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 employed by the USGS to organize and analyze the available data utilize up-to-date mathematical codes and create better tools to answer the wide variety of questions related to: 1) watershed delineation, 2) surface water/groundwater interaction, 3) groundwater travel time, 4) groundwater contaminant plumes, and 5) drinking water well impacts that have arisen during the MEP analysis of southeastern Massachusetts estuaries, including the Phinneys Harbor (inclusive of the Eel Pond/Back River) embayment system located in Bourne, Massachusetts. The Phinneys Harbor watershed is situated along the northwestern edge of Cape Cod and is bounded by Buzzards Bay.

In the present MEP effort, the USGS was responsible for the application of its groundwater modeling approach to define the watershed or contributing area to the Phinneys Harbor embayment system under evaluation by the Project Team. The Phinneys Harbor estuarine system is a moderately complex estuary comprised of 3 principal basins: a flooded kettle pond (Eel Pond),,a wetland dominated portion (Back River) and an artificial large outer basin (Phinneys Harbor). The present mouth of the Back River (between Rocky Point and Phinneys Point) was the seaward terminus of the functional estuarine system until the 1930's when the causeway to Hog Island and Mashnee Island was constructed. It is this causeway that extended the estuary, by semi-enclosing a basin now Phinneys Harbor. In addition the southern boundary of Phinneys Harbor has also become more enclosed with a causeway to Tobeys Island. Although Phinneys Harbor now functions as an "artificial" sub-embayment to Buzzards Bay, it previously had supported estuarine habitats as a coastal basin along the shore of the central Buzzards Bay Estuary. Therefore, ecological changes resulting from the enclosure are more associated with nutrient enrichment of a semi-enclosed basin receiving upland inputs than a major change in environmental forcing functions (e.g. estuarine/brackish, tidal/non-tidal, etc).

In addition to the delineation of the overall upland contributing area to the Phinneys Harbor Estuarine System, watershed modeling was undertaken to sub-divide the overall watershed 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. Particle tracking was also conducted relative to the now-closed septage disposal sites within the upper watershed. This additional modeling was necessary in order to determine the transport path of residual nitrogen enriched groundwater discharging to the coast. 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 (2002 to 2003).

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 Phinneys Harbor 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 Phinneys Harbor system including subwatersheds to Back River and Eel Pond 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 approximately 150 feet below NGVD 29 in the area of the Phinneys Harbor Estuary the two lowest model layers were generally inactive 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 Phinneys Harbor System watershed (including Eel Pond and Back River) is generally situated in the Buzzards Bay Plain outwash deposits with the easternmost portion extending into the Buzzards Bay Moraine; modeling and field measurements of contaminant transport at the MMR has shown that both moraine and outwash materials are highly permeable (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 2002 - 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 watershed of the Phinneys Harbor System, modeled return flow is returned to the groundwater in developed areas as septic system recharge.

III.3 PHINNEYS HARBOR, EEL POND AND BACK RIVER CONTRIBUTORY AREAS

Newly revised watershed and sub-watershed boundaries were determined by the United States Geological Survey (USGS) for the Phinneys Harbor System, including the sub-watersheds to the Phinneys Harbor basin, Eel Pond basin and Back River marshes (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 (Chapter V). 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, ten sub-watershed areas, including one freshwater pond (Clay Pond), were delineated within the watershed to the Phinneys Harbor Estuarine System..

Table III-1 provides the daily discharge volumes for various sub-watersheds as calculated by the groundwater model; these volumes were used to assist in the salinity calibration of the water quality modeling effort (Chapter VI) and to determine hydrologic turnover in the lakes/ponds (Chapter IV), as well as for comparison to measured surface water discharges. The overall estimated groundwater flow into Phinneys Harbor from the MEP delineated watershed is 24,036 m3/d.

The delineations completed for the MEP are the second set of watershed delineations completed in recent years for portions of the Phinneys Harbor estuary. Figure III-2 compares the delineation completed under the current effort with the Eel Pond/Back River delineation completed by the Cape Cod Commission in 1998 as part of the Coastal Embayment Project (Eichner, *et al*., 1998). Note that the direct contributing area to the Phinneys Harbor basin was not delineated in this earlier effort. 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).

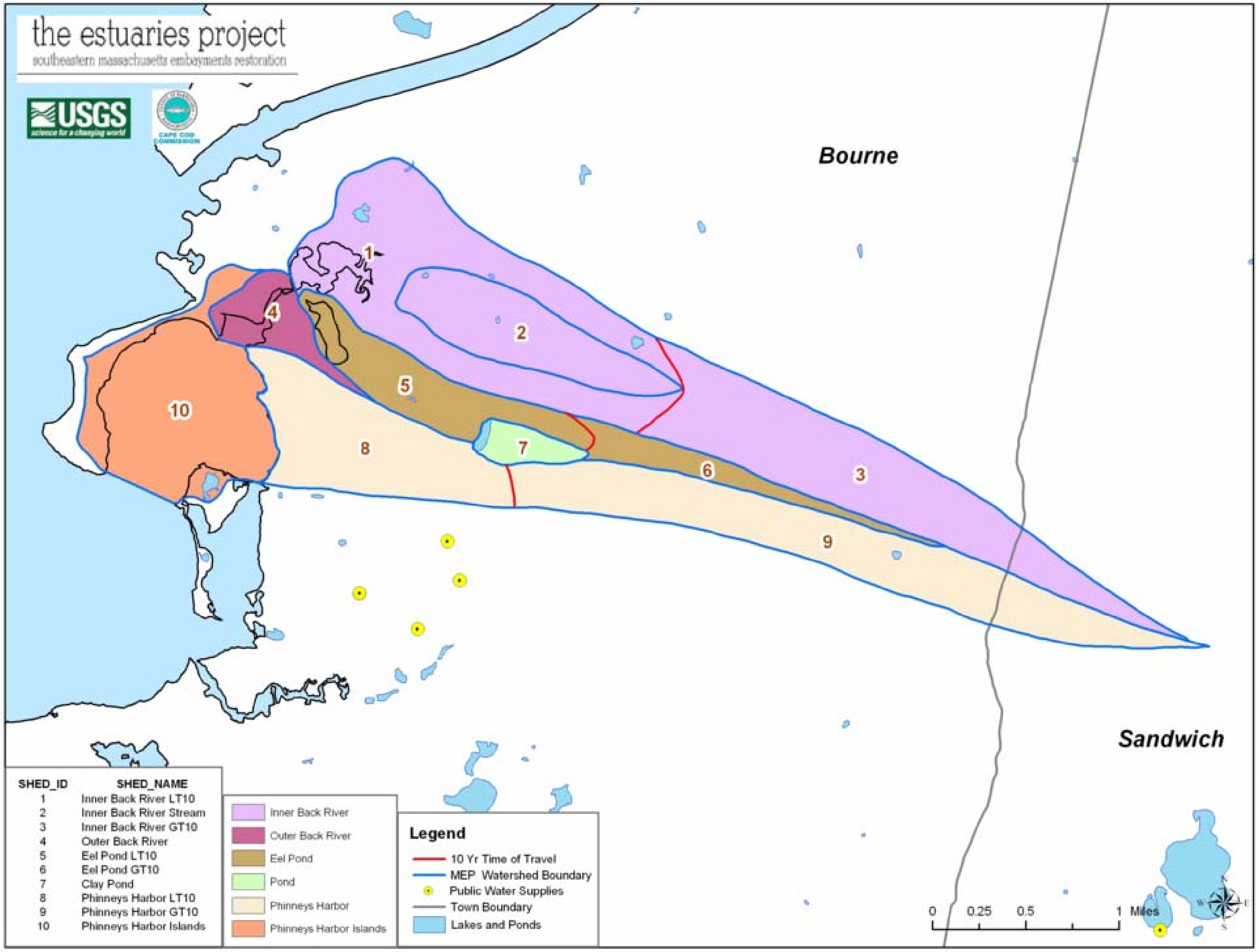

Figure III-1. Watershed and sub-watershed delineations for the Phinneys Harbor Estuarine System. Approximate ten year time-of-travel delineations were produced for quality assurance purposes and are designated with a “10” in the watershed names (above). Sub-watersheds to embayments were selected based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

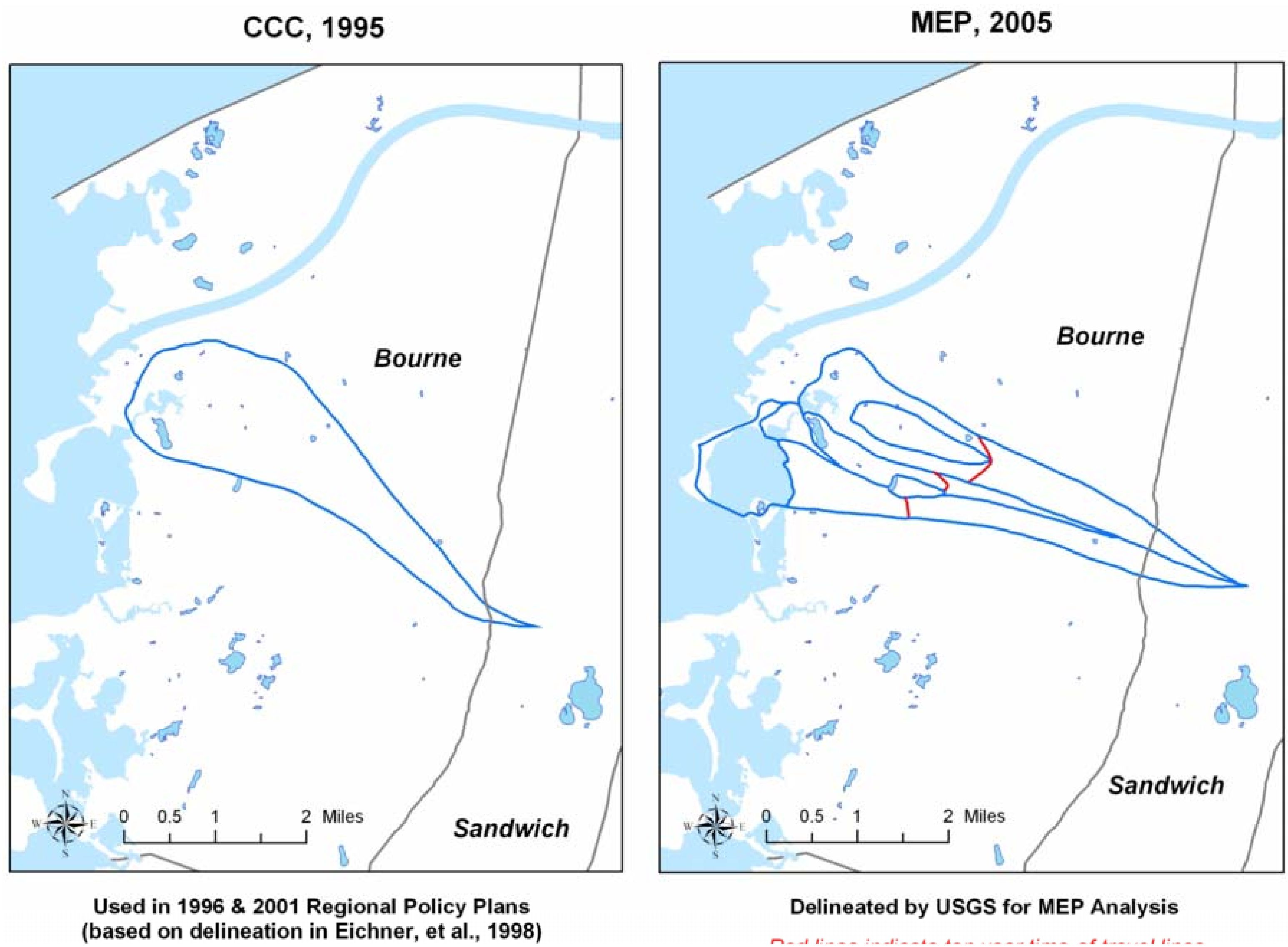

Figure III-2. Comparison of 1998 Cape Cod Commission and current Phinneys Harbor watershed and subwatershed delineations. The watershed area to the Eel Pond and Back River sub-estuaries is 18% smaller in the MEP analysis primarily due to better location of the top of the Sagamore Lens. Red lines represent ten year time of travel.

Table III-1. Daily groundwater discharge from each of the sub-watersheds to the Phinneys Harbor Estuary, as determined from the USGS groundwater model.

Watershed	Watershed #	Discharge	
		m^3/day	ft^3/day
Inner Back River LT10	1	4,633	163,607
Inner Back R Stream	2	2,197	77,580
Inner Back River GT10	3	4,690	165,629
Outer Back R	4	760	26,829
Eel Pd LT10	5	1,739	61,409
Eel Pd GT10	6	963	34,022
Clay Pd	7	473	16,713
Phinneys Hbr LT10	8	3,099	109,445
Phinneys Hbr GT10	9	4,602	162,512
Phinneys Hbr Islands	10	880	31,085
Whole System		24,036	848,832

NOTE: Discharge rates are based on 27.25 inches per year of recharge (Walter and Whealan, 2005).

Although direct comparisons are difficult because the watersheds are drawn from different portions of the Phinneys Harbor system, the MEP watershed area for roughly the same portion of the CCC watershed is 18% smaller. Most of this difference appears to be attributable to a more northern location for the top of the Sagamore Lens; it is approximately 0.5 mile further north in the current USGS configuration. The change in the top of the mound allows more direct flow paths to Phinneys Harbor and reduces some of the "bulge" in the northern boundary (see Figure III-2). Subwatersheds were not delineated in the CCC watershed.

The evolution of the watershed delineations for the Phinneys Harbor Estuarine System has provided increasing accuracy as each 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. In the present case of the Phinneys Harbor System watershed, the upper half (east of Rt. 28) is within a generally undeveloped region of the Massachusetts Military Reservation, which further minimizes potential inaccuracies in the nitrogen loading analysis stemming from the watershed delineation. 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 Phinneys Harbor system (Section V.1).