III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS). These USGS groundwater modelers were central to the development of the groundwater modeling approach used by the Estuaries Project. The USGS has a long history of developing regional models for the six-groundwater flow cells on Cape Cod. Through the years, advances in computing, lithologic information from well installations, water level monitoring, stream flow measurements, and reconstruction of glacial history have allowed the USGS to update and refine the groundwater models. The MODFLOW and MODPATH models utilized by the USGS organize and analyze the available data using up-to-date mathematical codes and create better tools to answer the wide variety of questions related to watershed delineation, surface water/groundwater interaction, groundwater travel time, and drinking water well impacts that have arisen during the MEP analysis of southeastern Massachusetts estuaries, including the Lewis Bay embayment system located in Barnstable, Massachusetts. The Lewis Bay watershed is situated along the southern edge of Cape Cod and is bounded by Vineyard/Nantucket Sound.

In the present investigation, the USGS was responsible for the application of its groundwater modeling approach to define the watershed or contributing area to the Lewis Bay embayment system under evaluation by the Project Team. The Lewis Bay estuarine system is a moderately complex estuary and includes wetland dominated portions at its northern edge. Further watershed modeling was undertaken to sub-divide the overall watershed to the Lewis Bay system into functional sub-units based upon: (a) defining inputs from contributing areas to each major portion within the embayment system, (b) defining contributing areas to major freshwater aquatic systems which generally attenuate nitrogen passing through them on the way to the estuary (lakes, streams, wetlands), and (c) defining 10 year time-of-travel distributions within each sub-watershed as a procedural check to gauge the potential mass of nitrogen from "new" development, which has not yet reached the receiving estuarine waters. The three-dimensional numerical model employed is also being used to evaluate the contributing areas to public water supply wells in the Sagamore flow cell on Cape Cod. Model assumptions for calibration were matched to surface water inputs and flows from MEP stream flow measurements (2003 to 2004).

The relatively transmissive sand and gravel deposits that comprise most of Cape Cod create a hydrologic environment where watershed boundaries are usually better defined by elevation of the groundwater and its direction of flow, rather than by land surface topography (Cambareri and Eichner 1998, Millham and Howes 1994a,b). Freshwater discharge to estuaries is usually composed of surface water inflow from streams, which receive much of their water from groundwater base flow, and direct groundwater discharge. For a given estuary, differentiating between these two water inputs and tracking the sources of nitrogen that they carry requires determination of the portion of the watershed that contributes directly to a stream and the portion of the groundwater system that discharge directly into an estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Lewis Bay system were delineated using a regional model of the Sagamore Lens flow cell (Walter and Whealan, 2005). The USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 (Harbaugh, *et al.*, 2000) was used to simulate groundwater flow in the aquifer. The USGS particle-tracking program MODPATH4 (Pollock, 2000), which uses output files from MODFLOW-2000 to track the simulated movement of water in the aquifer, was used to delineate the area at the water table that contributes water to wells, streams, ponds, and coastal water bodies. This approach was used to determine the contributing areas to Lewis Bay system including sub-watersheds to Halls Creek, outer Lewis Bay (Hyannis Harbor), Stewarts Creek, Snows Creek, and Mill Creek and also to determine portions of recharged water that may flow through fresh water ponds and streams prior to discharging into coastal water bodies.

The Sagamore Flow Model grid consists of 246 rows, 365 columns and 20 layers. The horizontal model discretization, or grid spacing, is 400 by 400 feet. The top 17 layers of the model extend to a depth of 100 feet below NGVD 29 and have a uniform thickness of 10 ft. The top of layer 8 resides at NGVD 29 with layers 1-7 stacked above and layers 8-20 below. Layer 18 has a thickness of 40 feet and extends to 140 feet below NGVD 29, while layer 19 extends to 240 feet below NGVD 29. The bottom layer, layer 20, extends to the bedrock surface and has a variable thickness depending upon site characteristics (up to 519 feet below NGVD 29); since bedrock is 300 to 400 feet below NGVD 29 in the Lewis Bay area the two lowest model layers were active in this area of the model. The rewetting capabilities of MODFLOW-2000, which allows drying and rewetting of model cells, was used to simulate the top of the water table, which varies in elevation depending on the location in the Lens.

The glacial sediments that comprise the aquifer of the Sagamore Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments. The sediments generally show a fining downward with sand and gravel deposits deposited in glaciofluvial (river) and near-shore glaciolacustrine (lake) environments underlain by fine sand, silt and clay deposited in deeper, lower-energy glaciolacustrine environments. Most groundwater flow in the aquifer occurs in shallower portions of the aquifer dominated by coarser-grained sand and gravel deposits. The Lewis Bay system watershed (including Snows and Stewarts Creeks) is generally split between the Barnstable Outwash Plain Deposits to the west and Harwich Outwash Plain Deposits to the east; the dividing line between the two deposits follows a line north from the northern portion of Mill Creek (Oldale, 1974a; Oldale, 1974b). The Halls Creek watershed is exclusively in the Barnstable Outwash Plain Deposits (Oldale, 1974a). Modeling and field measurements of contaminant transport at the MMR have shown that similar deposited materials are highly permeable (*e.g*., Masterson, *et al*., 1996). Given their high permeability, direct rainwater run-off is typically rather low for this type of watershed system. Lithologic data used to determine hydraulic conductivities used in the groundwater model were obtained from a variety of sources including well logs from USGS, local Town records and data from previous investigations. Final aquifer parameters in the groundwater model were determined through calibration to observed water levels and stream flows. Hydrologic data used for model calibration included historic water-level data obtained from USGS records and local Towns and stream flow data collected in 1989-1990 as well as 2003.

The groundwater model simulates steady state, or long-term average, hydrologic conditions including a long-term average recharge rate of 27.25 inches/year and the pumping of public-supply wells at average annual withdrawal rates for the period 1995-2000 with a 15% consumptive loss. This recharge rate is based on the most recent USGS information. Large withdrawals of groundwater from pumping wells may have a significant influence on water tables and watershed boundaries and therefore the flow and distribution of nitrogen within the aquifer. After accounting for the consumptive loss and measured discharge at the Hyannis Water Pollution Control Facility (WPCF), water withdrawn from the modeled aquifer by public drinking water supply wells is evenly returned within residential areas designated as using on-site septic systems.

III.3 LEWIS BAY SYSTEM AND HALLS CREEK CONTRIBUTORY AREAS

Newly revised watershed and sub-watershed boundaries were determined by the United States Geological Survey (USGS) for the Lewis Bay embayment system, including the Mill Creek and Hyannis Inner Harbor sub-embayments, and Halls Creek estuary (Figure III-1). Model outputs of MEP watershed boundaries were "smoothed" to (a) correct for the grid spacing, (b) to enhance the accuracy of the characterization of the pond and coastal shorelines, (c) to include water table data in the lower regions of the watersheds near the coast (as available), and (d) to more closely match the sub-embayment segmentation of the tidal hydrodynamic model. The smoothing refinement was a collaborative effort between the USGS and the rest of the MEP Technical Team. The MEP sub-watershed delineation includes one 10 yr time of travel boundary. Overall, twenty-eight (28) sub-watershed areas, including eight freshwater ponds, were delineated within the Lewis Bay/Halls Creek study area.

Table III-1 provides the daily discharge volumes for various sub-watersheds as calculated from the groundwater model. These volumes were used to assist in the salinity calibration of the tidal hydrodynamic models and to determine hydrologic turnover in the lakes/ponds, as well as for comparison to measured surface water discharges. The overall estimated groundwater flow into the Lewis Bay system, including outer Lewis Bay and Stewarts Creek based on the MEP delineated watershed is 61,743 m3/d. The estimated groundwater flow into Hall Creek is 9,796 m3/d.

The delineations completed for the MEP project are the second watershed delineation completed in recent years for portions of the Lewis Bay system and Halls Creek. Figure III-2 compares the delineation completed under the current effort with the study area delineations completed by the Cape Cod Commission in 1998 as part of the Coastal Embayment Project (Eichner, *et al*., 1998). The delineation completed in 1998 was defined based on regional water table measurements collected from available wells over a number of years and normalized to average conditions. Delineations based on this previous effort were incorporated into the Commission's regulations through the Regional Policy Plan (CCC, 1996 & 2001).

The MEP watershed area for the Lewis Bay system as a whole is 9% larger (658 acres) than the 1995 CCC delineation. The differences are largely attributable to the inclusion of the outer Lewis Bay portion of the MEP delineation. The Halls Creek MEP watershed is 14% smaller than the 1995 CCC delineation; this is likely due to a better understanding of stream flow out of the Creek that were developed for the MEP (see Chapter IV). The MEP area calculations include corrections for portions of the pond and well sub-watersheds that discharge outside of the system, as well as accounting for differential flow from the Hyannis WPCF. Modeling completed by the USGS to assist the Wastewater Implementation Committee of Barnstable County helped the Town of Barnstable evaluate how much of the WPCF's flows are received by various ponds, public water supply wells, and estuary components in the study area. This effort was another benefit of the update of the regional groundwater model (Walter and Whealan, 2005). Interior sub-watersheds to individual freshwater ponds and public water supplies were not delineated in the CCC watersheds.

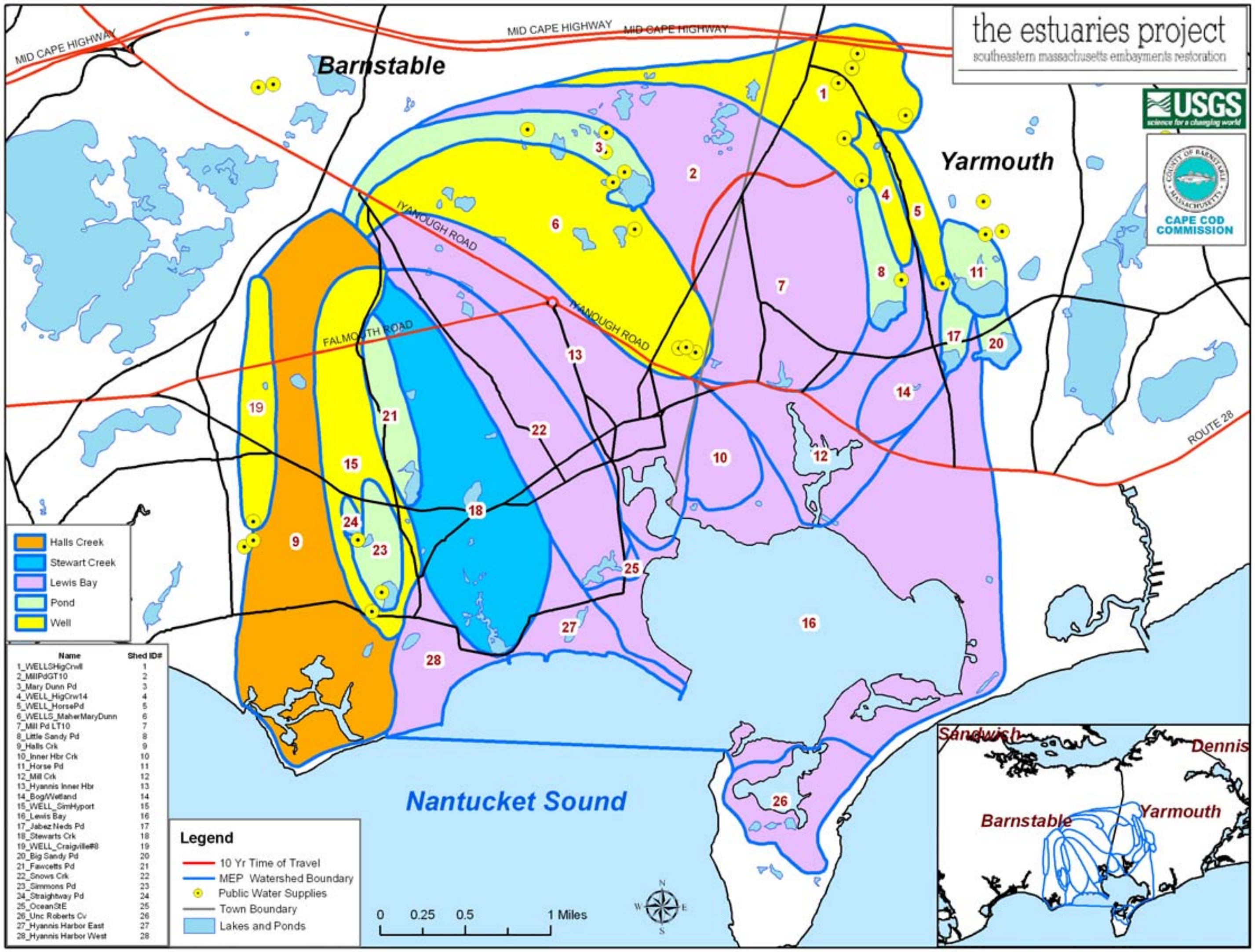
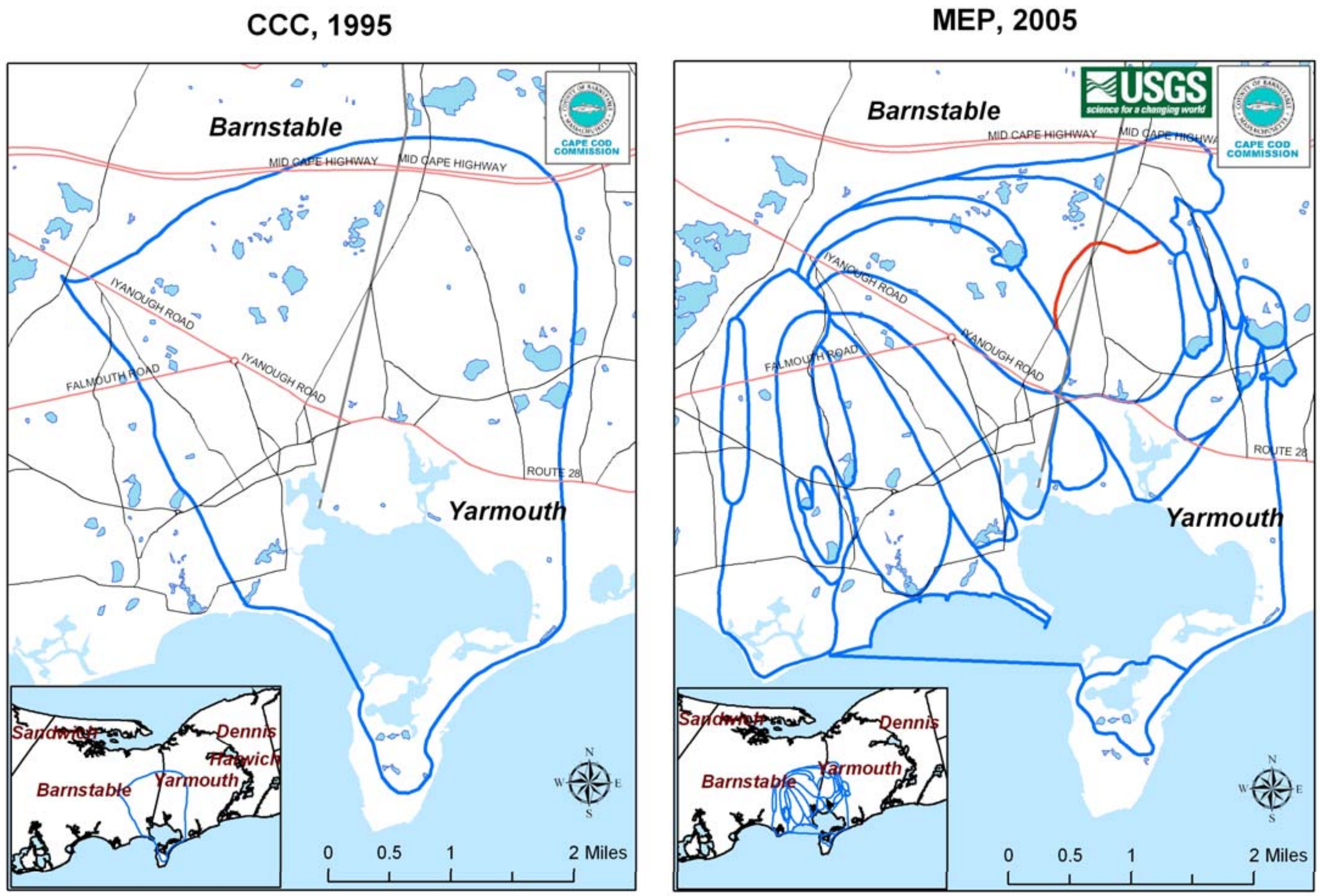


Figure III-1. Watershed and sub-watershed delineations for the Lewis Bay estuary system. Approximate ten year time-of-travel delineations were produced for quality assurance purposes and are designated with a “10” in the watershed names (above). Sub-watersheds to embayments were selected based upon the functional estuarine sub-units in the water quality model (see section VI).



Used in 1996 & 2001 Regional Policy Plans
(based on delineation in Eichner, et al., 1998)

Delineated by USGS for MEP Analysis
Red lines indicate ten year time-of-travel lines

Figure III-2. Comparison of 1998 Cape Cod Commission and current Lewis Bay watershed and sub-watershed delineations.

Table III-1. Daily groundwater discharge to each of the sub-watersheds in the watershed to the Lewis Bay system estuary and Halls Creek estuary, as determined from the USGS groundwater model.

Watershed	#	Watershed Area (acres)	% contributing to Estuaries	Discharge	
				m^3/day	ft^3/day
WELLS_HigginsCrowell	1	455	49	1,698	59,972
Mill Pond GT10	2	511	100	3,920	138,443
Mary Dunn Pond	3	245	100	1,878	66,337
WELL_HigginsCrowell14	4	73	100	560	19,785
WELL_HorsePond	5	85	100	655	23,126
WELLS_MaherMaryDunn	6	801	100	6,144	216,973
Mill Pond LT10	7	693	100	5,322	187,934
Little Sandy Pond	8	89	100	686	24,210
Halls Creek	9	935	100	7,174	253,346
Inner Harbor Creek	10	147	100	1,126	39,762
Horse Pond	11	98	24	180	6,359
Mill Creek	12	359	100	2,752	97,189
Hyannis Inner Harbor	13	638	100	4,895	172,854
Bog/Wetland	14	148	100	1,137	40,139
WELL_SimmonsHyannisport	15	372	100	2,856	100,856
Lewis Bay	16	955	100	7,330	258,852
Jabez Neds Pond	17	44	100	334	11,805
Stewarts Creek	18	695	100	5,334	188,366
WELL_Craigville#8	19	84	50	324	11,444
Big Sandy Pond	20	40	27	83	2,938
Fawcetts Pond	21	127	100	977	34,501
Snows Creek	22	544	100	4,178	147,554
Simmons Pond	23	100	100	767	27,076
Straightway Pond	24	12	100	93	3,278
OceanStE	25	8	100	64	2,243
Uncle Roberts Cove	26	174	100	1,332	47,031
Hyannis Harbor East	27	141	100	1,121	39,584
Hyannis Harbor West	28	186	100	1,437	50,748
Hyannis WPC Facility*			100	6,435	227,257
TOTAL LEWIS BAY SYSTEM				61,743	2,180,432
TOTAL HALLS CREEK				9,796	345,931

*Hyannis Water Pollution Control Facility is assumed to discharge 1.7 million gallons per day based on average effluent discharge 2002-2006 (n=1,504)

Note: discharge volumes are based on 27.25 in of annual recharge over the watershed area; up-gradient ponds often discharge to numerous down-gradient sub-watersheds, percentage of outflow is determined by length of down-gradient shoreline going to each sub-watershed; totals may not exactly match columns sums due to apportionment of WPC facility flows. Measured flow at stream gage locations will not exactly match calculated whole watershed recharge values as ponds often sit on groundwater divides thereby splitting flows between different sub-watersheds.

The evolution of the watershed delineations for the Lewis Bay system and Halls Creek have allowed increasing accuracy as each new version adds new hydrologic data to that previously collected; the model allows all this data to be organized and to be brought into congruence with adjacent watersheds. The evaluation of older data and incorporation of new data during the development of the model is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model used for the evaluation of nitrogen management alternatives. Errors in watershed delineations do not necessarily result in proportional errors in nitrogen loading as errors in loading depend upon the land-uses that are included/excluded within the contributing areas. Small errors in watershed area can result in large errors in loading if a large source is counted in or out. Conversely, large errors in watershed area that involve only natural woodlands have little effect on nitrogen inputs to the down-gradient estuary. The MEP watershed delineation was used to develop the watershed nitrogen loads to each of the aquatic systems and ultimately to the estuarine waters of the Lewis Bay system and Halls Creek (Section IV.1).