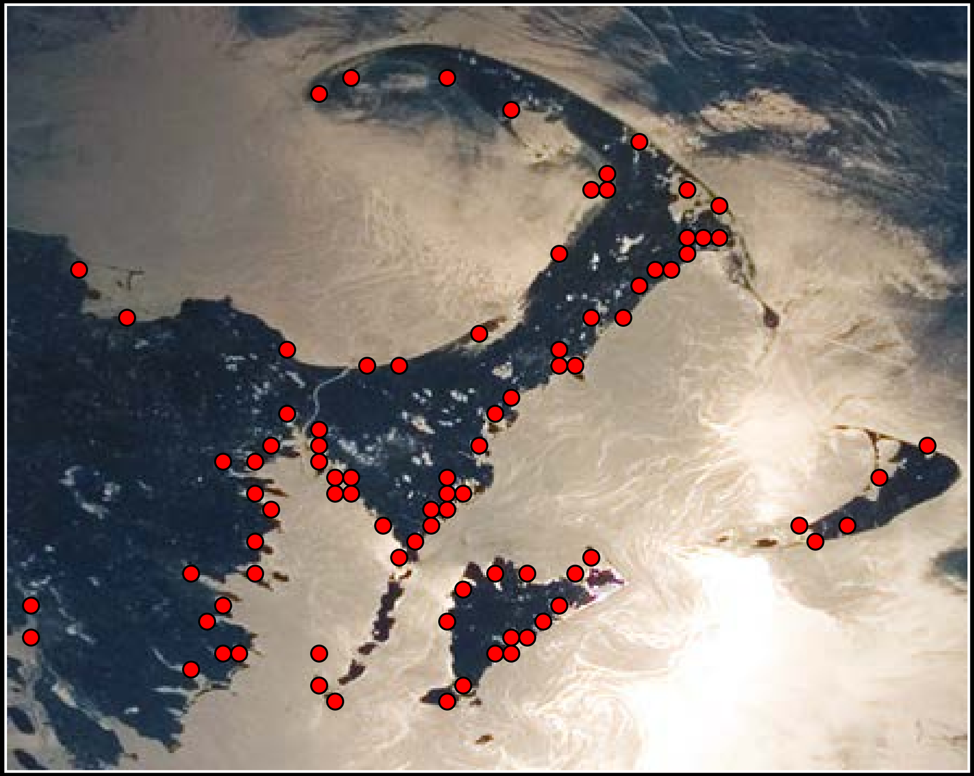


2006

http://www.mass.gov/eea/agencies/massdep/water/watersheds/eelgrass-mapping-project.html

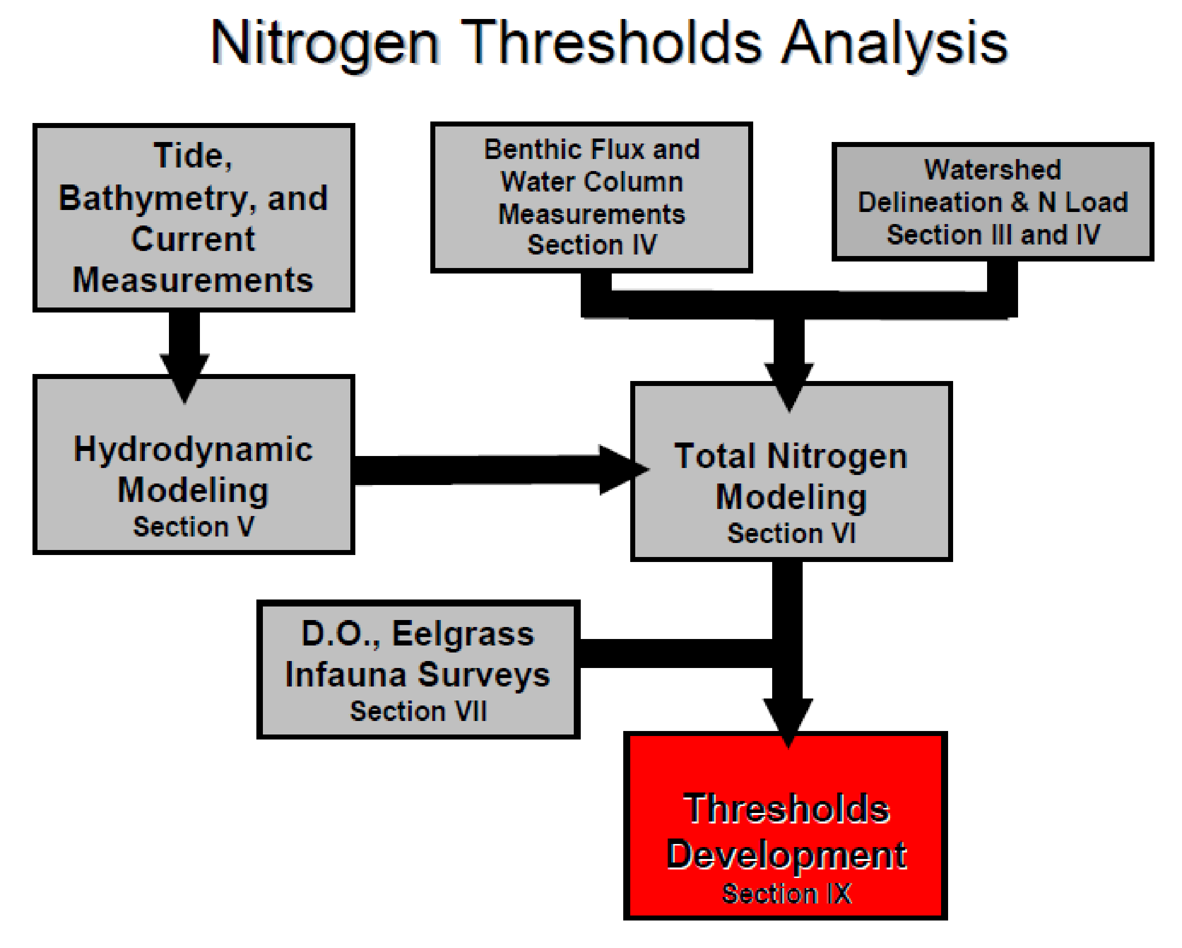
MassDEP Massachusetts Estuaries Project

- Started in 2001 to address habitat loss in coastal waters, southeastern Massachusetts
- Data collection to evaluate watershed characteristics in 89 estuarine systems: land use, hydrology, tidal dynamics, water quality, and ecology
- Develop linked watershed-hydrodynamic models to establish TMDL's for nitrogen



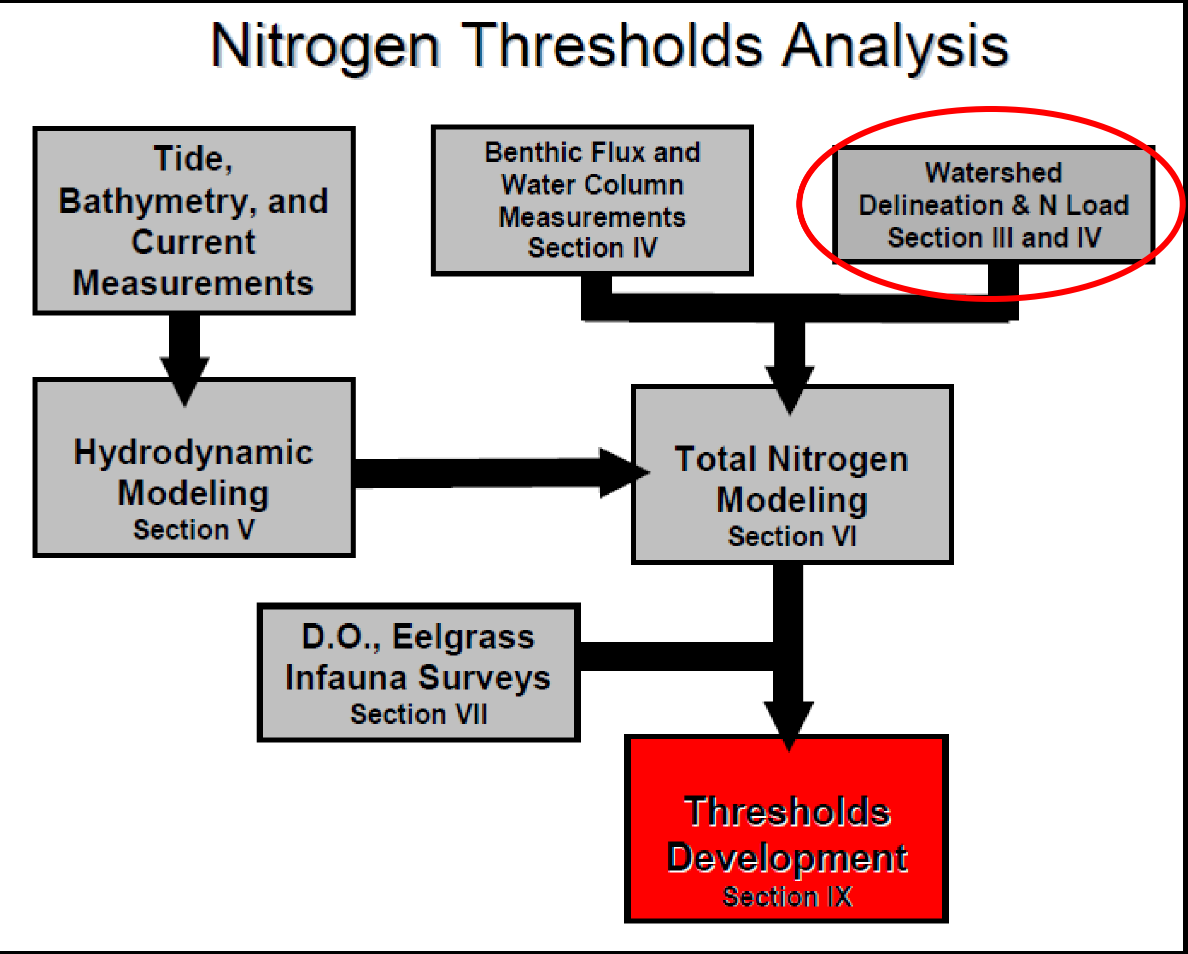
- Develop predictive tools to assist in the evaluation of nitrogen-management scenarios to meet TMDL's
- Partners include MassDEP, SMAST, USGS, and the private sector

Overview of MEP



- Integrates data collection and modeling
- Data collection:
  - Hydrodynamic
  - Water and sediment chemistry
  - Ecologic data
- Modeling
  - Groundwater
  - Hydrodynamic
  - Water quality

Overview of MEP: Terrestrial Nitrogen Loads

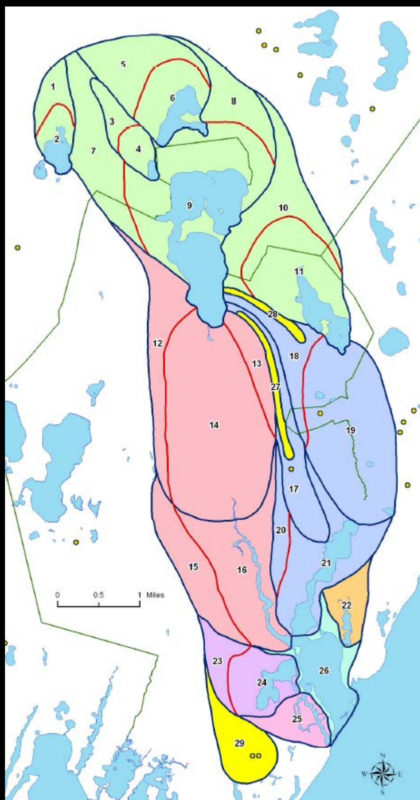


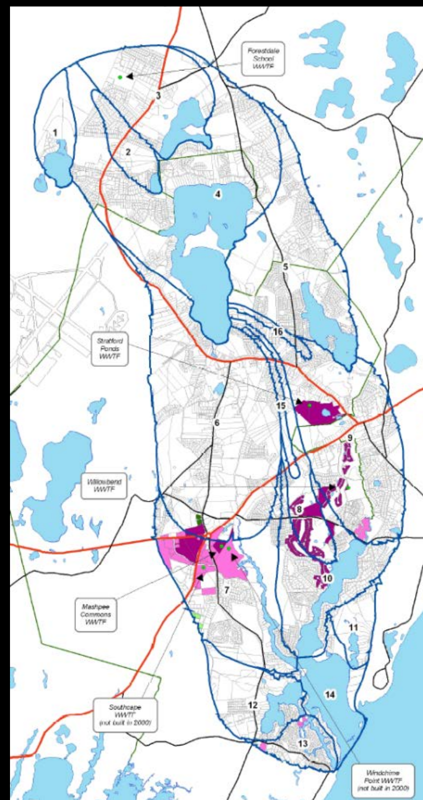
- Integrates groundwater models, GIS, and parcel-scale data

Estimating Terrestrial Nitrogen Loads

- Groundwater-flow models used to delineate watersheds for over 500 receptors: Estuaries, Streams, Ponds, and Wells
- Parcel-scale nitrogen inputs estimated from water use
- Parcels mapped to watersheds and nitrogen loads summed in a GIS
- Separate loads estimated for travel times greater than and less than or equal to 10 years
- Surface-water attenuation represented as adjusted source terms

Estimating N Loads: Popponesset Bay, Mashpee

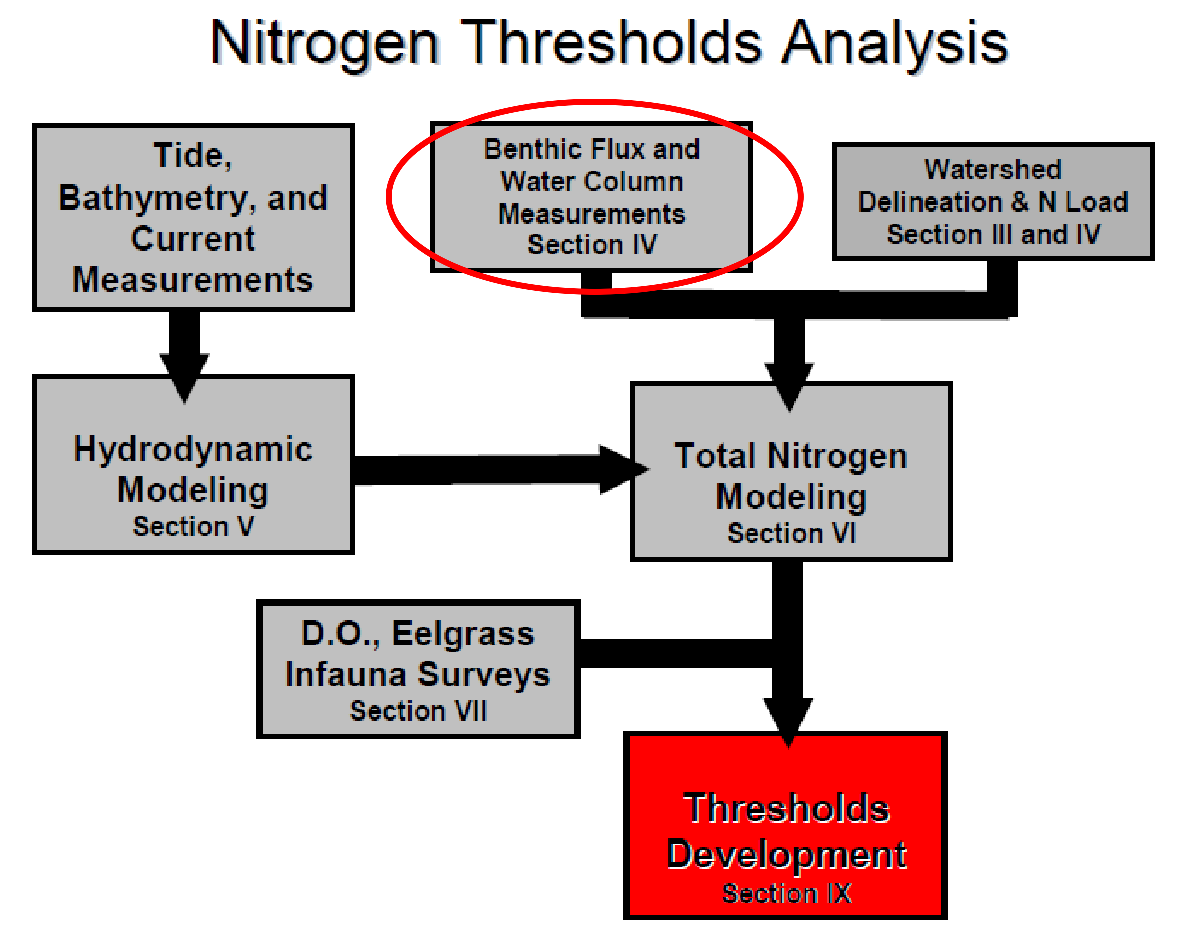




- Modeled watersheds modified for use in estimating N loads
- Multiple sources: on-site septic, treatment facilities, lawn fertilizer, impervious surfaces, surface waters, atmospheric

*All values in kilograms/year		*Popponesset Bay Subwatershed N Loads by Input:*							% of Pond Outflow	Present N Loads			Buildout N Loads		
Name	Watershed ID#	Wastewater	From WWTF	Lawn Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout		UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Popponesset Bay System	11, 12, 13, 14 + Shoestring Bay + Mashpee River	32300	227	3765	2668	7584	1971	9394		48513		31885	57804		39644
Mashpee River	6, 7 + MWP	16199	54	1458	1411	4238	1153	6643		24512		13010	31051		18796
Upper Mashpee River	6 + MWP	12692	0	1206	1016	3996	941	4566		19851	30%	8349	24314	30%	12058
Mashpee-Wakeby Pond (MWP)	1, 2, 3, 4	7828	0	676	513	3989	503	771	100%	13509	50%	5585	14176	50%	5781
Direct to MWP	4	4572	0	421	321	3212	307	117		8833			8950		
Snake Pond (SNP)	1	5	0	3	2	121	17	10	34%	148	50%	74	54	50%	27
Pimlico Pond (PIP)	2	1139	0	90	63	74	42	563	100%	1407	50%	704	1971	50%	985
Peters Pond (PEP)	3	2112	0	163	126	582	138	80	100%	3121	50%	1560	3201	50%	1601
Lower Mashpee River	7	3507	54	251	395	242	212	2077		4661		4661	6737		6737
Shoestring Bay	8, 9, 10, 15, 16 + SAP	12986	173	1978	986	1379	636	2058		18139		13012	20196		14293
Santuit River	9, 16	8853	173	1075	675	564	440	1623		11780	30%	6653	13403	30%	7500
Cotuit Well No. 5	16	329	0	33	16	0	11	66		388		388	454		454
Quaker Run	8, 15	1598	0	405	99	0	82	232		2183		2183	2415		2415
Quaker Run Wells	15	659	0	37	23	0	18	51		736		736	787		787
Santuit Pond (SAP)	5	4386	0	429	326	758	216	1112	100%	6114	50%	3057	7226	50%	3613
Ockway Bay	12	874	0	103	90	399	83	402		1549		1549	1951		1951
GW Flow to Popponesset B:	11, 13, 14	2241	0	226	180	1568	98	290		4314		4314	4604		4604
Pinquickset Cove	11	210	0	19	10	106	40	80		385		385	465		465
Popponesset Creek	13	1455	0	171	146	0	31	151		1803		1803	1954		1954
Popponesset Bay	14	576	0	36	24	1462	28	59		2126		2126	2185		2185

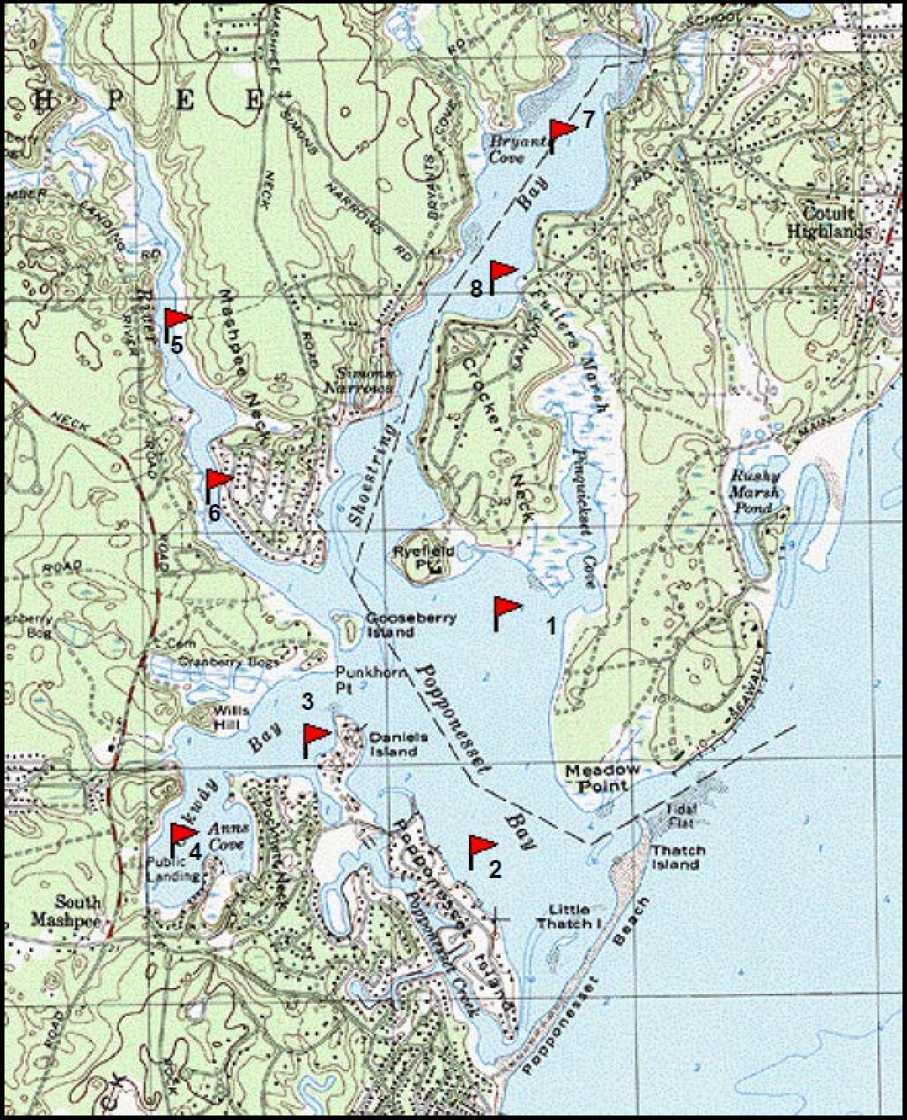
Overview of MEP: Benthic Nitrogen Loads



- Cycling of nitrogen between sediments and the water column
- More significant in low-velocity environments
- Occurs primarily in the summer
- Can account for as much as 30 to 50 percent of total N load

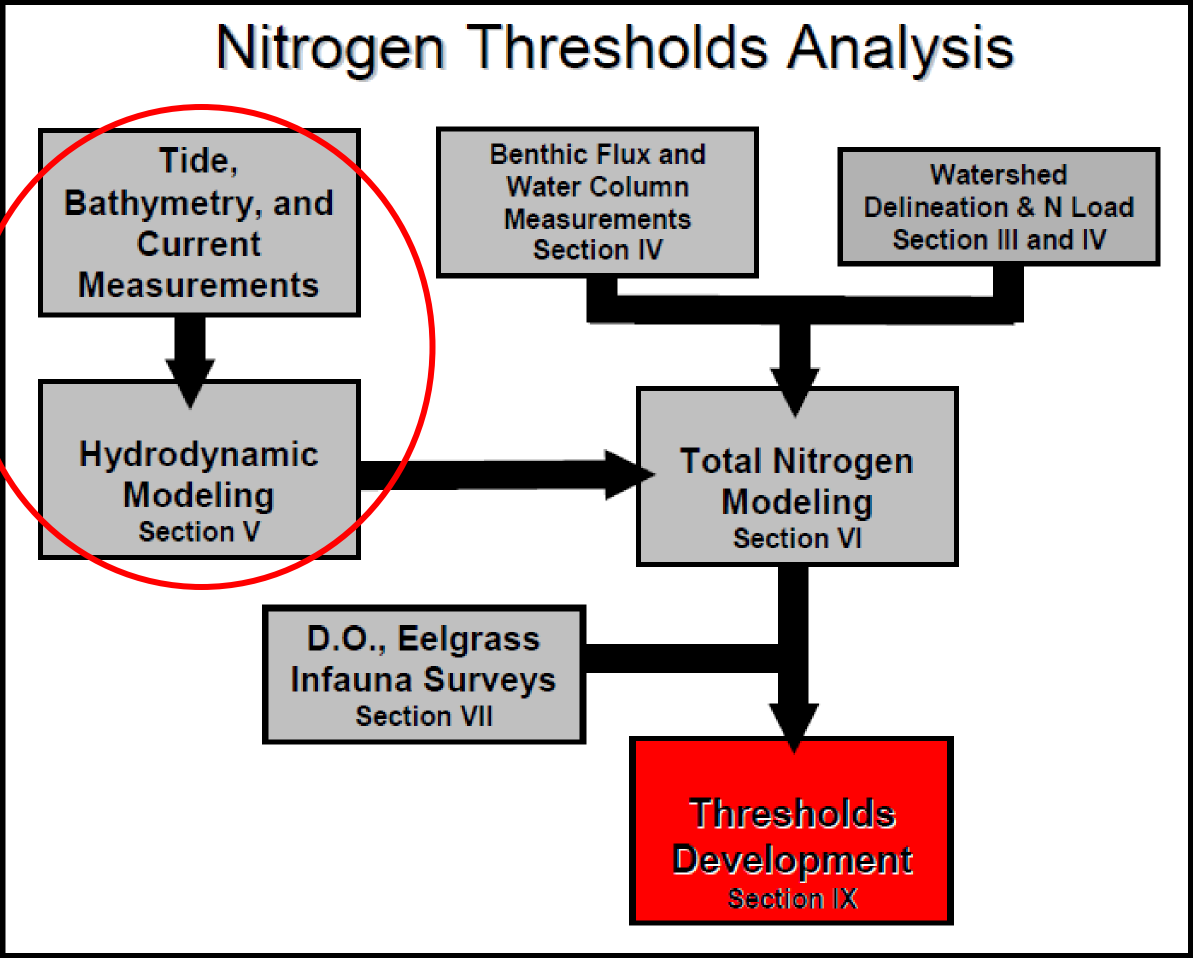
Overview of MEP: Benthic Nitrogen Loads

Sediment collection sites



- Sediment cores collected by SCUBA divers; in-situ conditions maintained
- Bottom-water samples also collected
- Cores incubated and N exchange rates estimated

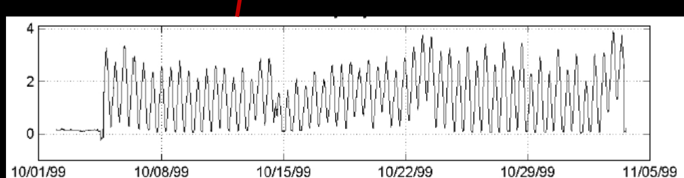
Overview of MEP: Hydrodynamic Analysis



- Data collection: Tidal gages, bathymetry, streamflow
- Data incorporated into finite-element model
- Predict velocities and flushing rates

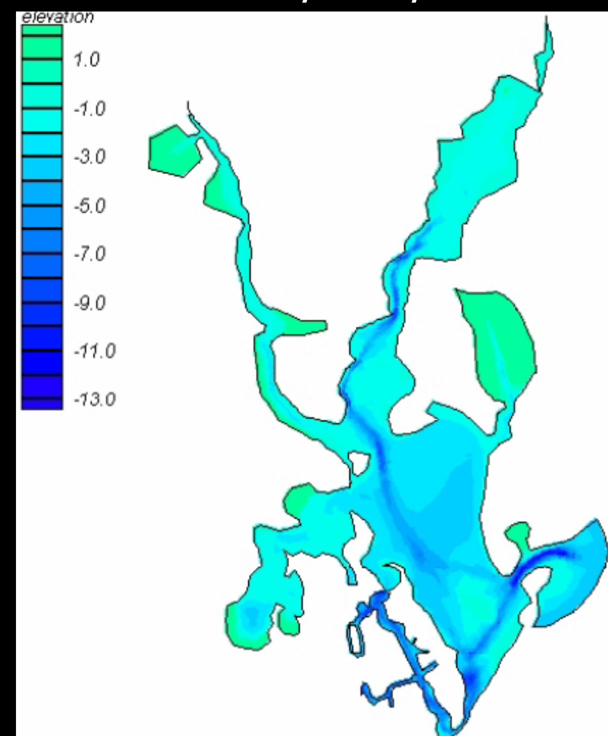
Overview of MEP: Hydrodynamic Data Collection

Tidal and streamflow sites



- Tidal fluctuations measured for at least one lunar cycle using pressure transducers
- Bathymetry measured along transects using a fathometer and GPS

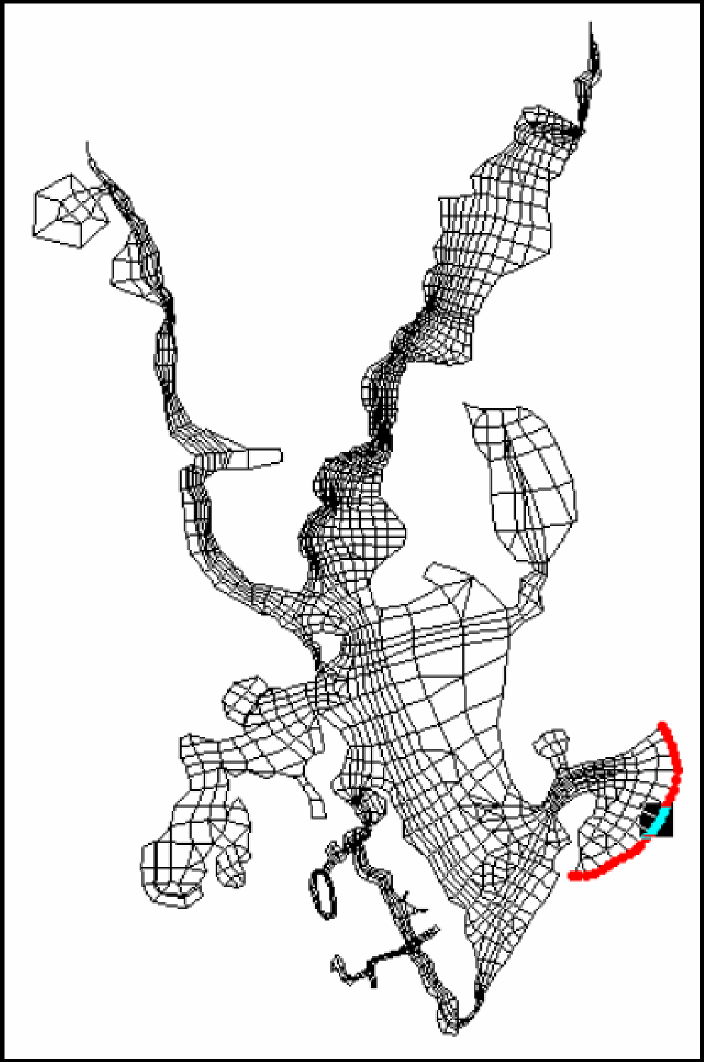
Bathymetry



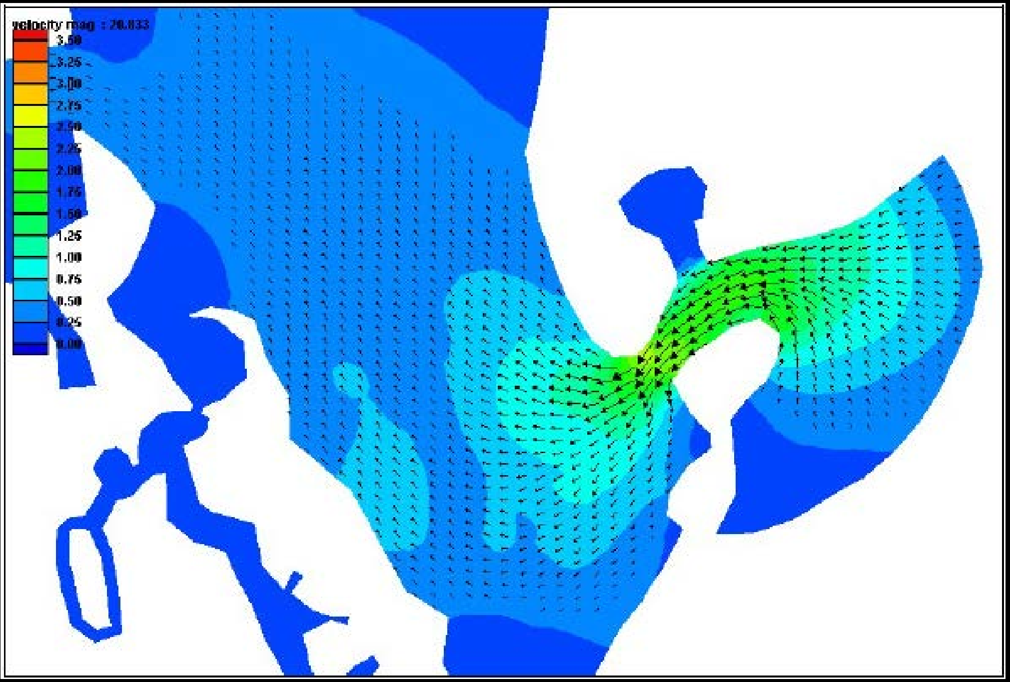
Overview of MEP: Hydrodynamic Modeling

- Finite-element model, RMA-2
- Geometry defined from bathymetry
- Boundaries include freshwater inflow, tidal elevations, and shoreline geometry
- Can predict velocities and flushing rates

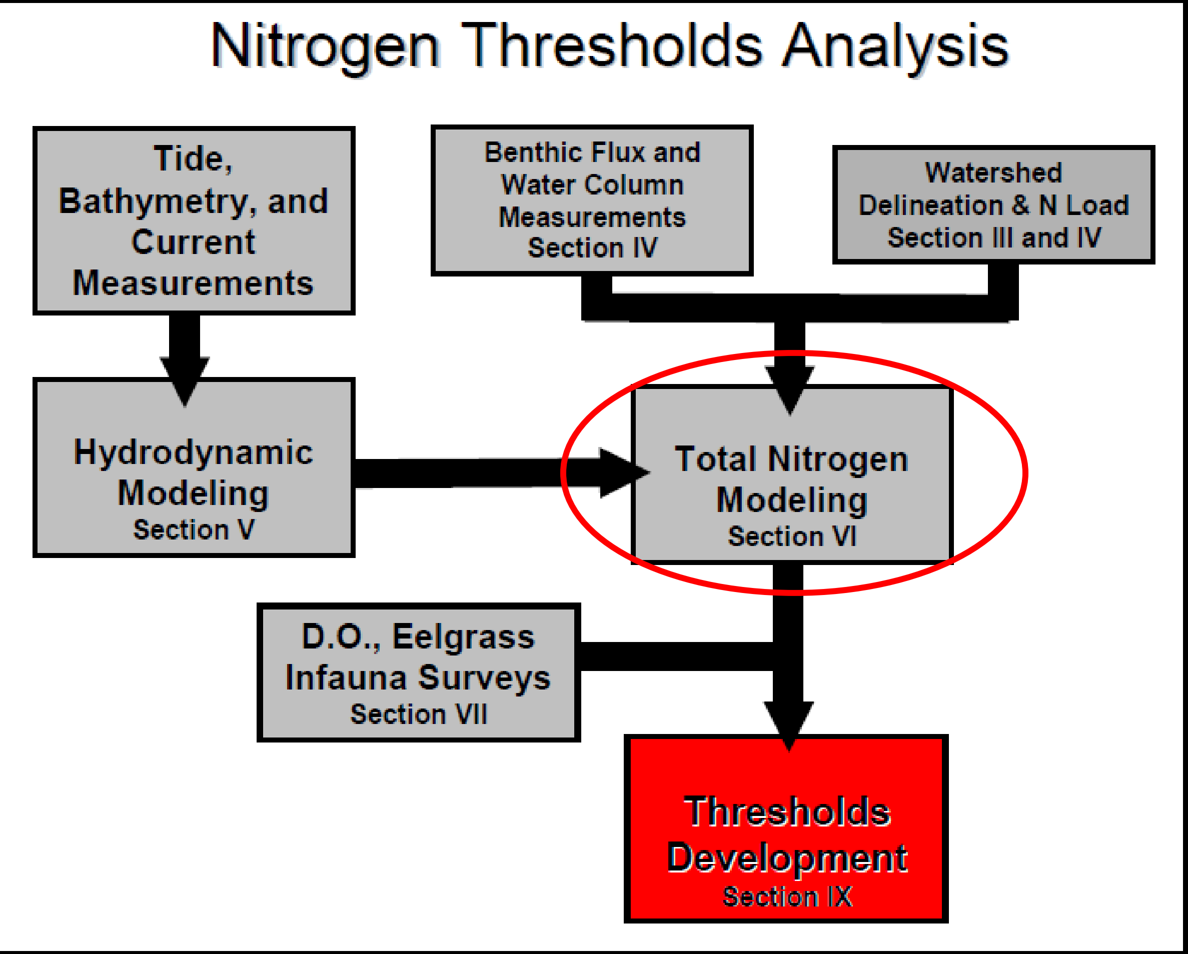
Model grid



Predicted velocities



Overview of MEP: Total Nitrogen (Water-Quality) Modeling

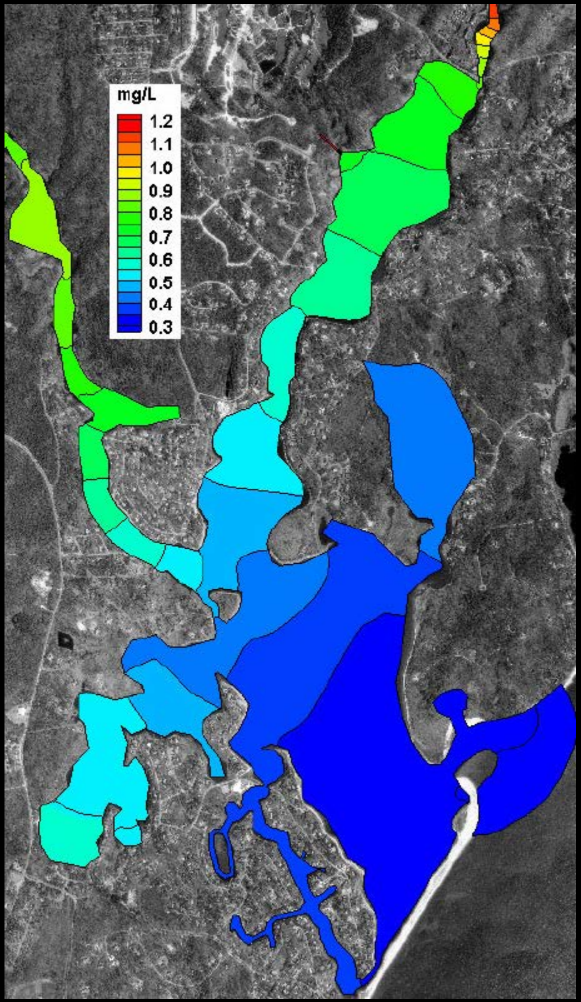


- Synthesizes hydrodynamic model and nitrogen load estimates
- Predict nitrogen concentrations for given nitrogen loads
- Calibrated to measured estuarine water quality

Overview of MEP: Total Nitrogen (Water-Quality) Modeling

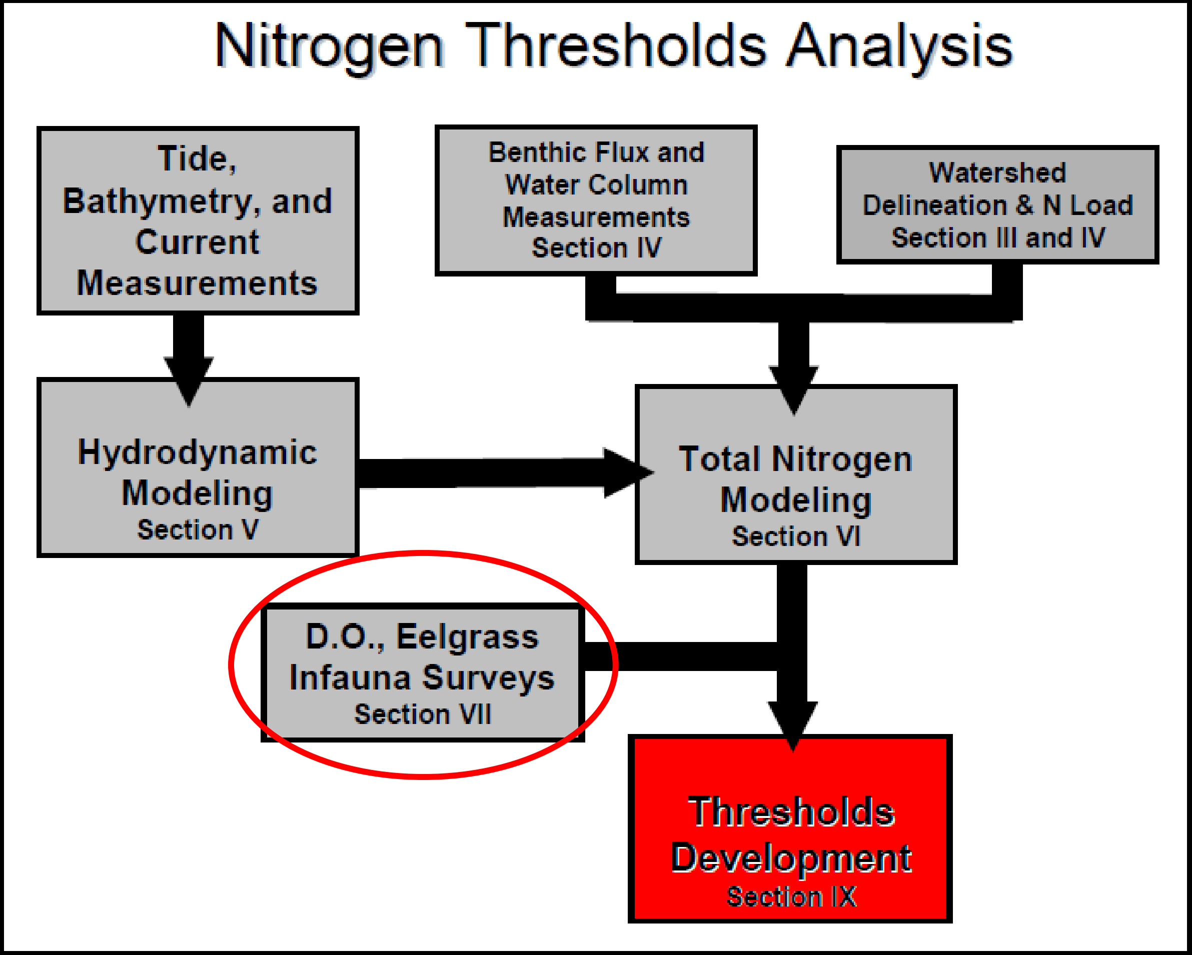
Water-quality sites

Current nitrogen concentrations



- Simulated hydrodynamics and nitrogen loads incorporated into a water-quality model, RMA-4
- Calibrated to match observed nitrogen concentrations
- Verified using measured salinities

Overview of MEP: Ecological Characterization Threshold

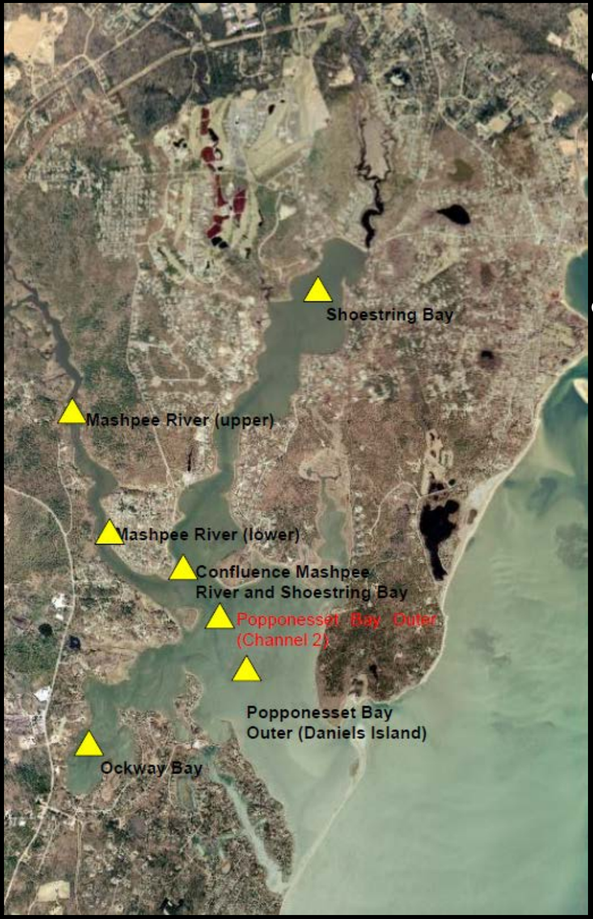


- Determine current ecological health in an estuary
- Evaluate relationship between current water-quality and ecological health

Overview of MEP: Total Nitrogen (Water-Quality) Modeling

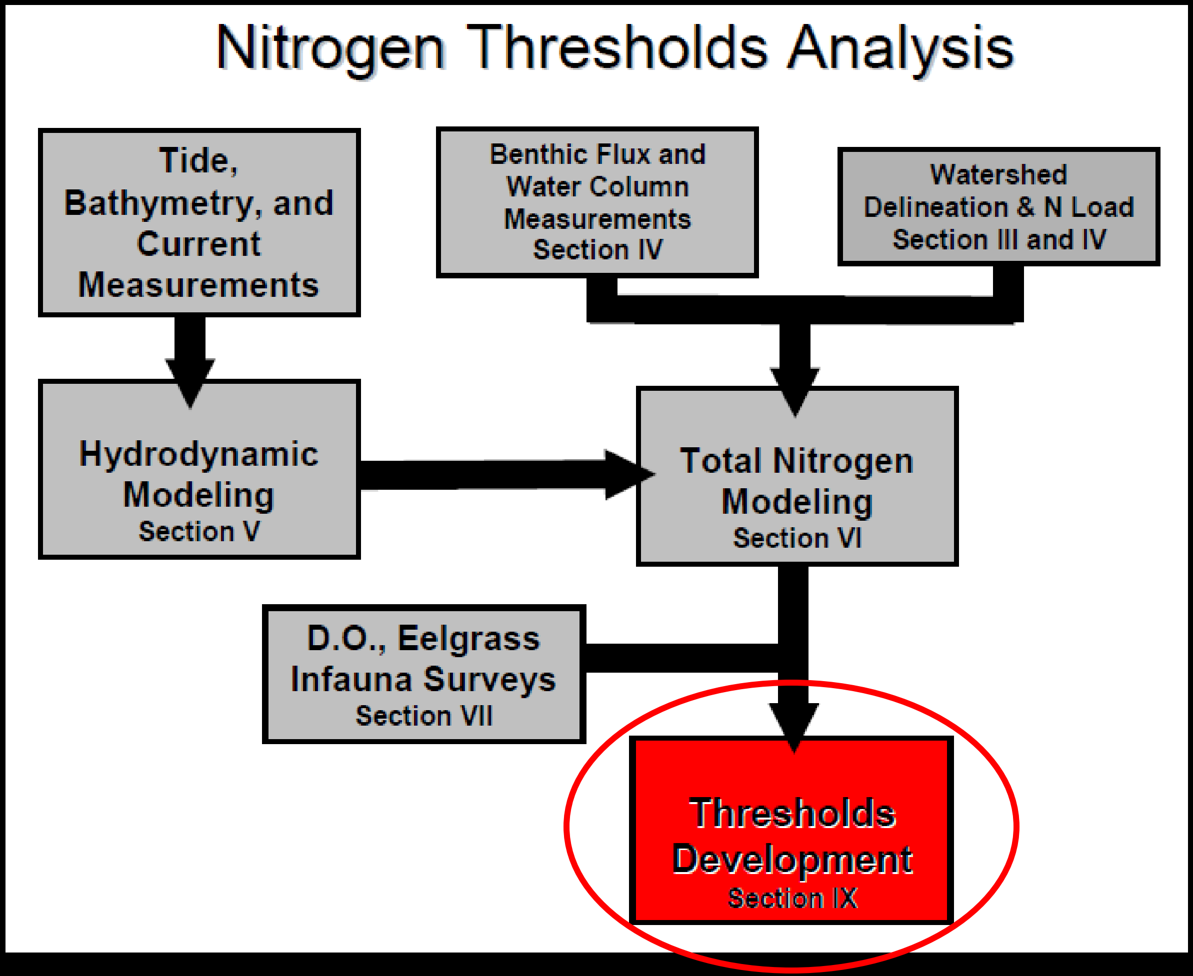
Benthic faunal sites

Dissolved oxygen sites



- Dissolved oxygen and chlorophyll in bottom water
- Benthic fauna: number and diversity of species, indicator species
- Eelgrass distribution

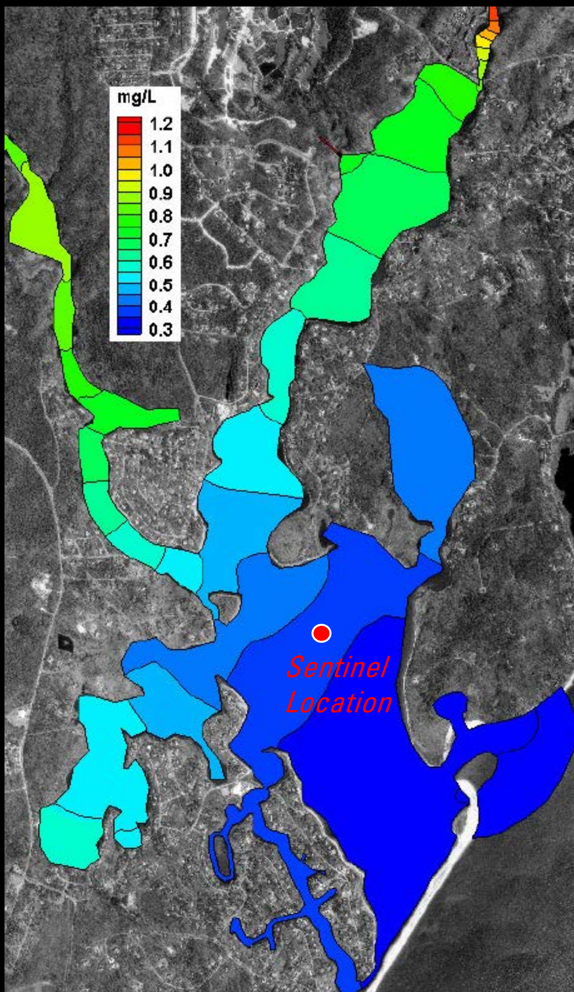
Overview of MEP: Threshold Conditions



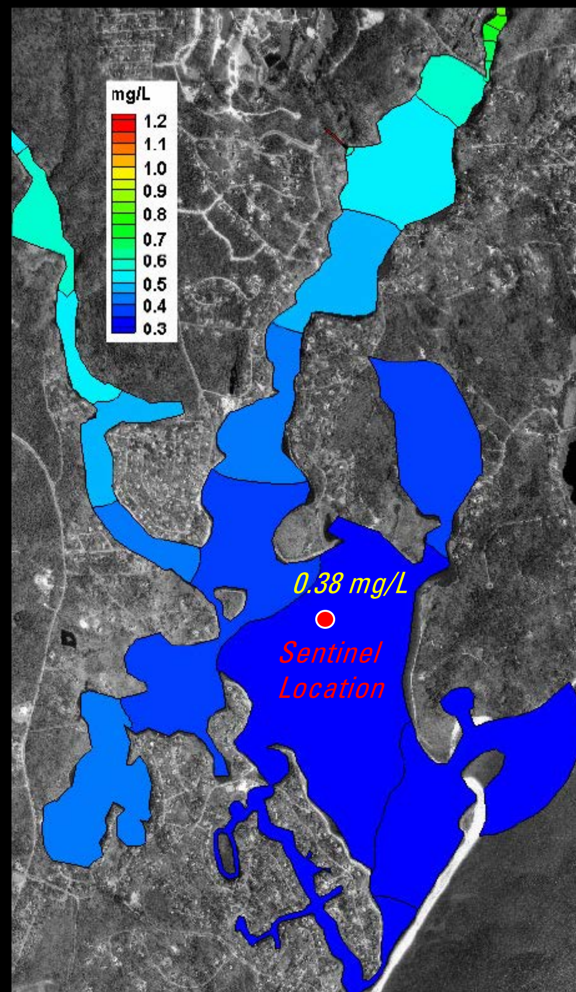
- Use current relationship between water-quality and ecology to estimate "threshold" concentrations
- Threshold concentrations represent conditions that would allow for reestablishment of estuarine habitats
- Nitrogen TMDLs derived from the maximum load that would result in the desired threshold concentrations

Overview of MEP: Threshold Concentrations and TMDLs

Current nitrogen concentrations



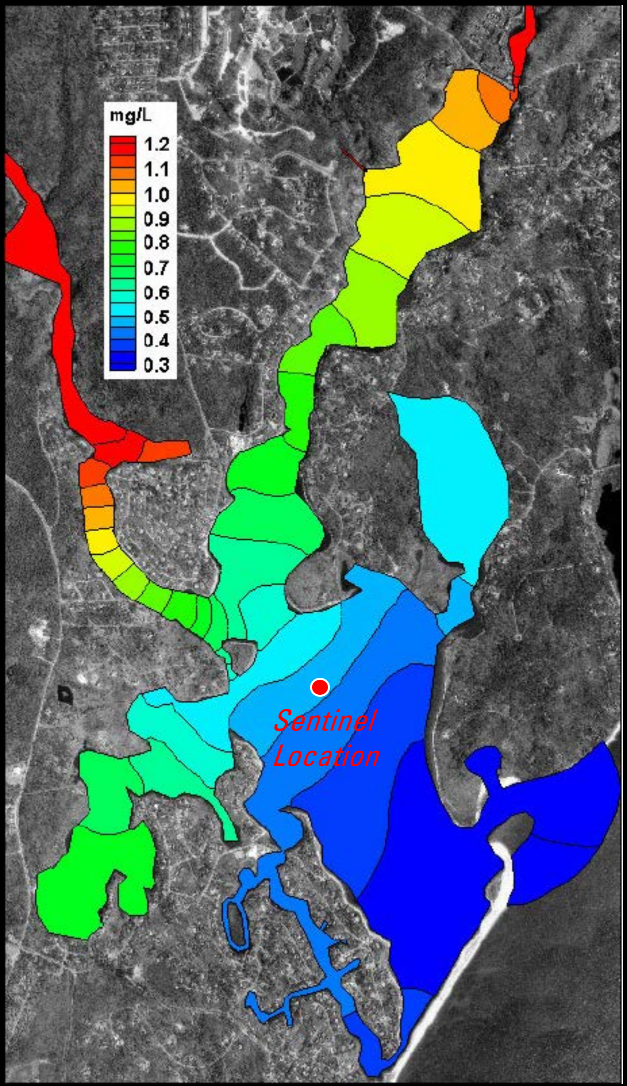
Threshold concentrations



- Threshold concentrations determined for a sentinel location
- Location determined to suitably represent conditions in the estuary
- Nitrogen concentrations at the sentinel location suitable for eel grass habitat
- Various nitrogen loads used in the linked-watershed model to determine that which yields the desired concentration

Overview of MEP: Implementation of TMDLs

Build Out



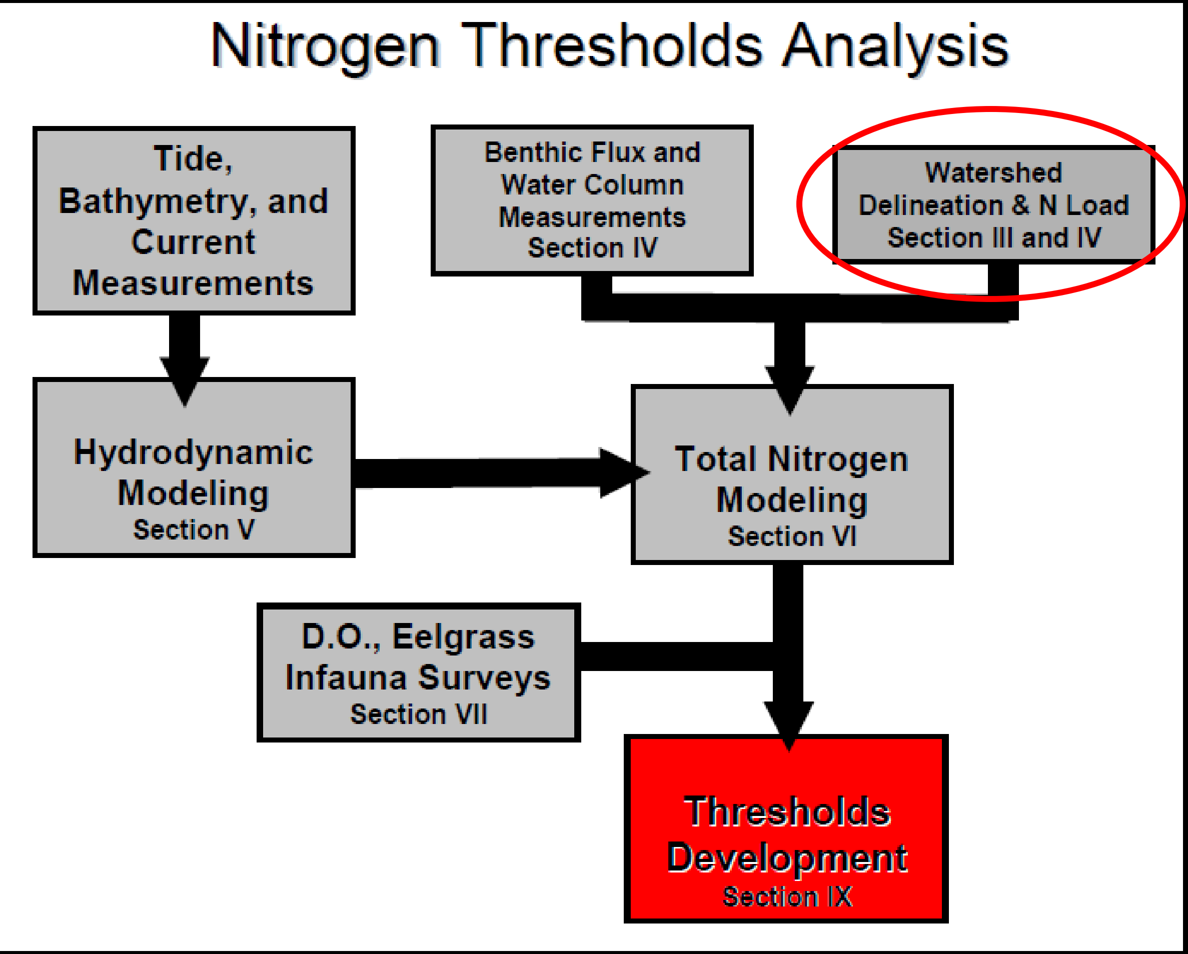
- Alternative loads as input into the linked model to determine resulting nitrogen concentrations
- Comparison to threshold concentrations determines TMDL compliance

USGS Activities in Support of TMDL Development and Implementation

- *Development:* Watershed delineation (2002-04):
  - Watersheds to fresh and coastal waters, about 600 estuaries, ponds, streams, and wells
  - Direct support of the MEP
- *Implementation:* Develop solute-transport methods to improve evaluation of TMDL compliance (20010-12)
  - Time-varying responses to wastewater-management actions
  - Avoid limitations inherent in static watersheds and “instantaneous” loads

USGS
science for a changing world

Watershed Delineations



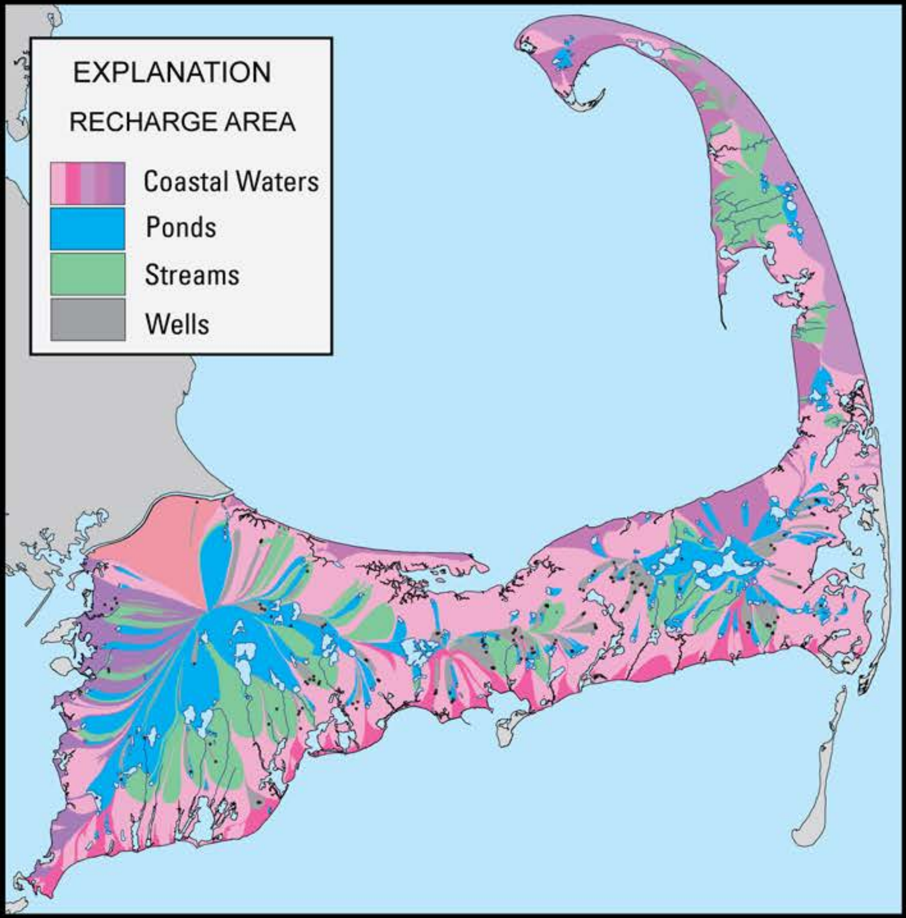
Watershed Delineations

- Discharge of freshwater to estuaries can come from:
  => ground-water discharge
  => streams
  => bogs and wetlands
  => ponds
- The mechanisms of freshwater discharge can effect nitrogen attenuation in the watershed

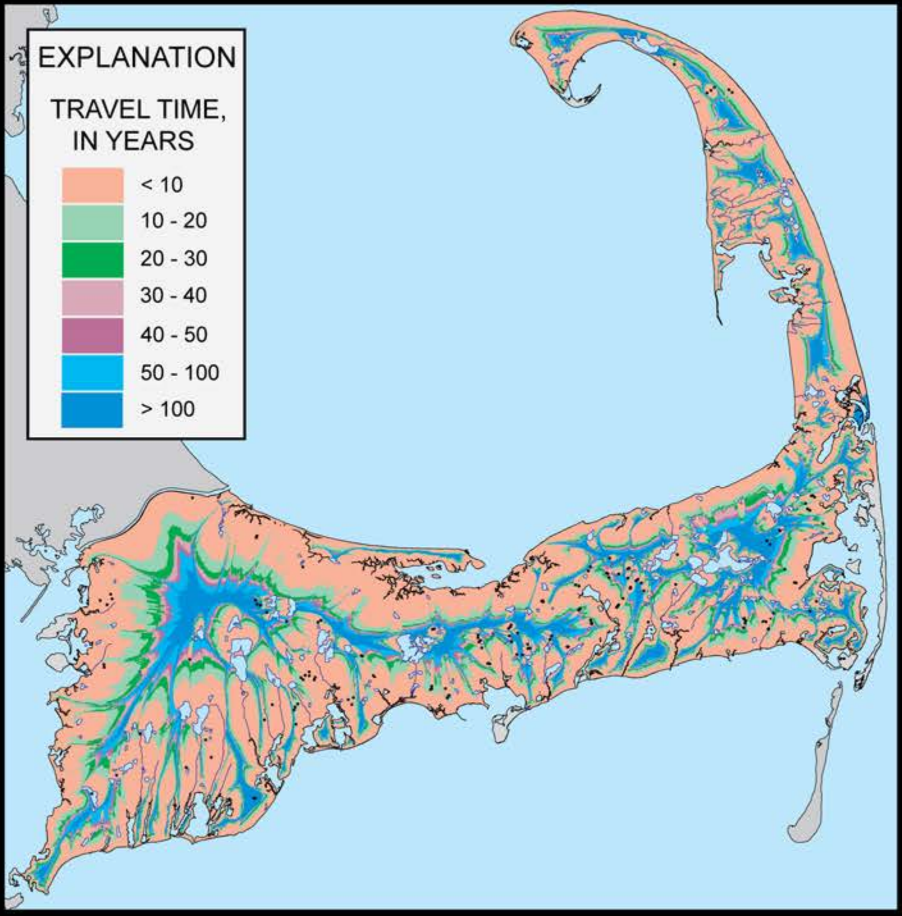
Flow-Based Analyses Using Recharge Areas

- Recharge areas delineated for estuaries, ponds, streams, and wells
- Useful for estimating "instantaneous" loads under static hydrologic conditions

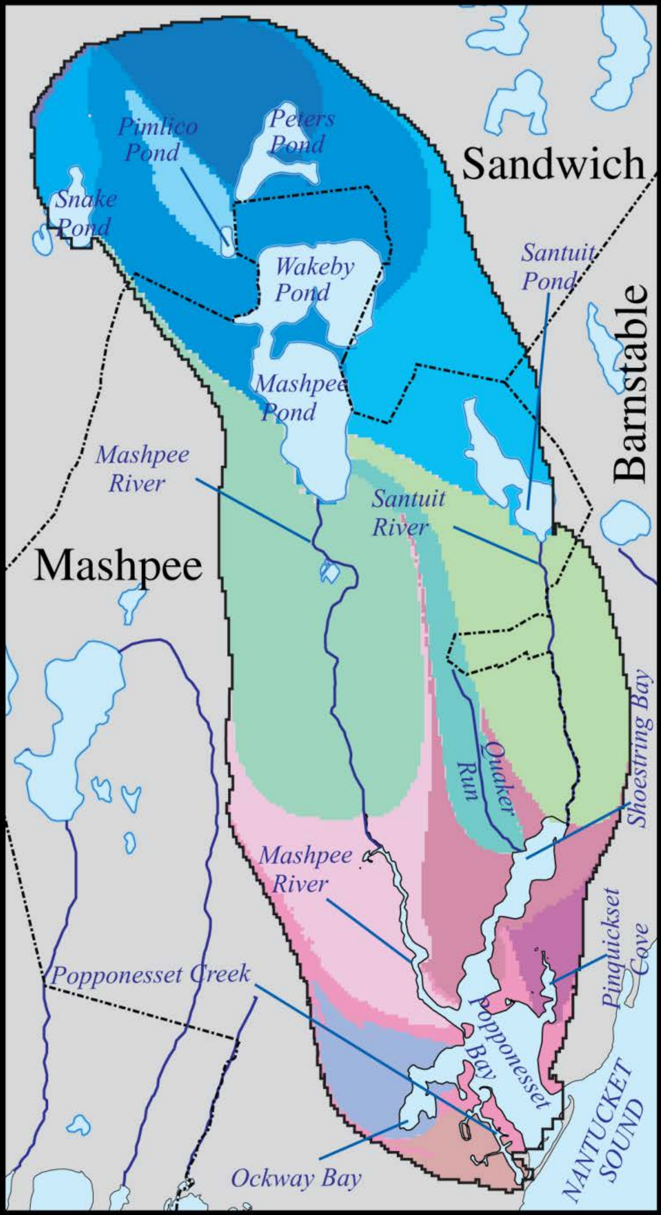
Recharge Areas



Travel Times

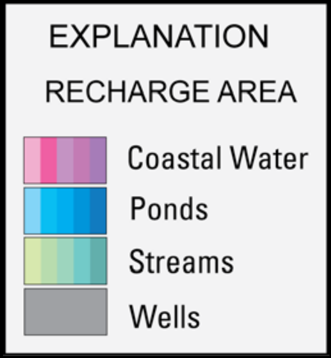


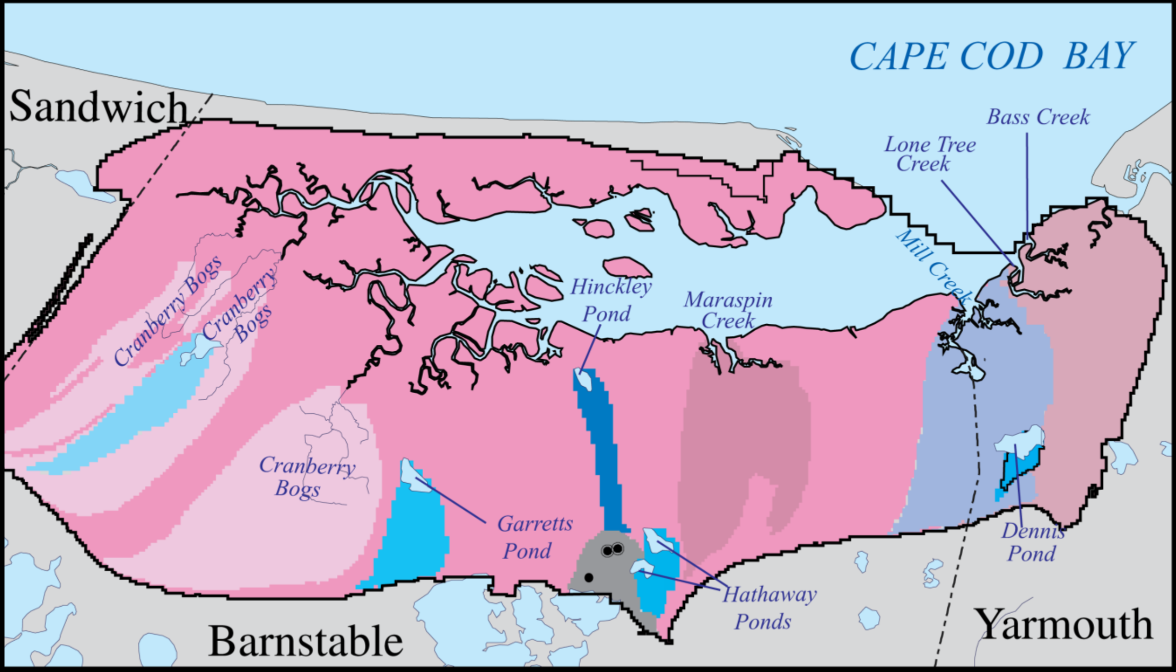
Barnstable Harbor and Popponesset Bay Watersheds



Surface-water Dominated: Popponesett Bay

Ground-water Dominated: Barnstable Harbor

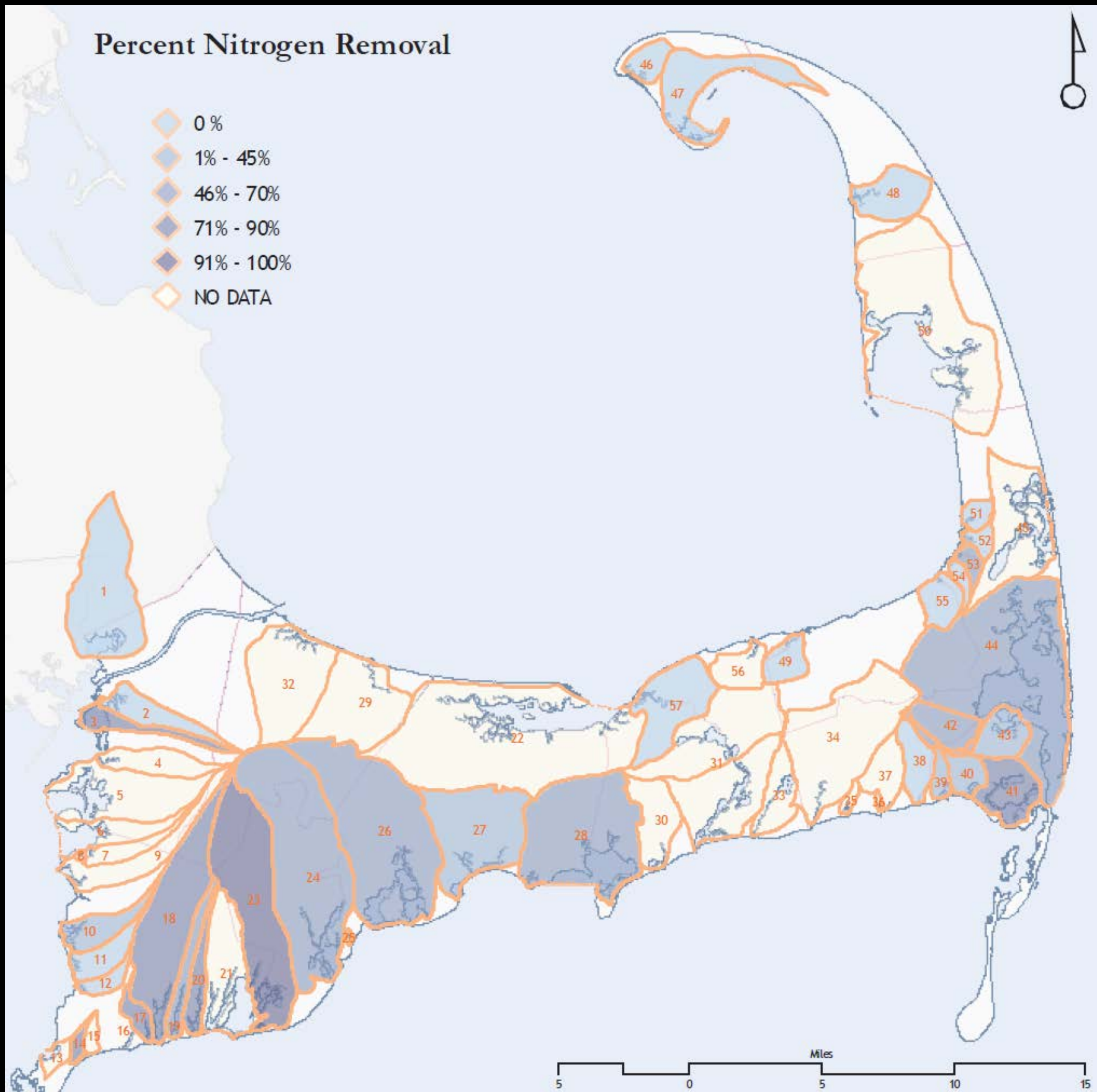




Nitrogen Load Estimates

- Parcel-scale nitrogen loads (estimated from water use) are mapped to watersheds
- Estimated for travel times of greater than or less than or equal to 10 years travel times
- Surface-water attenuation implicitly accounted for as loss terms at the source
  - 30 percent attenuation discharge into streams
  - 50 percent attenuation for discharge through ponds
  - No attenuation assumed for direct GW discharge

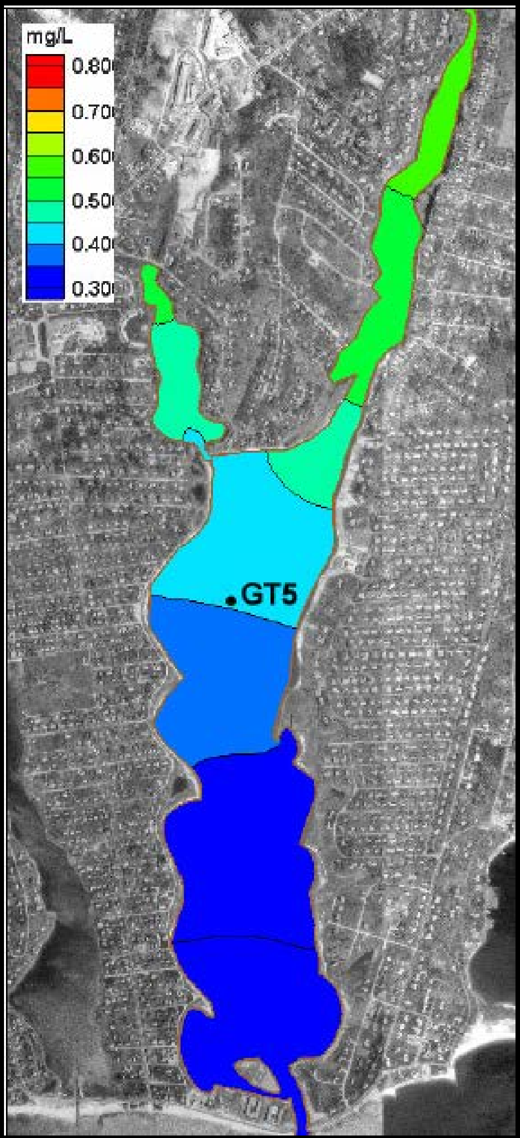
Implementation of the MEP



- MEP analysis results in target nitrogen reductions for each estuarine system
- Towns use MEP analytical approach to evaluate TMDL compliance as part of developing a Comprehensive Wastewater Management Plan
- The process uses the same watersheds as used in developing nitrogen TMDLs

Overview of MEP: Total Nitrogen (Water-Quality) Modeling

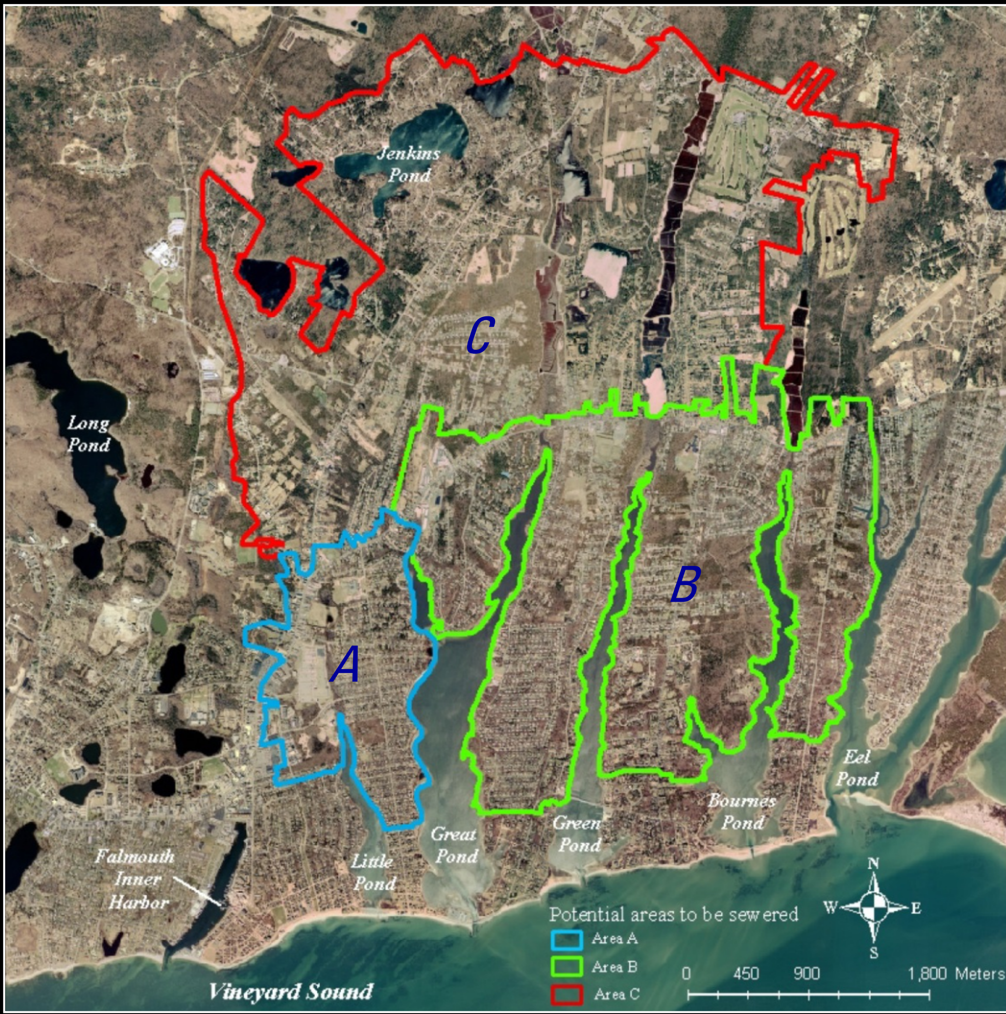
Threshold Concentrations



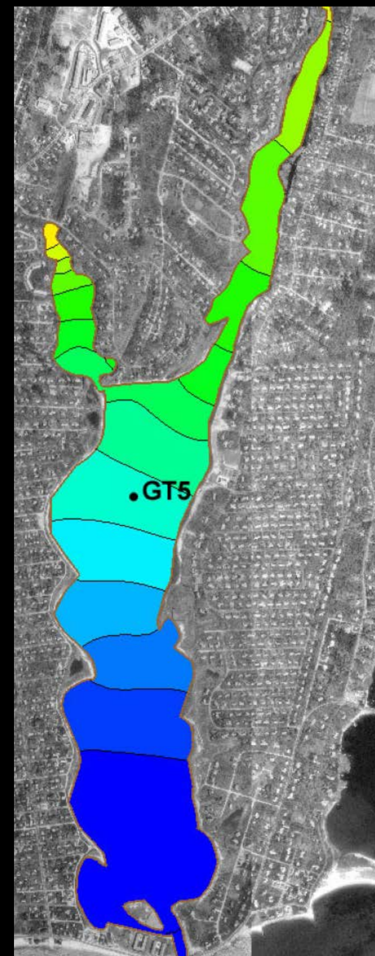
Proposed Wastewater Management Actions

Overview of MEP: Total Nitrogen (Water-Quality) Modeling

Three areas of potential sewering



A only



Not compliant

A + B + C

TMDL compliant

Implementation of TMDLs Using Static Watershed Delineations

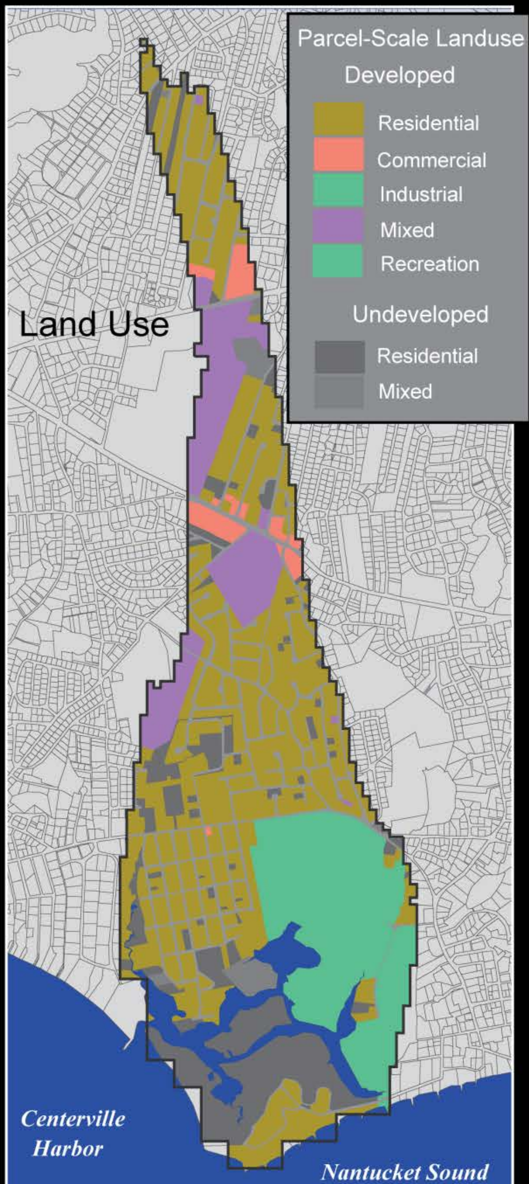
- Mass is represented implicitly
- Does not account for dynamic watersheds
- Can not simulate time-varying nitrogen loads following implementation of multi-phase wastewater management actions (response times)
- Does not represent other transport processes: dispersion, attenuation, etc.
- Does not account for complex surface-water interactions

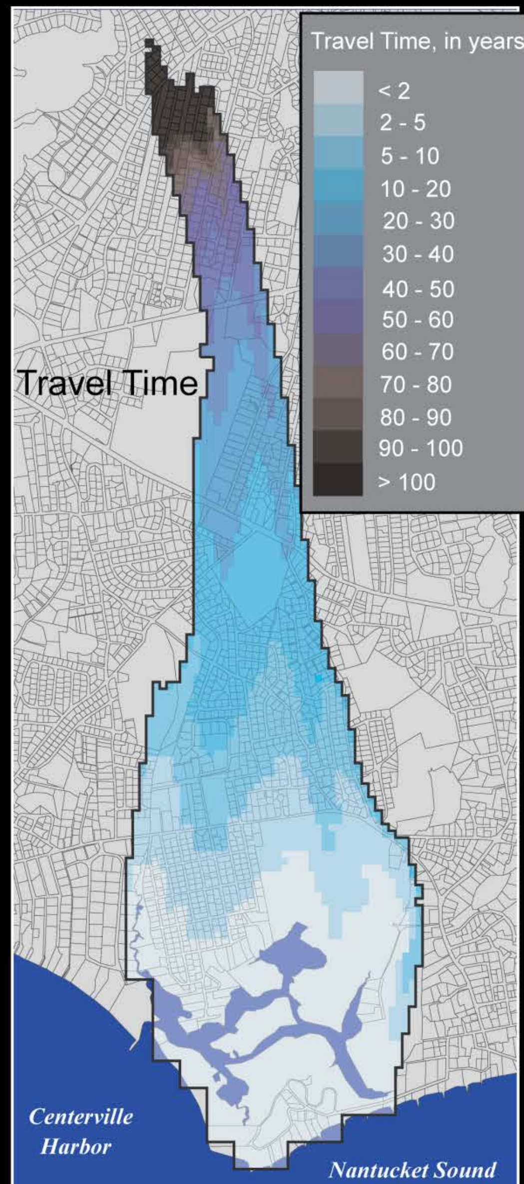
Solute-transport model capabilities:

- Accounts for changes in watershed boundaries in response to changing stresses
- Transport time fully integrated into simulation
- Ability to represent dispersion and attenuation
- Minimal post-processing required
- Can simulate complex scenarios with linked management actions

USGS
science for a changing world

Watersheds Result in Instantaneous Loads





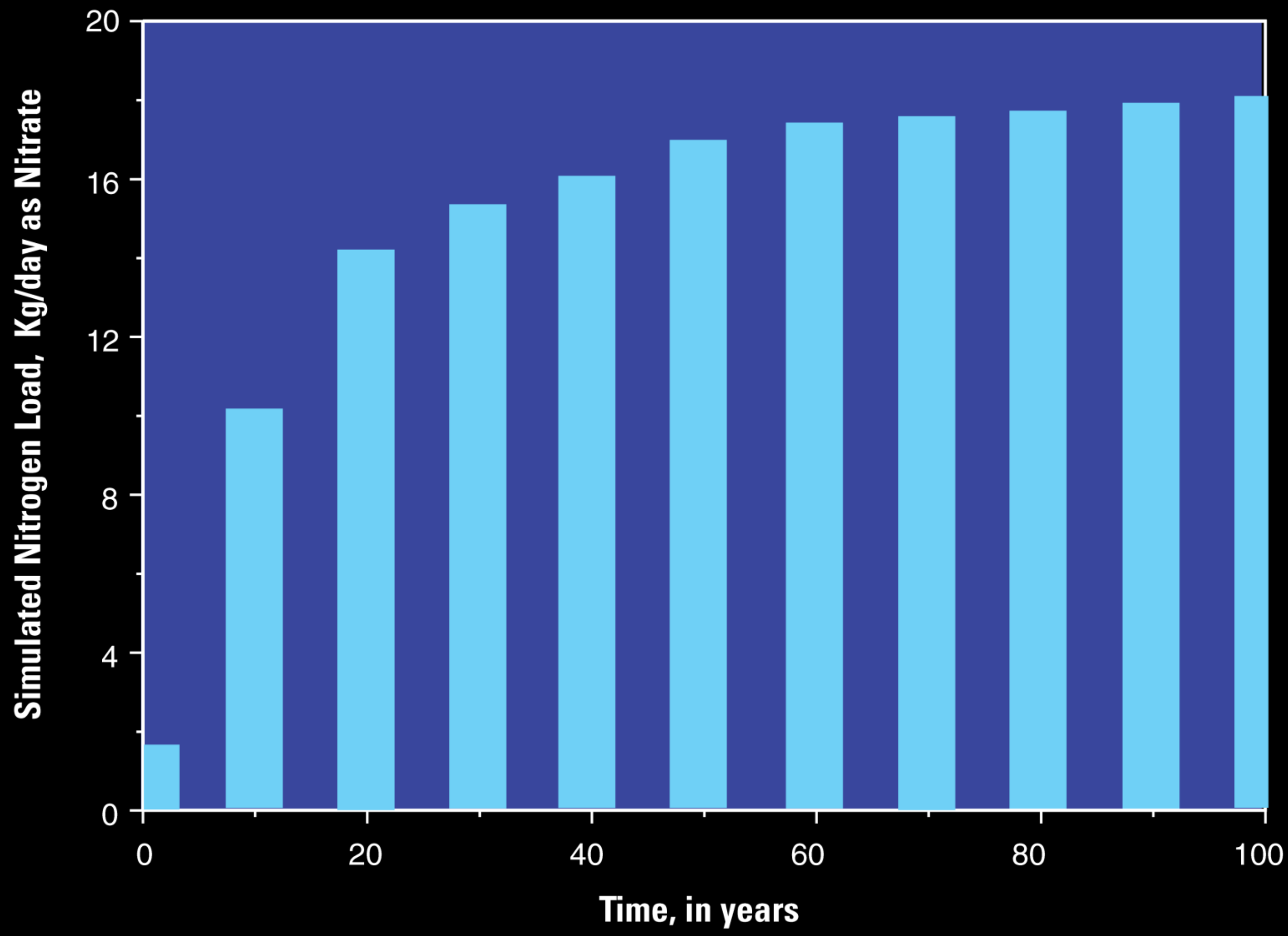
For Each Parcel

$$Q_{septic} \times N_{septic} = \text{N Load}$$

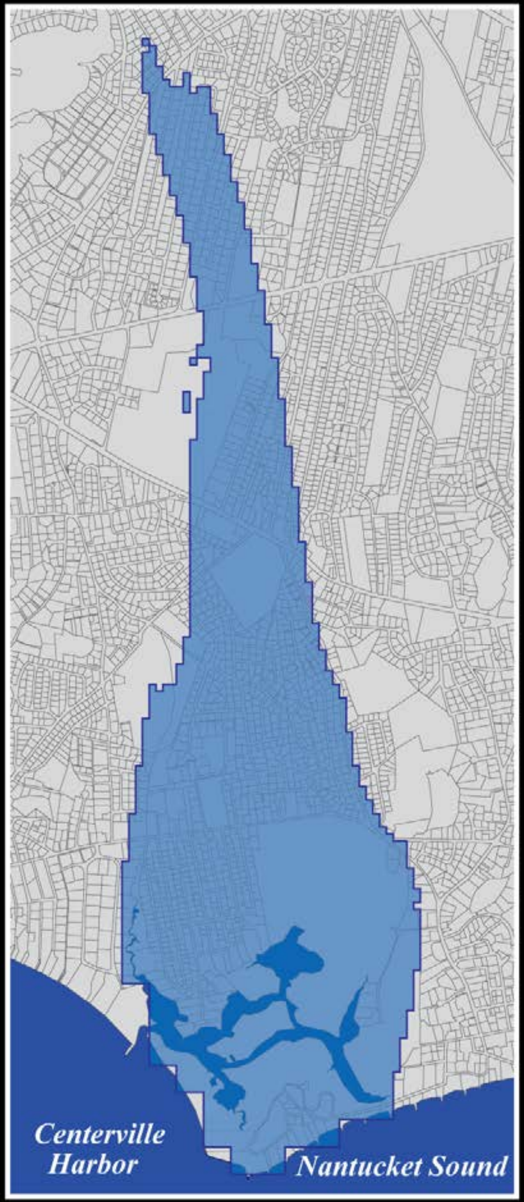
For Each Travel Time Band

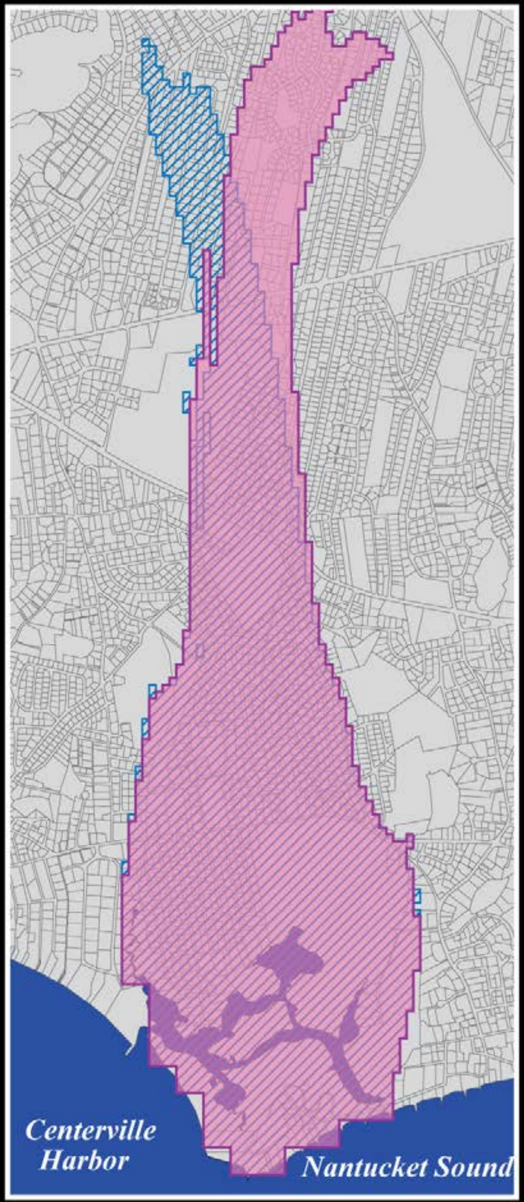
$$\sum \text{N loads} = \text{Estimated Load}$$

Nitrogen Loads Calculated for Travel Time Bands

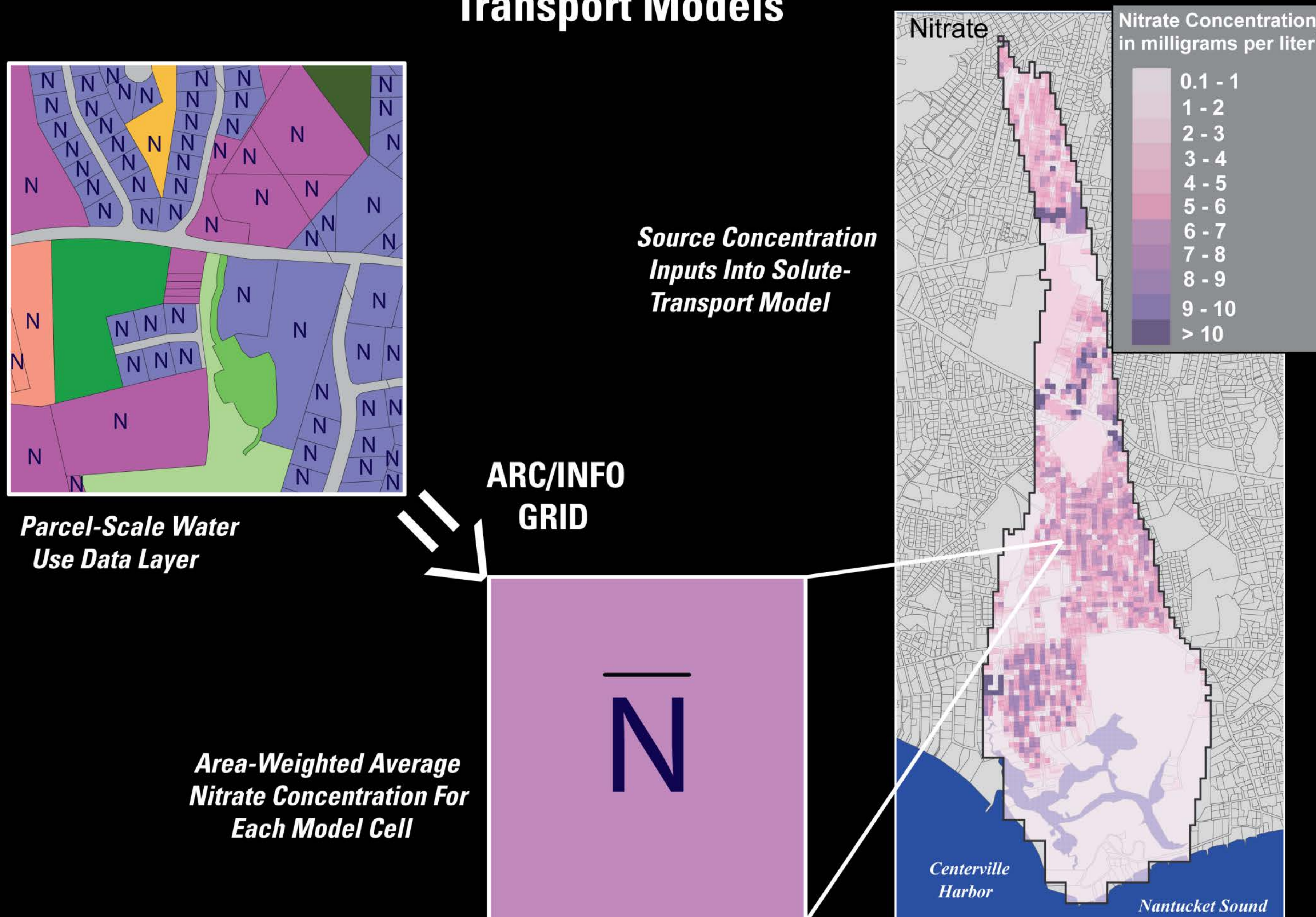


Watershed Change in Response to WTF Disposal

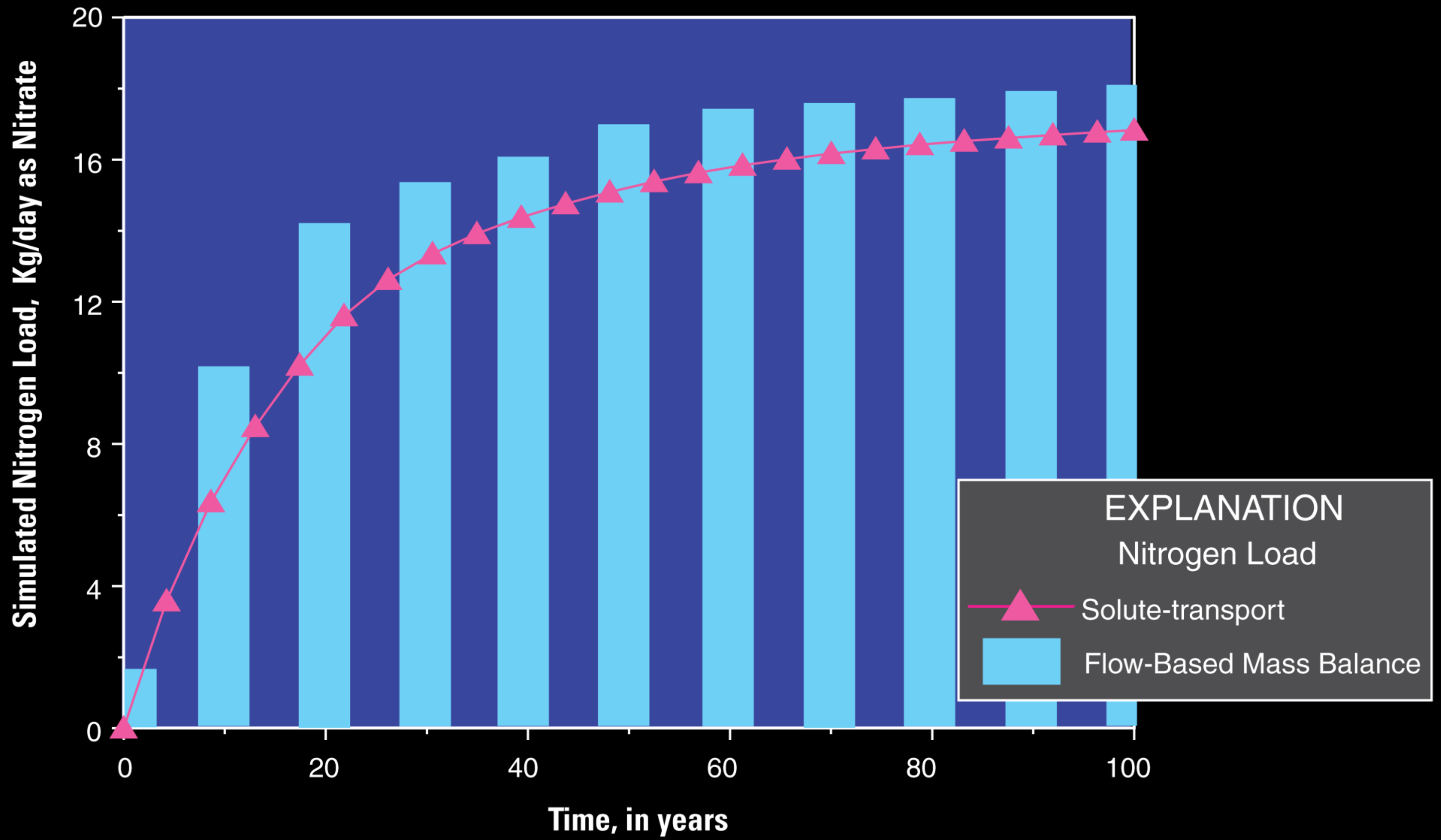




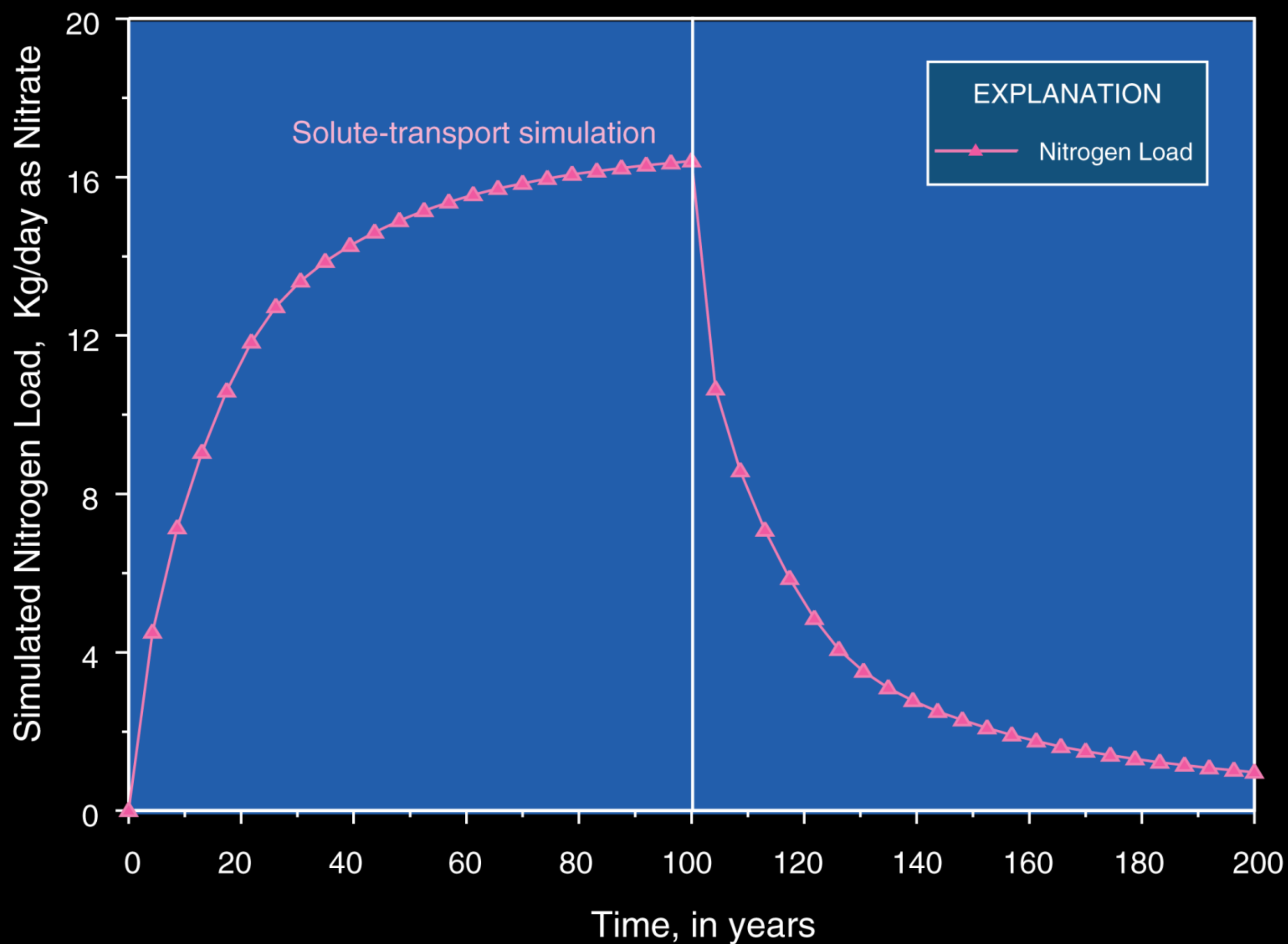
GIS Rasterization Of Parcel-Scale and Incorporation into Solute-Transport Models



Nitrogen Loads to Halls Creek Estimated Using A Flow-Based Mass Balance Approach And Simulated Using A Solute Transport Model



Simulated Nitrogen Load to Halls Creek System for 100 Years of Loading and 100 Years Of Sewering In The Watershed



TMDL implementation Using Solute-Transport Methods

- Develop subregional model in watershed of interest
- Incorporate solute-transport methods into the subregional model
    - GIS pre-processing of parcel-scale water use data
    - Incorporation into solute-transport model
    - Use of model to evaluate complex wastewater scenarios
- Use assumptions consistent with MEP
- Compare implicit and explicit methods for estimating nitrogen loads