III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS). The 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 to organize and analyze the available data use 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 Pleasant Bay embayment system. The Pleasant Bay System and its watershed are located within the Towns of Orleans, Brewster, Harwich, and Chatham. Pleasant Bay is the largest estuarine system on Cape Cod, situated along its southeastern edge. The Pleasant Bay System currently exchanges tidal water with the Atlantic Ocean, but prior to the formation of the New inlet through Nauset Spit, it exchanged water off south Chatham, i.e. Chatham Roads.

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 Pleasant Bay system under evaluation by the Project Team. Further modeling of the Pleasant Bay system 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. The three-dimensional numerical model employed is also being used to evaluate the contributing areas to public water supply wells in the overall Monomoy groundwater flow cell. Model assumptions for calibration were matched to surface water inputs and flows from current (2002 to 2003) stream gauge information. Given the recent alteration of the hydrodynamics of the Pleasant Bay System, resulting from the new inlet formation, the USGS used the present mean tidal levels in Pleasant Bay as the boundary condition in its watershed delineation effort.

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 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 Pleasant Bay Estuarine System and local freshwater bodies were delineated using a regional model of the Monomoy 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 watershed contributing areas to the Pleasant Bay System and also to determine portions of recharged water that may flow through ponds and streams prior to discharging into coastal water bodies.

The Monomoy Flow Model grid consists of 164 rows, 220 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 National Geodetic Vertical Datum (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 525 feet below NGVD 29). 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. Since water elevations are less than +40 ft in the portion of the Monomoy Lens in which the Pleasant Bay system resides, the three uppermost layers of the model are inactive.

The glacial sediments that comprise the aquifer of the Monomoy Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments. The sediments generally show a fining downward sequence 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 Pleasant Bay watershed is located in the Harwich Plains, which were deposited as glacial ice lobes were retreating to positions near the current Cape Cod Bay shoreline and the barrier beach along the eastern edge of Pleasant Bay (Walter and Whealan, 2005). Lithologic data used to determine hydraulic conductivities used in the 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 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 wastewater 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 Pleasant Bay watershed, modeled return flow is discharged to groundwater in developed areas.

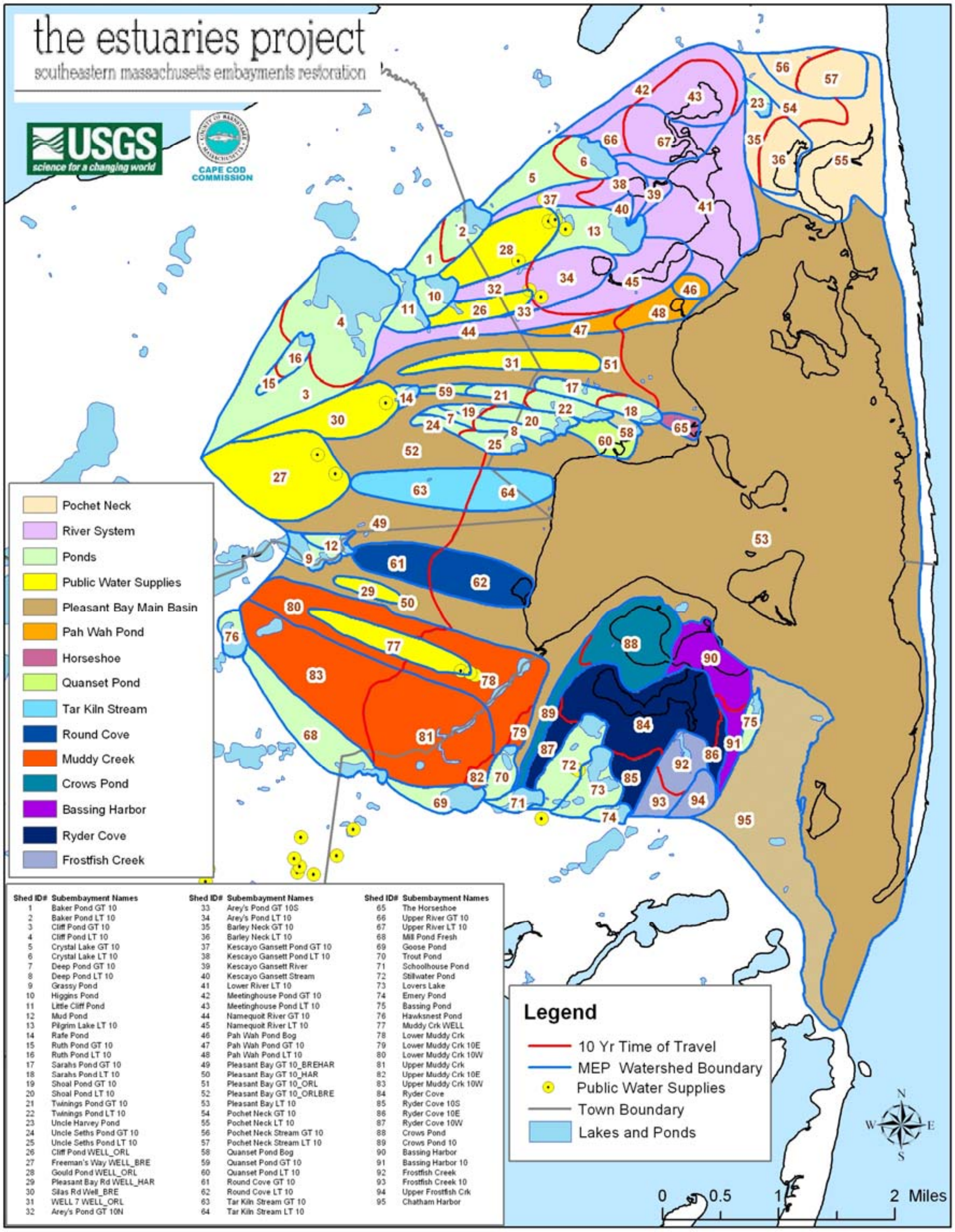
III.3 PLEASANT BAY CONTRIBUTORY AREA

Newly revised watershed and sub-watershed boundaries were determined by the United States Geological Survey (USGS) for the Pleasant Bay estuary 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. The MEP sub-watershed delineations also include 10 yr time of travel boundaries. Overall, 95 sub-watershed areas, including 25 freshwater ponds and 7 public water supply wellfields, were delineated within the watershed to the Pleasant Bay estuary system.

Table III-1 provides the daily freshwater discharge volumes for each of the subwatersheds as calculated by the groundwater model and 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 MEP delineation includes 10 yr time of travel boundaries. The overall estimated freshwater inflow to the estuarine waters of Pleasant Bay from the MEP watershed is approximately 107,000 m3/d.

The delineations completed by the MEP are the second watershed delineation completed in recent years for the Pleasant Bay estuary. Figure III-2 compares the delineation completed under the current effort with the delineation completed by the Cape Cod Commission in 1998 as part of a nitrogen loading study (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).

Overall, the MEP contributing area to Pleasant Bay based upon the groundwater modeling effort is very similar to the previous delineation based upon available well data, the MEP area is only 1% or 164 acres larger. However, some of the interior subwatersheds areas are different; for example more refined delineation of the pond subwatersheds in the MEP delineations causes the Arey’s Pond/Namequoit River subwatershed to shift more to the north and reduces the watershed area from 2,737 acres to 921 acres. On the other hand, the subwatershed to Kescayo Gansett Pond only changes by 7 acres or 2%.



Shed ID#	Subembayment Names	Shed ID#	Subembayment Names	Shed ID#	Subembayment Names
1	Baker Pond GT 10	33	Arey's Pond GT 10S	65	The Horseshoe
2	Baker Pond LT 10	34	Arey's Pond LT 10	66	Upper River GT 10
3	Cliff Pond GT 10	35	Barley Neck GT 10	67	Upper River LT 10
4	Cliff Pond LT 10	36	Barley Neck LT 10	68	Mill Pond Fresh
5	Crystal Lake GT 10	37	Kescayo Gansett Pond GT 10	69	Goose Pond
6	Crystal Lake LT 10	38	Kescayo Gansett Pond LT 10	70	Trout Pond
7	Deep Pond GT 10	39	Kescayo Gansett River	71	Schoolhouse Pond
8	Deep Pond LT 10	40	Kescayo Gansett Stream	72	Stillwater Pond
9	Grassy Pond	41	Lower River LT 10	73	Lovers Lake
10	Higgins Pond	42	Meetinghouse Pond GT 10	74	Emery Pond
11	Little Cliff Pond	43	Meetinghouse Pond LT 10	75	Bassing Pond
12	Mud Pond	44	Namequoit River GT 10	76	Hawksnest Pond
13	Pilgrim Lake LT 10	45	Namequoit River LT 10	77	Muddy Crk WELL
14	Rafe Pond	46	Pah Wah Pond Bog	78	Lower Muddy Crk
15	Ruth Pond GT 10	47	Pah Wah Pond GT 10	79	Lower Muddy Crk 10E
16	Ruth Pond LT 10	48	Pah Wah Pond LT 10	80	Lower Muddy Crk 10W
17	Sarahs Pond GT 10	49	Pleasant Bay GT 10_BREHAR	81	Upper Muddy Crk
18	Sarahs Pond LT 10	50	Pleasant Bay GT 10_HAR	82	Upper Muddy Crk 10E
19	Shoal Pond GT 10	51	Pleasant Bay GT 10_ORL	83	Upper Muddy Crk 10W
20	Shoal Pond LT 10	52	Pleasant Bay GT 10_ORLBRE	84	Ryder Cove
21	Twinings Pond GT 10	53	Pleasant Bay LT 10	85	Ryder Cove 10S
22	Twinings Pond LT 10	54	Pochet Neck GT 10	86	Ryder Cove 10E
23	Uncle Harvey Pond	55	Pochet Neck LT 10	87	Ryder Cove 10W
24	Uncle Seths Pond GT 10	56	Pochet Neck Stream GT 10	88	Crows Pond
25	Uncle Seths Pond LT 10	57	Pochet Neck Stream LT 10	89	Crows Pond 10
26	Cliff Pond WELL_ORL	58	Quanset Pond Bog	90	Bassing Harbor
27	Freeman's Way WELL_BRE	59	Quanset Pond GT 10	91	Bassing Harbor 10
28	Gould Pond WELL_ORL	60	Quanset Pond LT 10	92	Frostfish Creek
29	Pleasant Bay Rd WELL_HAR	61	Round Cove GT 10	93	Frostfish Creek 10
30	Silas Rd Well_BRE	62	Round Cove LT 10	94	Upper Frostfish Crk
31	WELL 7 WELL_ORL	63	Tar Kiln Stream GT 10	95	Chatham Harbor
32	Arey's Pond GT 10N	64	Tar Kiln Stream LT 10		

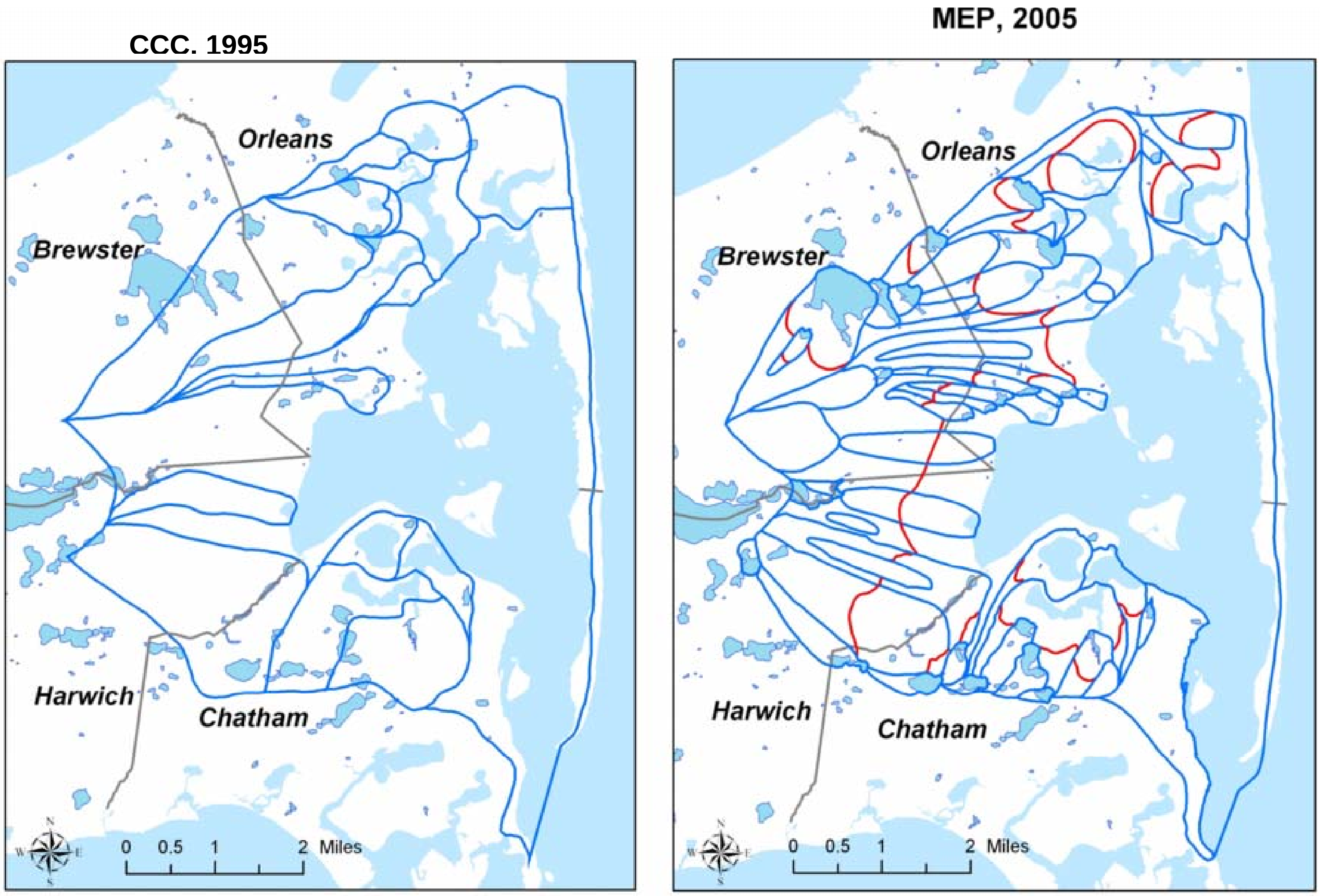
Figure III-1. Watershed delineation for the Pleasant Bay Embayment System. Approximate ten year time-of-travel delineations were produced for quality assurance purposes and are designated with a "10" in the watershed names (above). Sub-watersheds to great ponds were developed for determining nitrogen loss in transport. 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 to each of the sub-embayments in the Pleasant Bay system, as determined from the USGS groundwater model.

Watershed	Discharge	
	m3/day	ft3/day
Pochet Neck	6,757	238,638
Meetinghouse Pond	2,510	88,641
Upper River	2,980	105,224
Kescayo Gansett Pond	3,235	114,239
Kescayo Gansett Stream	1,066	37,649
Kescayo Gansett River	1,240	43,782
Areys Pond	3,272	115,563
Namequoit River	3,798	134,113
Lower River	4,409	155,718
Pah Wah Pond	1,382	48,808
Quanset Pond	1,531	54,076
Tar Kiln Stream	2,500	88,277
Round Cove	2,503	88,394
The Horseshoe	1,035	36,546
Upper Muddy Creek	8,648	305,416
Lower Muddy Creek	6,626	233,980
Ryders Cove	7,465	263,613
Crows Pond	2,680	94,660
Bassing Harbor	1,859	65,638
Frostfish Creek	1,765	62,342
Pleasant Bay Proper	33,876	1,196,337
Chatham Harbor	6,494	229,343
TOTAL	107,632	3,800,998

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

The evolution of the watershed delineations for the Pleasant Bay Estuarine System 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 data from 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. In addition, most of these “errors” are between adjacent sub-watersheds, within the overall Pleasant Bay System watershed. Therefore they do not result in a difference in total loading to the Pleasant Bay Estuarine System. For example, a shift in watershed load between the Areys Pond watershed and the adjacent Namequoit River sub-watershed has little effect even on the results for Areys Pond and no effect on the results for The River sub-embayment and to greater Pleasant Bay.



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 previous CCC (left) and MEP (right) Pleasant Bay watershed and subwatershed delineations. The MEP system watershed area is 1% or 164 acres larger. The MEP sub-watersheds to Bassing Harbor and Muddy Creek are unchanged from the previous MEP analysis for these systems.