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 used 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 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 West Falmouth Harbor embayment system located in Falmouth, Massachusetts.

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 West Falmouth Harbor embayment system under evaluation by the Project Team. The West Falmouth Harbor estuarine system is composed of a complex estuary, originating from sea level flooding of a knob and kettle landscape formed by a terminal moraine and a small river valley (Mashapaquit Creek). As sea level rose the harbor was originally an open basin with an island that is now known as Chappaquoit Point, marking the outer boundary with Buzzards Bay. With the progression of coastal processes the main basins were formed as a lagoonal estuary by deposition of the sand spit (Chappaquoit Beach) enclosing the present Harbor.

Watershed modeling was undertaken to sub-divide the overall watershed to the West Falmouth Harbor 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 historic (1989, 1990 and 2003) stream flow measurements.

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 the 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 the stream and the portion of the groundwater system that discharges directly into the estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the West Falmouth Harbor system and local freshwater bodies were delineated using a regional model of the Sagamore Lens (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 the main basins of the West Falmouth Harbor system and also to determine portions of recharged water that may flow through freshwater 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. Layers 1-7 are stacked above NGVD 29 and layers 8 to 20 extend below. Layer 18 has a thickness of 40 feet and layer 19 extends to 240 feet below sea level. The bottom layer, layer 20, extend from 240 feet below sea level to the bedrock surface and has a variable thickness depending upon site characteristics. 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. In the portion of the Sagamore Lens in which the West Falmouth Harbor system resides, groundwater elevations are generally less than +40 ft and, therefore, over much of the study area the uppermost layers of the model are inactive.

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 West Falmouth Harbor watershed extends from the Buzzards Bay outwash deposits near the Harbor to the Buzzards Bay Moraine; modeling and field measurements of contaminant transport at the Massachusetts Military Reservation (MMR) has shown that both moraine and outwash 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 and town records and stream flow 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 for the Sagamore Lens. 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. In the West Falmouth Harbor watershed area, return flow is included in the non-sewered residential areas close to the harbor and additional water from outside the watershed is included by the discharge of the Town of Falmouth Wastewater Treatment Facility.

III.3 WEST FALMOUTH HARBOR CONTRIBUTORY AREAS

Revised watershed and sub-watershed boundaries were determined by the United States Geological Survey (USGS) for the West Falmouth Harbor embayment system (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, and (c) 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. Overall, thirteen sub-watershed areas were delineated within the watershed to the West Falmouth Harbor embayment system. The MEP sub-watershed delineation includes 10 yr time of travel boundaries as part of assessing the watershed nitrogen loading model and its ability to resolve present nitrogen inputs to the estuary.

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 tidal hydrodynamic model and for comparison to measured surface water discharges. The overall estimated groundwater flow into West Falmouth Harbor from the MEP delineated watershed is 14,436 m^3d^{-1}. The long-term average freshwater discharges from the sub-watersheds to Upper (1,877 m^3d^{-1}) and Lower (3,544 m^3d^{-1}) Mashapaquit Creek are consistent with direct measurements of discharge made in 1998-99 of 1,693 m^3d^{-1} and 4,377 m^3d^{-1}) respectively (Smith 1999) or ~10% difference overall.

West Falmouth Harbor has been the subject of a number of watershed delineation efforts. Each of these efforts has utilized information collected during the prior effort and the delineations completed for the MEP project benefit from information developed by the Cape Cod Commission (Eichner, *et al.*, 1998) and additional information developed during the regulatory review of the proposed expansion of the Town of Falmouth WWTF (e.g., Howes, *et al.*, 2000). Figure III-2 compares the delineation completed under the current effort with the delineation completed by the Cape Cod Commission. The CCC delineation completed in 1995 was defined based on regional water table measurements collected over a number of years and normalized to average conditions; delineations based on this effort were incorporated into the Commission's regulations through the Regional Policy Plan (CCC, 1996 & 2001).

The MEP watershed area for the West Falmouth Harbor system as a whole is 25% smaller (566 acres) than the 1995 CCC delineation. This significant change is largely due to the more western location and more northeast/southwest orientation of the Buzzards Bay/Vineyard Sound groundwater divide. The change in location has the greatest impact on the more southern portions of the watershed delineation; the combined Oyster Pond/Harbor Head delineation is 60% smaller than the 1995 CCC delineation. On the other hand, the Snug Harbor plus Mashapaquit Creek delineation, which includes the WWTF, is only 5% (45 acres) smaller.

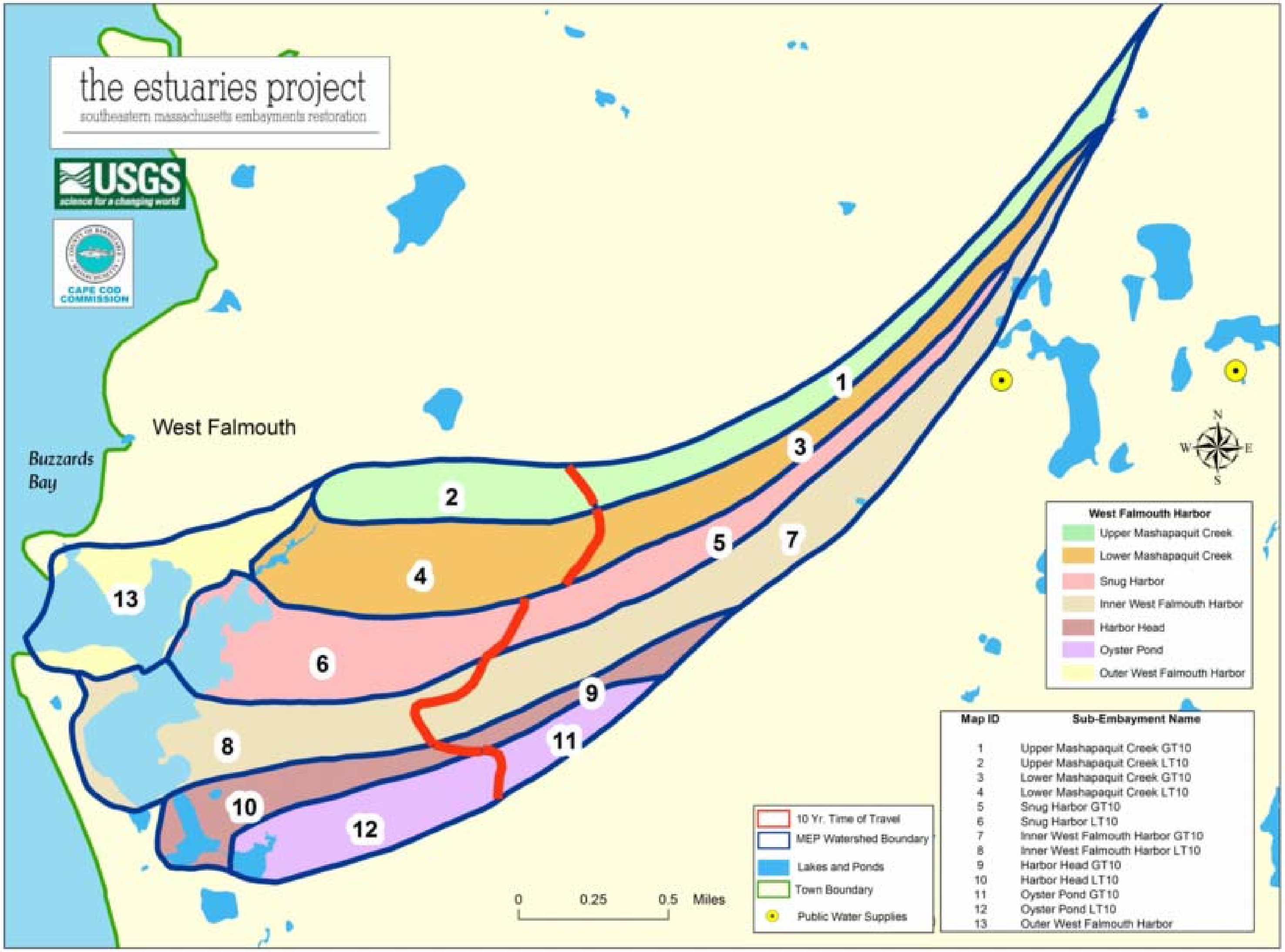

Figure III-1. Watershed and sub-watershed delineations for the West Falmouth Harbor estuary system. Approximate ten year time-of-travel delineations were produced for quality assurance purposes and are designated with a "10" in the watershed names (above). Sub-watersheds to embayments were selected based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

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

Watershed	Watershed #	Discharge	
		ft^3/day	m^3/day
Upper Mashapaquit Creek GT10	1	36,818	1,043
Upper Mashapaquit Creek LT10	2	29,471	835
Lower Mashapaquit Creek GT10	3	39,046	1,106
Lower Mashapaquit Creek LT10	4	86,106	2,438
Snug Harbor GT10	5	41,347	1,171
Snug Harbor LT10	6	48,157	1,364
Inner West Falmouth Harbor GT10	7	83,086	2,353
Inner West Falmouth Harbor LT10	8	39,962	1,132
Harbor Head GT10	9	12,543	355
Harbor Head LT10	10	23,730	672
Oyster Pond GT10	11	12,535	355
Oyster Pond LT10	12	31,501	892
Outer West Falmouth Harbor	13	25,508	722
Whole System		509,811	14,436

Note: 100% of Oyster Pond flow discharges into the Inner West Falmouth Harbor watershed.

The evolution of the watershed delineations for West Falmouth Harbor 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 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 West Falmouth Harbor system (Section V.1).

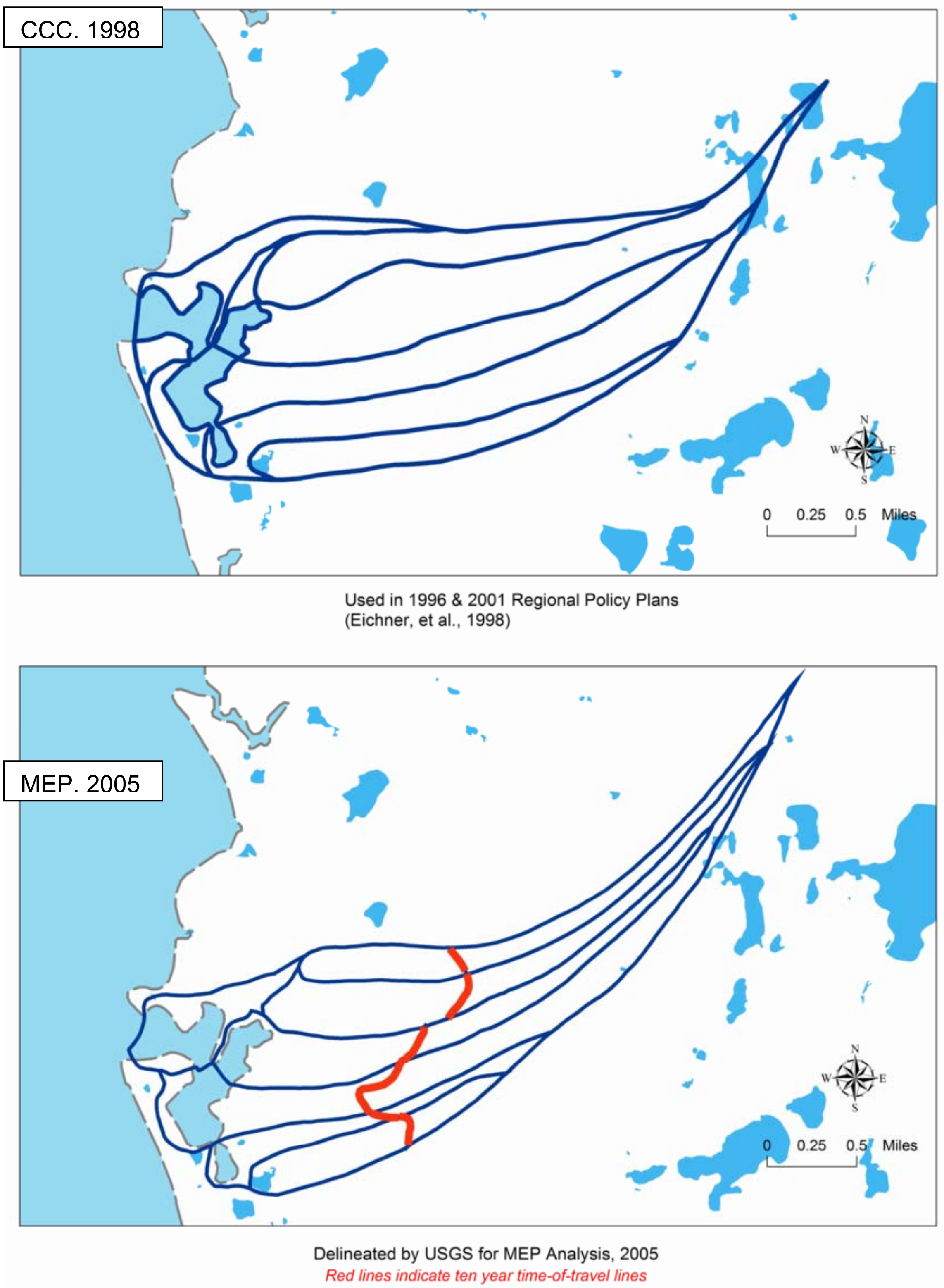

Figure III-2. Comparison of 1998 Cape Cod Commission and current West Falmouth Harbor watershed and subwatershed delineations.