III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project Technical Team includes 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, new lithologic information from well installations, groundwater 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 to 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 Oyster Pond 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 Oyster Pond system under evaluation by the Project Team. The Oyster Pond estuarine system is composed of a simple estuary, originating from sea level flooding of a coastal kettle basin. The system is naturally tidally restricted due to the formation of a barrier beach to Vineyard Sound. In 1872 the construction of a railroad on the barrier beach complex further restricted the tidal exchange. The present tidal channel and restricted tidal exchange and approximate water levels have likely been in place for ~100 years, with only periodic short-term disruptions. Watershed modeling was undertaken to sub-divide the overall watershed to the Oyster Pond 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 current stream gage information (2002-2003).

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 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 input pathways 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 Oyster Pond system and local freshwater bodies were delineated using a regional model of the Sagamore Lens (Walter and Whealan, in press). 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 Oyster Pond 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 sea level and have a uniform thickness of 10 ft. The top of layer 8 resides at sea level with layers 1-7 stacked above sea level to a maximum elevation of +70 feet. In the portion of the Sagamore Lens in which the Oyster Pond system resides, water elevations are generally less than +40 ft and, therefore, over much of the study area the uppermost layers are inactive. Layer 18 has a thickness of 40 feet and layer 19 extends to 240 feet below sea level. The bottom layer, layer 20, extends to the bedrock surface and has a variable thickness depending upon site characteristics.

The glacial sediments that comprise the aquifer of the Sagamore flow cell 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. Oyster Pond is situated on the boundary between the Buzzards Bay Moraine and very-coarse grained Mashpee Pitted Plain deposits (Masterson, et al., 1996). In fact the upper basins of Oyster Pond and watershed are situated in glacial till and only the lower deep basin and adjacent watershed are in outwash (Emery 1997). 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 water level and streamflow data collected in May 2002.

The regional 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. Since all of the watersheds to Oyster Pond are unsewered, 85% of the water pumped from wells was modeled as being returned to the ground via on-site septic systems.

III.3 OYSTER POND CONTRIBUTORY AREAS

Revised watershed and sub-watershed boundaries were determined by the United States Geological Survey (USGS) for the Oyster Pond embayment system (Figure III-1). Model outputs of MEP watershed boundaries were “smoothed” to (a) account for the grid spacing, (b) to enhance the accuracy of the characterization of the shoreline, 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, five sub-watershed areas were delineated within the watershed to the Oyster Pond embayment system.

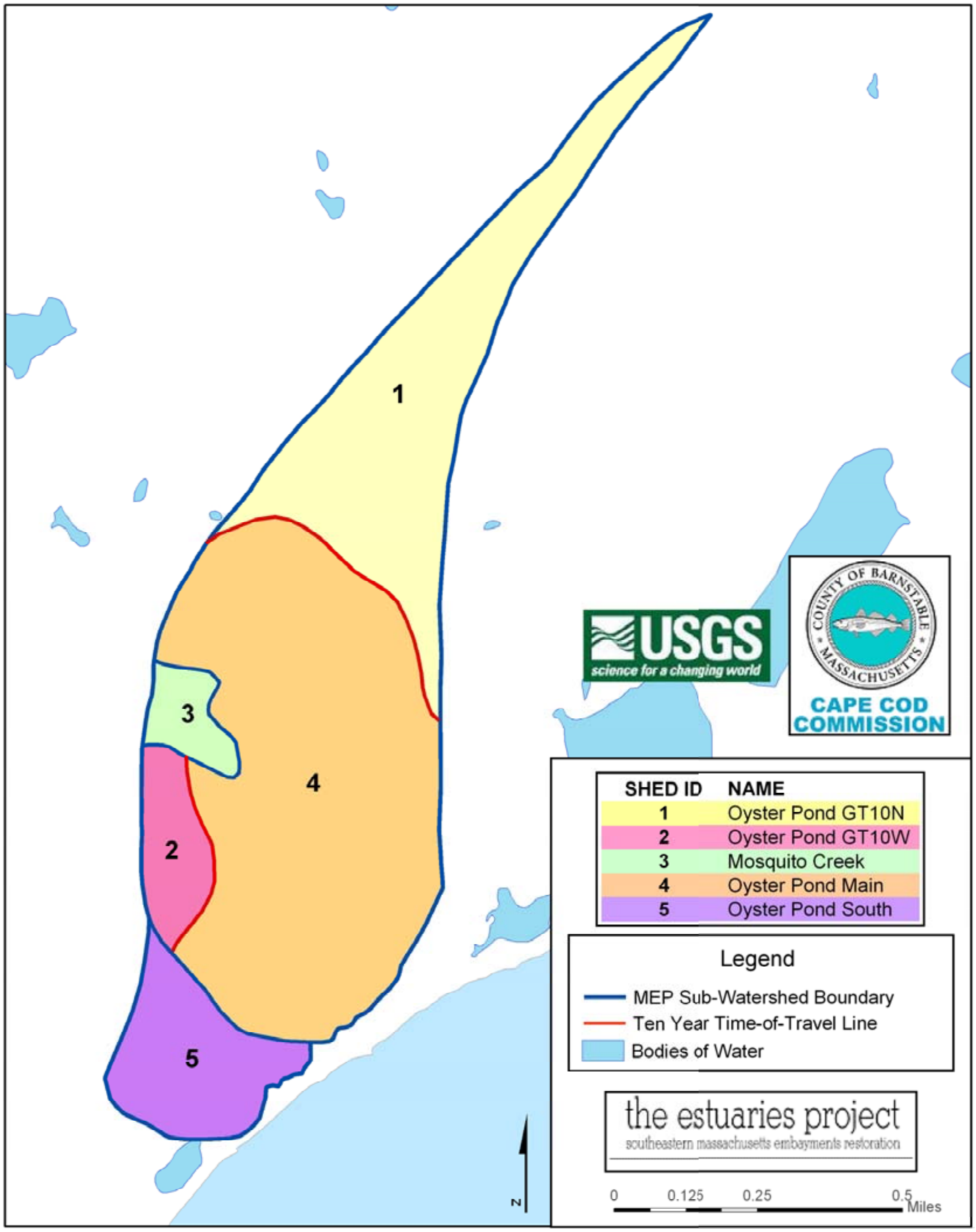

Figure III-1. Watershed and sub-watershed delineations for the Oyster Pond estuary system. Approximate ten year time-of-travel delineations were produced for quality assurance purposes and are designated with a “10” in the watershed names (above). Sub-watersheds to embayments were selected based upon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

Table III-1 provides the daily discharge volumes for various watersheds as calculated by the groundwater model; these volumes were used to assist in the salinity calibration of the tidal hydrodynamic models and for comparison to measured surface water discharges. The MEP delineation includes 10 yr time of travel boundaries. The overall estimated groundwater flow into Oyster Pond from the MEP watershed is 2,587 m3/d. This flow compares favorably with the 2,600 m3/d average calculated from estimates by K.O. Emery (1969) from a variety of measurement methods. Note that the values re-calculated from Emery, are based upon Pond level changes and freshwater discharge to Vineyard Sound. These results provide and independent validation of the regional model, which is founded on watershed hydrologic information.

Table III-1. Daily groundwater discharge to each of the sub-embayments in the Oyster Pond system, as determined from the USGS groundwater model.

Watershed	**Discharge**	
	ft^3/day	**m^3/day**
Oyster Pond GT10N	31,594	895
Oyster Pond GT10W	5,794	164
Mosquito Creek_Oyster Pond	3,571	101
Oyster Pond_Main	39,283	1,113
Oyster Pond_South	11,100	314
Whole System	91,343	2,587

The delineations completed for the MEP project are the third watershed delineation completed in recent years for the Oyster Pond estuary. Figure III-2 compares the delineation completed under the current effort with the delineation completed by the Cape Cod Commission in 1995 (Eichner, et al., 1998). The 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 third watershed delineation was based upon the 1995 Commission effort with additional groundwater elevation information and topographic interpretation (Howes and Hart 1997). As this latter watershed was not a regulatory effort and was in between the MEP and Commission delineations, it will not be discussed further here.

The MEP watershed area for the Oyster Pond as a whole is 22% larger (74 acres) than the 1995 Cape Cod Commission (CCC) delineation. Most of this change is attributable to the larger northern section of the watershed in the MEP watershed. The expansion of this area is due to the USGS model assigning a more northern location to the groundwater divide between Vineyard Sound and Buzzards Bay. The more northern location for the divide also results in a slight expansion to the west for the MEP watershed as compared to the CCC watershed (see Figure III-2). It should also be noted that the CCC watershed includes an area surrounding a small pond to the southwest of the Oyster Pond estuary; this area is not included in the MEP watershed. Sub-watersheds were not delineated in the 1995 CCC watershed.

The evolution of the watershed delineations for the Oyster Pond System have built one on another as the underlying hydrologic data supporting the modeling has increased, thereby yielding higher accuracy. This 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 present watershed delineation to Oyster Pond appears to be relatively robust given its general similarity to the previous 2 delineations and the good agreement with the estimates of freshwater exiting to Vineyard Sound through the salinity control/fish weir at the south end of the Pond.

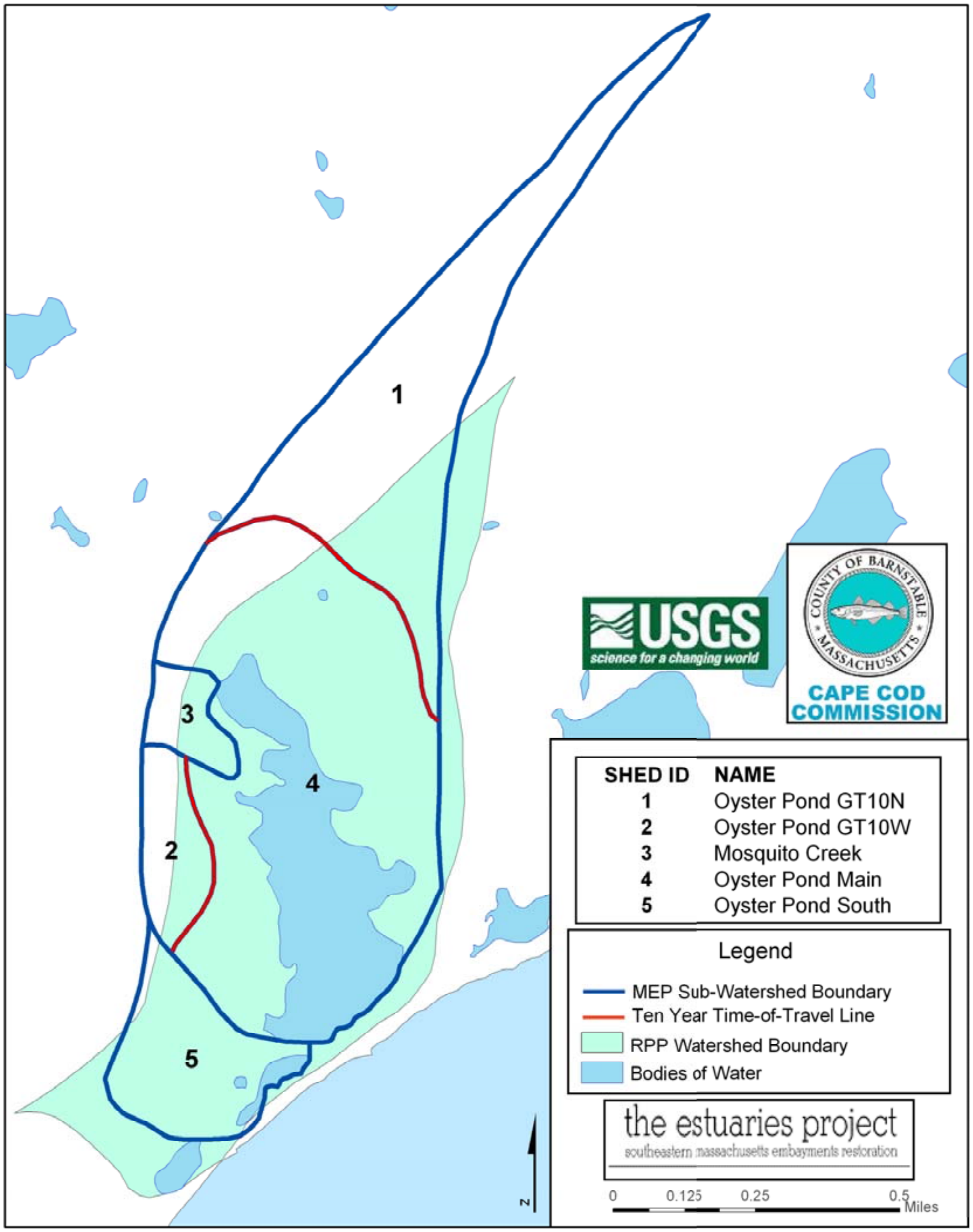

Figure III-2. Comparison of previous and current Oyster Pond watershed and subwatershed delineations.