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 Centerville River/East Bay embayment system located in Barnstable, Massachusetts. The Centerville River/East 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 Centerville River/East Bay embayment system under evaluation by the Project Team. The Centerville River/East Bay estuarine system is a moderately complex estuary and includes significant wetland dominated eastern portion. Further watershed modeling was undertaken to sub-divide the overall watershed to the Centerville River/East 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 Centerville River/East Bay system were delineated using a regional model of the Sagamore Lens flow cell (Walter and Whealan, 2004). 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, 1994), 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 Centerville River/East Bay system including a subwatershed to Scudder Bay/Bumps River 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 Centerville River/East 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 Centerville River/East Bay watershed (including Scudder Bay/Bumps River) is generally split between the Mashpee Outwash Plain Deposits to the west and Barnstable Plain Deposits to the east; modeling and field measurements of contaminant transport at the MMR has 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 coastal 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 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 streamflow data collected in 1989-1990 as well as 2003.

The 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 municipal treatment facilities, water withdrawn from the modeled aquifer by public drinking water supply wells is evenly returned within designated residential areas utilizing on-site septic systems. Since no municipal wastewater treatment facilities discharge within the Centerville River/East Bay watershed, modeled return flow is returned to the groundwater in developed areas as septic system recharge.

III.3 CENTERVILLE RIVER/EAST BAY CONTRIBUTORY AREAS

Newly revised watershed and sub-watershed boundaries were determined by the United States Geological Survey (USGS) for the Centerville River/East Bay embayment system, including Scudder Bay/Bumps River sub-embayment and Lake Wequaquet (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 10 yr time of travel boundaries. Overall, twenty-two (22) sub-watershed areas, including nine freshwater ponds, were delineated within the watershed to the Centerville River/East Bay embayment system.

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 Centerville River/East Bay from the MEP delineated watershed is 54,416 m3/d.

The delineations completed for the MEP project are the second watershed delineation completed in recent years for portions of the Centerville River/East Bay estuary. Figure III-2 compares the delineation completed under the current effort with the Centerville River/East Bay delineation 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 Centerville River/East Bay system as a whole is 11% smaller (913 acres) than the 1995 CCC delineation. The differences are largely attributable to a more southern location for the Cape Cod Bay/Vineyard Sound groundwater divide and a more eastern location for the western boundary of the system watershed in the MEP watershed. The change in the western boundary is generally due to the refinements of the Three Bays watershed documented in that system's MEP Technical Report (Howes, *et al*., 2005). It should also be noted that the Three Bays watersheds to Micah and Joshua's ponds were corrected in the Centerville River/East Bay analysis in order to better account for the measured streamflow in Skunknet River (see section IV.2.2). Subwatersheds to individual freshwater ponds were not delineated in the CCC watershed.

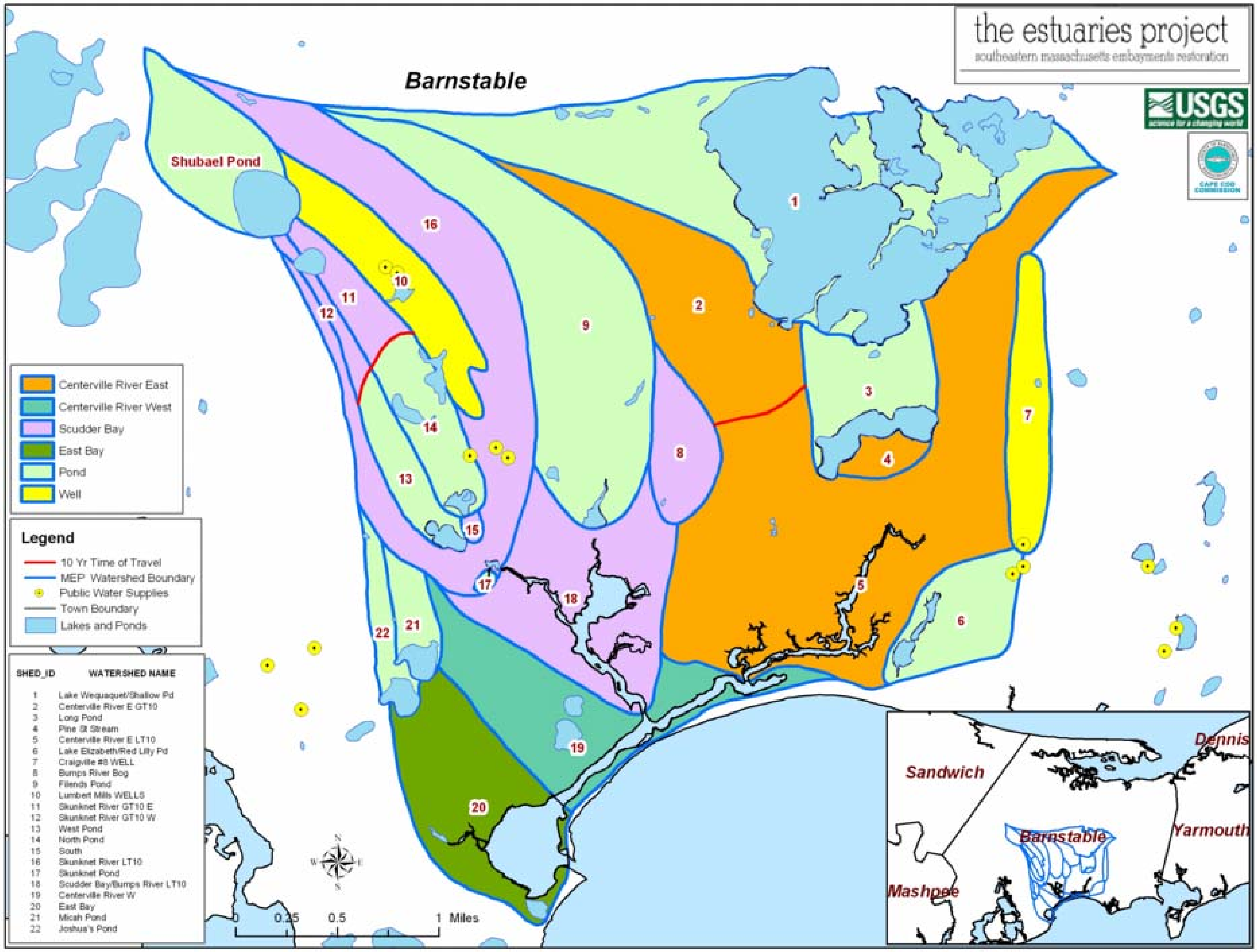

Figure III-1. Watershed and sub-watershed delineations for the Centerville River/East Bay estuary system. Approximate ten year time-of-travel delineations were produced for quality assurance purposes and are designated with a “10” in the watershed names (above). Sub-watersheds to embayments were selected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

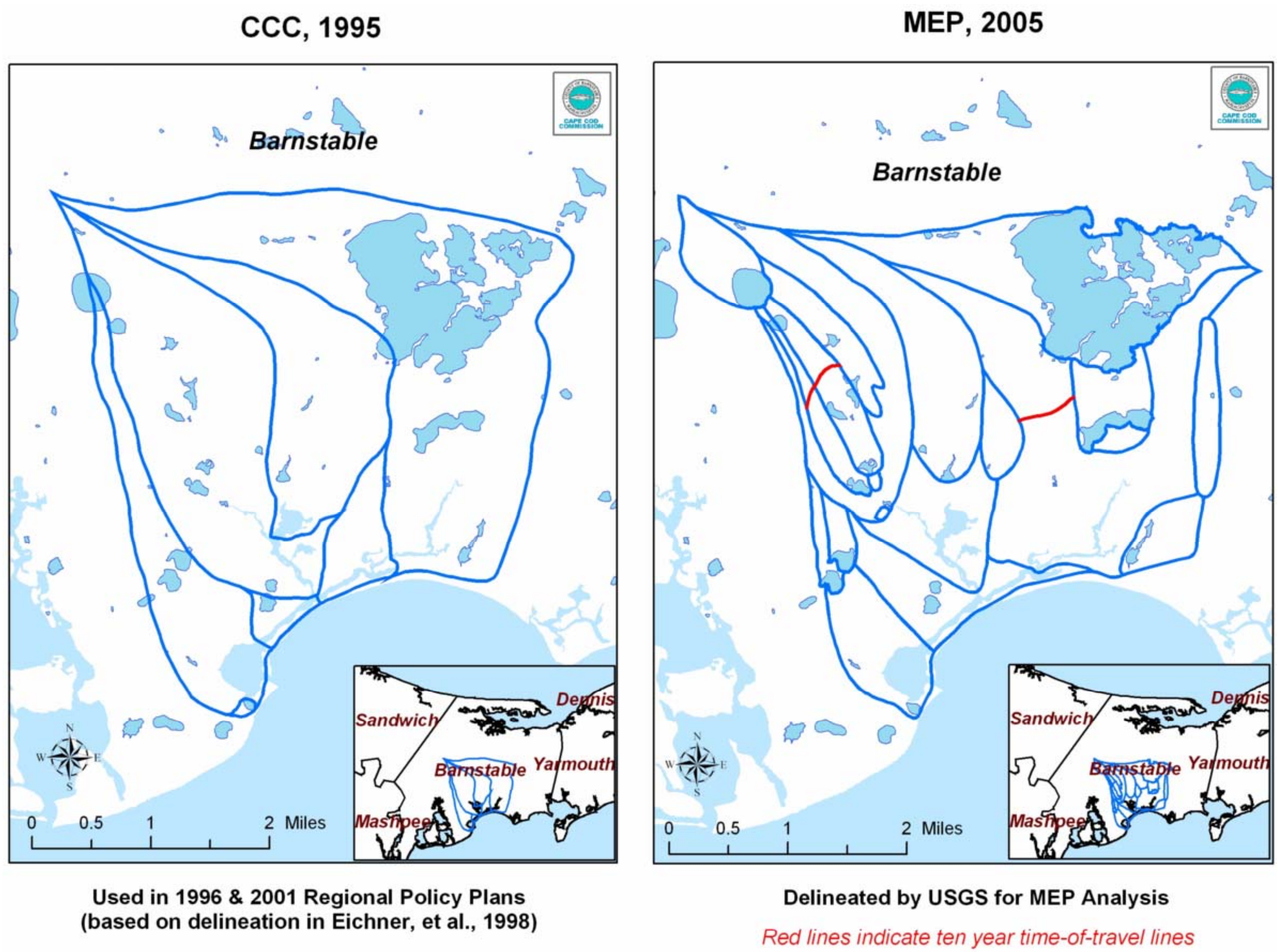

Figure III-2. Comparison of 1998 Cape Cod Commission and current Centerville River/East Bay watershed and subwatershed delineations.

Table III-1. Daily groundwater discharge from each of the sub-watersheds to the Centerville River/East Bay Estuary, as determined from the USGS groundwater model.

Watershed	Watershed #	Discharge	
		m³/day	ft³/day
Lake Wequaquet/Shallow Pond	1	10,637	375,647
Centerville River E GT10	2	3,202	113,086
Long Pond	3	1,804	63,715
Pine Street Stream	4	345	12,174
Centerville River E LT10	5	9,615	339,559
Lake Elizabeth/Red Lilly Pond	6	1,358	47,946
Craigville #8 WELL	7	638	22,514
Bumps River Bog	8	1,006	35,514
Filends Pond	9	5,217	184,254
Lumbert Mills WELLS	10	1,769	62,472
Skunknet River GT10 E	11	695	24,532
Skunknet River GT10 W	12	298	10,523
West Pond	13	794	28,053
North Pond	14	1,160	40,979
South	15	61	2,150
Skunknet River LT10	16	4,894	172,833
Skunknet Pond	17	40	1,405
Scudder Bay/Bumps River LT10	18	3,147	111,121
Centerville River W	19	2,752	97,185
East Bay	20	2,430	85,805
Micah Pond	21	483	17,041
Joshua's Pond	22	430	15,194
Shubael Pond		1,642	57,997
TOTAL		54,416	1,921,697

NOTE: Discharge rates are based on 27.25 inches per year of recharge (Walter and Whealan, 2005); discharge flows from Shubael, Micah, and Joshua's Ponds and Craigville #8 WELL are adjusted to account for flow out of the system watershed.

The evolution of the Centerville River/East Bay watershed has 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 downgradient 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 Centerville River/East Bay system (Section V.1).