Potential Effects of Sea-Level Rise on Puget Sound Wetlands

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Eco Modeling

Potential Effects of Sea-Level Rise on Puget Sound Wetlands

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Abstract

Remote sensing and simulation modeling of coastal areas around Puget Sound, Washington (U.S.A.) suggest that sea-level rise due to global warming could lead to a large loss of tidal flats with a significant decrease in shellfish and habitat loss for diving ducks and geese. In contrast, if small dikes enclosing most of the former salt- and brackish marshes are allowed to deteriorate, saltmarshes will gradually reclaim these lowlands; if the dikes are strengthened, saltmarshes will disappear. Freshwater marshes and swamps could exhibit a slight increase in area as the base level changes and the water table rises adjacent to the shoreline.

Introduction

Global warming could raise sea level 50 to 100 cm by the year 2100 (Figure 1). An accelerated rise could have serious impacts on coastal wetlands and associated wildlife and fisheries. In the contiguous United States inundation and erosion could destroy 50 to 80 percent of the existing coastal marshes and swamps (Park *et al.* 1989a).

Historically, many coastal marshes in the Pacific Northwest were diked to prevent flooding during spring tides and to enable cattle to graze in the marshes (cf. Bortleson *et al.* 1980). Subsequently some of these marshes were drained and the dike or levee systems were strengthened so that the flat-lying rich soils could be farmed. As a result, the extensive tidal flats produced by the high tidal ranges of the region are not matched by equally extensive saltmarshes such as would occur under natural conditions. The remaining saltmarshes continue to support the detrital food chain, provide rearing habitat for chinook salmon and other fishes, and serve as wintering habitat for large waterfowl populations. Tidal flats in Washington State are important ecologic and economic resources because they support large oyster and clam populations; they also serve as waterfowl habitat.

One would expect the high tidal ranges, with corresponding broad elevational ranges for wetlands, to mitigate the effects of sea-level rise, while extensive diking of wetlands may exacerbate the effects. In particular, tidal flats are subject to inundation with accelerated sea-level rise; and, if adjacent saltmarshes are protected from inundation by dikes, new tidal flats will not be created.

Methods

The effects of sea-level rise were projected using a rule-based simulation model (SLAMM3), remotely

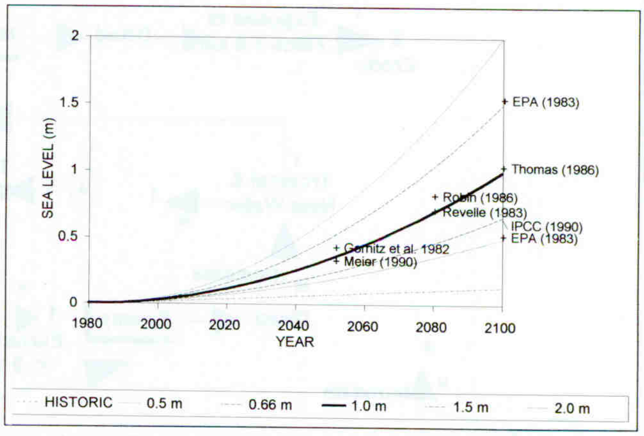

Figure 1 A comparison of various estimates of sea-level rise and the scenarios used in this study (Park 1991). Note: EPA (1983) refers to Hoffman *et al.* (1983).

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sensed land-cover data, and digital elevation data.

Simulation Modeling

The model simulates the dominant processes involved in wetland conversions and shoreline reconfigurations during long-term sea-level rise (Lee *et al.* 1992). A complex decision tree, incorporating geometric and qualitative relationships, represents transfers among coastal classes (Figure 2). Each site is divided into cells of equal area (250 by 250 m for the Puget Sound sites), and each class within a cell is simulated separately. Map distributions of wetlands are predicted under conditions of accelerated sea-level rise, and results are summarized in tabular and graphical form.

Relative sea-level change is computed for each site using the historic eustatic trend (assumed to be 1.2 mm/yr), the observed site-specific rate of change due to local subsidence and tectonic movements, and the accelerated rise calculated by one of series of quadratic equations depending on the scenario chosen (Barth and Titus 1984). Sea-level rise is offset by sedimentation and accretion; the values used in this study for marsh accretion adjacent to water courses were five mm/yr for Padilla Bay and two mm/yr for the other sites based on general trends between accretion rates and wetland dominance. Marshes not adjacent to water tend to have accretion rates that are approximately half those of streamside marshes (cf. Gosselink 1984), and that relationship was used here. Sedimentation rates for tidal flats and open water areas also are assumed to be half the accretion rates for wetlands. The model is not generally sensitive to these assumptions for sea-level rise scenarios of 100 cm or more (Park *et al.* 1989b). However, in an area such as Puget Sound with low subsidence, the predicted changes in wetlands for a 50-cm rise could be as much as 50% less if the accretion rates were twice as great (the maximum deviation expected). The time step of 5 to 25 years depends on the sea-level rise scenario chosen; a shorter step is used for higher scenarios. For each time step the fractional conversion from one class to another is computed based on the relative change in elevation divided by the elevational range of the class in that cell. For that reason, marshes that extend across wide tidal ranges such as are experienced in Puget

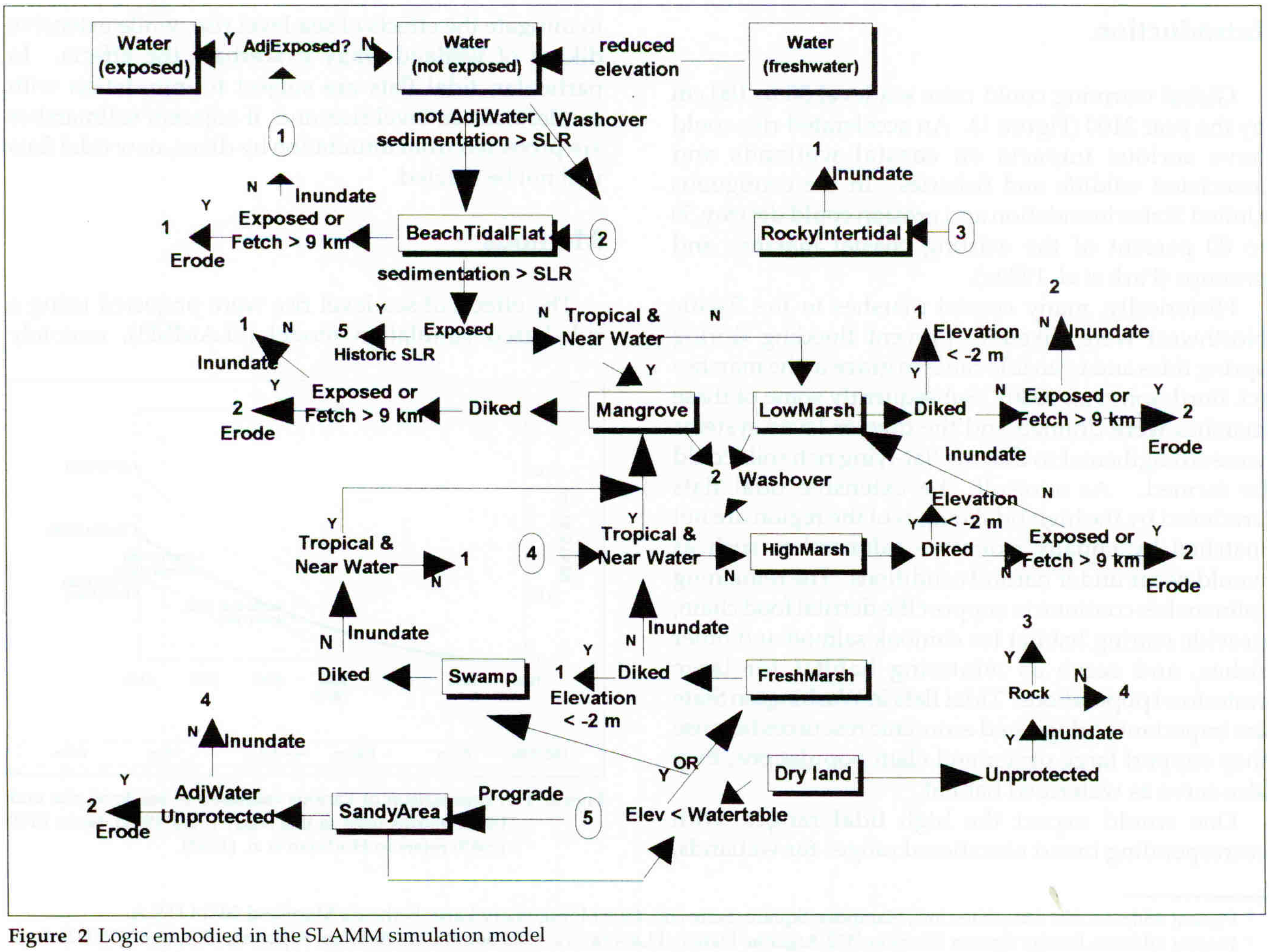

Figure 2 Logic embodied in the SLAMM simulation model

Sound are only slowly converted to unvegetated tidal flats.

Ordinarily, if a cell is protected by a dike or levee it is assumed not to change; however, this was considered on a site by site basis depending on the purpose of the dikes. For a standard simulation, cells that are largely developed are assumed to be protected by dikes as necessary to prevent inundation. The existence of these dikes can severely affect the ability of wetlands to migrate onto adjacent shorelines.

Besides the effects of inundation, changes occur due to the spatial relationships among the coastal elements. Erosion is an important process that can increase with accelerated sea-level rise. In particular, the model computes exposure to wave action; if the fetch (the distance across which waves can be formed by prevailing winds) is greater than nine km, the model assumes moderate erosion. Inundation will increase the fetch beyond this critical distance in some areas. If a cell is exposed to open ocean, such as through loss of a barrier island or spit, severe erosion of wetlands is assumed. Beach erosion is represented using a relationship reported by Bruun (1962, 1986) by which recession is 100 times the change in sea level. Wetlands on the lee side of coastal barriers are subject to conversion due to overwash as erosion of backshore and dune areas occurs and as other lowlands are drowned. Erosion of sandy areas to maintain equilibrium with adjacent beaches is modeled, but erosion of other dry lands is ignored. In Puget Sound the availability of sediment from accelerated bluff erosion may or may not allow wetlands to keep pace with sea-level rise. Coastal swamps and fresh marshes reflect the importance of high water tables in this maritime region; therefore, provision was added for response of the water table to rising sea level close to the coast.

Developing the Initial Conditions for the Simulations

The initial conditions were set by mapping current land-cover patterns and digital elevation data for the sites. Landsat Multispectral Scanner (MSS) data were used to generate land-cover information for the seven modeling sites in the Puget Sound area. Three MSS scenes, all acquired in 1986, were used for the seven simulation sites in the Puget Sound area. From the Landsat MSS data, a sub-image was developed for each simulation site and was geometrically rectified based on the Universal Transverse Mercator (UTM) projection. The bilinear interpolation technique was applied for the resampling of digital values of MSS data.

An unsupervised classification procedure was used to develop spectral classes from MSS data. The spectral values of the MSS data were grouped together to generate spectrally homogeneous classes through a clustering analysis. One hundred spectral classes were developed from the initial clustering analysis, and they were reduced to a manageable number of classes based on the statistical information of each spectral class and reference data. Then, the spectral classes were converted to information classes by associating each class with land-cover or land-use types.

Verifications of the classification results were performed using digitized National Wetland Inventory (NWI) data. The digitized NWI data, available in Digital Line Graph - (DLG) 3 Optional format, were converted to ARC/INFO polygon coverages. Each polygon represented a land-cover class defined in the U.S. Fish and Wildlife Services's classification system (Cowardin *et al.*, 1979). The only polygons of interest, all marshes and swamps, were selected from the NWI data file and overlayed onto the classified MSS data to compare the classification results with the NWI data. Some disagreement was found between the classified MSS data and NWI data for small wetlands. In the study sites, many small marshes were not detectable from the MSS data, but are shown in the NWI data. Those classes were checked against transects and verified in field checking by the staff at the Washington Department of Ecology. Since the SLAMM3 model simulates classes in coastal wetlands and lowlands, the classification of uplands was very general. Although classification accuracy was not estimated due to limited time and expenses, the overall classification results were reviewed by one of us (Canning).

Elevational data is very important for the modeling. Only part of the simulation sites were covered by the 7.5-minute U.S. Geological Survey (USGS) Digital Elevation Model (DEM) data. Elevational contours were digitized from topographic maps to generate DEM data through an interpolation process; the USGS DEM data were used where available. The DEMs from two different sources were merged to create continuous elevational surfaces for each site. These elevational data were resampled and registered to MSS-derived land-cover maps in 57-m pixel size. Elevations of saltwater wetlands were back-calculated from their relationships to tidal ranges. An elevational mosaic was assumed for saltwater wetlands, with each cover class traversing its full elevational range within a cell (representing the usual microtopography that occurs with small tidal flats and beaches, tidal creeks, natural levees, and back-levee areas). Saltwater wetland elevational ranges were computed by assuming constant relationships of the wetlands to tidal datums (cf. Lefor *et al.* 1987), with mean or half tide level (MTL) as 0; beach and tidal flats extending from mean low water (MLW) to mean high water (MHW), or from MLW to MTL on coasts with low wave energy and vegetated wetlands; low marsh extending from MTL to MHW; and high marsh extending from MHW to MHWS. (Occasionally saltwater wetlands occur above MHWS, but the area is small and can be ignored.)

Interfacing Data with the Model

The class and digital elevation data were further processed for simulation modeling. Class data were aggregated and stored as percent cover for each 250-m grid cell. The elevational data were generated in two forms: minimum and maximum elevational values for each class existing within each grid cell, so that the elevational range could be computed for a class within a grid cell (assuming sandy and rocky areas to have a convex profile, and other lowland and upland areas to have a concave profile). For each site, cell- and site-specific information was added manually to the class and elevation data based on the topographic maps; these included tidal ranges, coastal protection, wind direction, and fetch.

The Earth Resources Data Analysis System (ERDAS) was used to process Landsat MSS data to generate class information, and pc-ARC/INFO was used to digitize contour data. A set of interface routines was written in FORTRAN 77 to interface the two systems with the SLAMM3 model, which was written in Turbo Pascal.

Site Descriptions and Results

Coastal wetlands of Puget Sound occur primarily in river deltas. Therefore, 7.5-minute quadrangle fourplex sets were selected for specific areas in Puget Sound (Figure 3): South Sound because it centers on the Nisqually River delta and National Wildlife Refuge area; Olympia because it centers on the rapidly urbanizing state capitol area; Elliott Bay because it centers on the Seattle metropolitan area; Port Orchard because it centers on the rapidly urbanizing Bremerton area; Possession Sound because it centers on the Snohomish River delta and Port of Everett; Padilla Bay because it centers on the Padilla Bay National Estuarine Research Reserve and adjacent Anacortes; and Bellingham Bay because it centers on Bellingham and the Nooksack River delta.

South Sound

Located at the south end of Puget Sound, this site includes the Nisqually River delta. It is a diverse wetland system of saltmarsh, brackish marsh, and swamps important to wildlife (Kunze 1984). The delta was extensively diked and farmed by the turn of the century, and continued so until the 1950s. In 1974

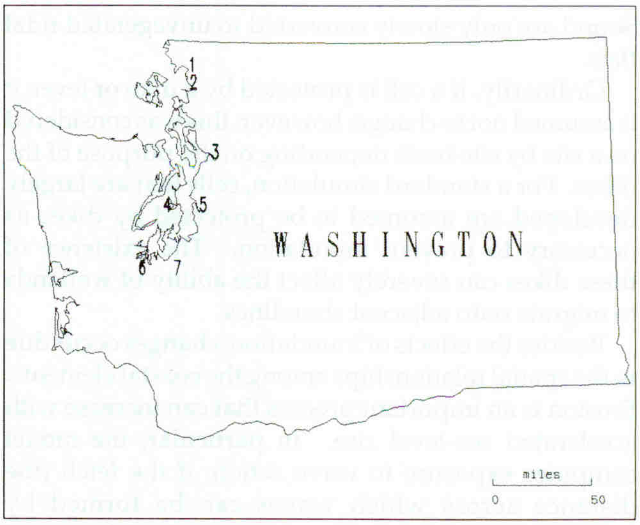

Figure 3 Index map of sites. 1 = Bellingham Bay, 2 = Padilla Bay, 3 = Possession Sound, 4 = Port Orchard, 5 = Elliott Bay, 6 = Olympia, 7 = South Sound.

most of the delta was acquired for the new Nisqually National Wildlife Refuge. Following a major flood and breaching of the Nisqually River dike in 1975, the refuge dike system was reconstructed; it is anticipated that the dikes will be maintained in the future. Similar to other sites that have been diked, tidal flats cover a larger area than saltmarsh currently.

The model predicts (Figures 4 and 5) that saltmarsh will expand gradually from 12% (43 ha) with a 50-cm rise to 56% with a 2-m rise as the diked wetlands are supplemented by additional inundation of lowland. Concurrently, tidal flats could decline by 26% with a 50-cm rise; 45% with a 1-m rise; and 67% with a 2-m rise. The simulations suggest that swamps could decline by 11% with a 2-m rise, but then expand with a 2.5-m rise. Freshwater marshes could be virtually unchanged.

Olympia

This site is immediately west of South Sound. It is characterized by steep-sided inlets with very small saltmarshes, slightly more extensive freshwater marshes, and even more extensive coastal swamps. Tidal flats are by far the most extensive wetlands, covering three times as much area as the vegetated wetlands combined.

Because of the shoreline topography, tidal flats and saltmarshes probably will decline steadily with sea-level rise (Figure 6). With a 50-cm rise, 28% (477 ha) of tidal flats could be lost; a 1-m rise could result in a 48% decline; and a 2-m rise could result in a 73% decline. Although much smaller in extent, saltmarshes could decline by 29% (15 ha) with a 50-cm rise; 47% with a 1-m rise; and 55% with a 2-m rise. Freshwater marshes and swamps could expand slightly (12 and 16 ha

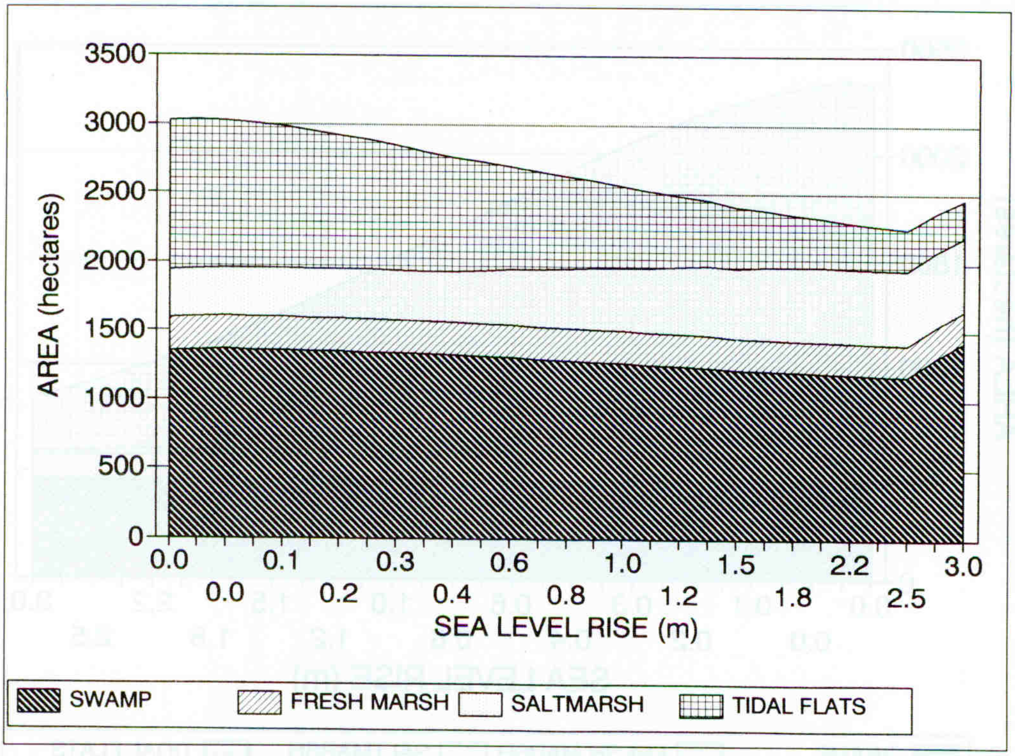

Figure 4 Changes in wetlands in the South Sound site with sea level rise to 3 m.

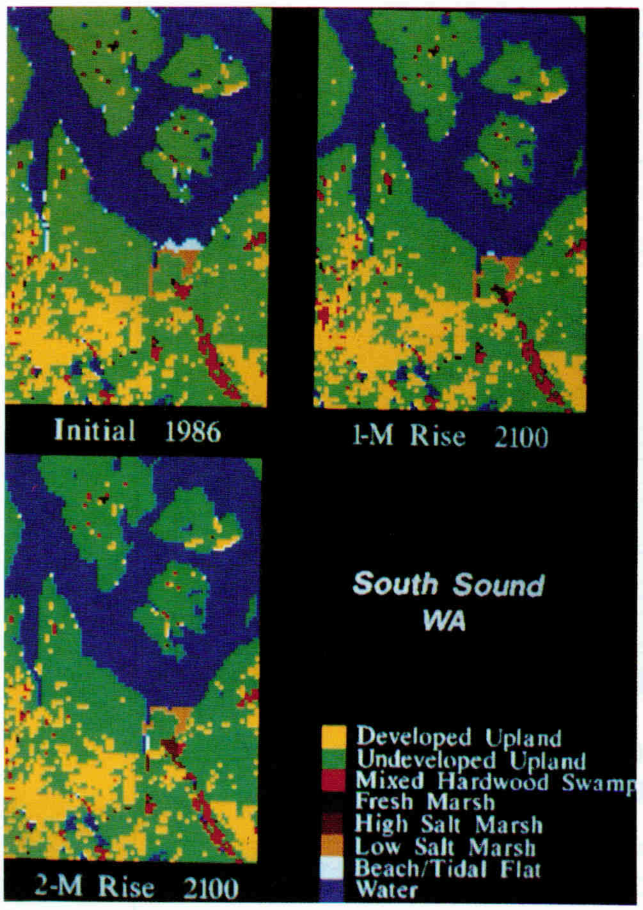

Figure 5 Initial conditions and simulation results for 1- and 2-m scenarios for South Sound.

respectively for a 1-m rise) with the rise in water table accompanying sea level rise; this could have a correspondingly minor impact on shorefront property around the inlets.

Elliott Bay

This site encompasses most of Seattle, including Elliott Bay and Shilshole Bay on Puget Sound and the western part of Lake Washington. Most of the shorelines are heavily developed; saltmarsh covers only 9 ha and freshwater marsh only 19 ha according to our interpretation of Landsat data.

The more extensive tidal flats could exhibit a steady decline; 26% could be lost with a 50-cm rise; 46% could be lost with a 1-m rise; and 69% could be lost with a 2-m rise (Figure 7). Saltmarshes could be unchanged; swamps could decline by 19% with a 2-m rise. The modelling assumed that diking and other actions detrimental to wetland maintenance and creation would not be allowed.

Port Orchard

This site is due west of the Elliott Bay site and includes Bainbridge Island and the city of Bremerton. Tidal flats are extensive, but marshes are small and isolated. The simulations suggest that the tidal flats will gradually decline with increasing sea level; with a 50-cm rise a 34% decline could occur; with 100 cm a 57% decline could occur; a 2-m rise could result in 80% of the tidal flats being lost. Saltmarshes could expand

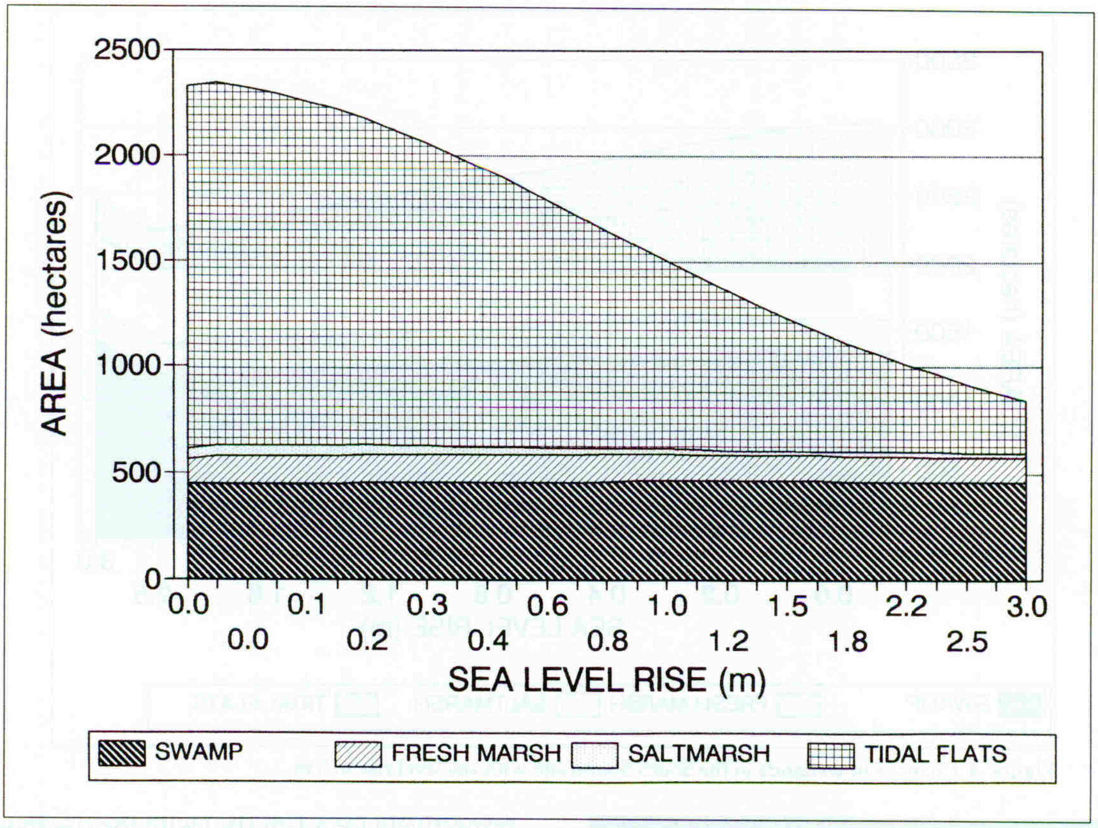

Figure 6 Changes in wetlands in the Olympia site with sea level rise to 3 m.

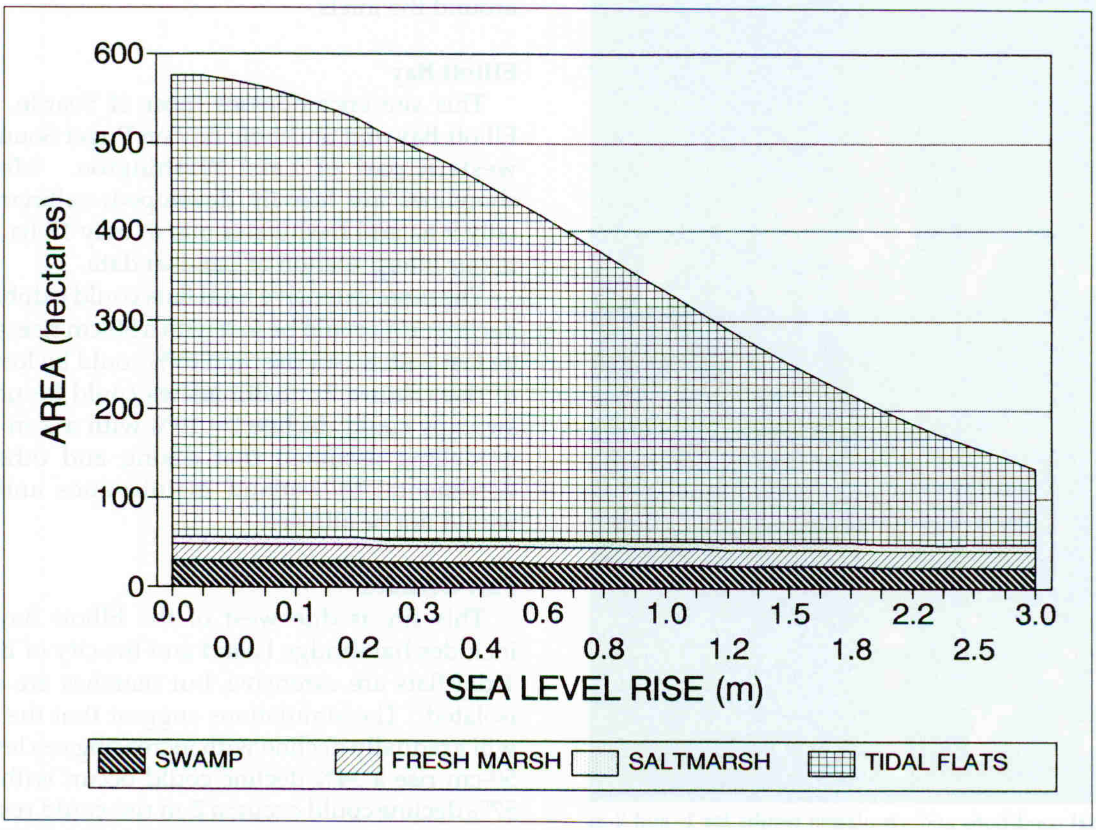

Figure 7 Changes in wetlands in the Elliott Bay site with sea level rise to 3 m.

by 20% (8 ha) with a 50-cm rise; a 1-m rise could mean a 49% (19 ha) increase; a 2-m rise could result in a decline to the same area expected for a 50-cm rise. Freshwater marshes and swamps could remain essentially unchanged with a rise in sea level (Figure 8).

Possession Sound

This site includes the estuary of the Snohomish River, an area that encompassed extensive marshes before settlement around 1880. However, 90% of the marshes were diked, drained, and converted into farmland; some farmland has reverted to wetlands as dikes have been breached by floods and not repaired. Since 1965 wetlands have been filled for industrial development, and solid-waste and dredge-material disposal sites (Boule *et al.* 1983). In recent years local efforts to protect the remaining wetlands have resulted in the purchase of tracts and islands in the Snohomish delta.

The pattern of response to sea-level rise will be complex given the diverse wetlands and the human disturbance (Figures 9 and 10). In the simulations we assumed that dikes would not be maintained as the seas encroached, given the history of abandoning dikes and the concern with protecting wetlands. Therefore, saltmarshes could increase rapidly in area by 86% (285 ha) as a 50-cm rise inundates farmland; they could continue to expand to 154% with a 1-m rise; and then decline to 127% with a 2-m rise. There could be a corresponding increase in habitat for some types of waterfowl and other wildlife. Tidal flats could suffer a gradual decline in area. The simulations predict a 32% decline with a 50-cm rise; 49% decline with a 1-m rise; and 57% decline with a 2-m rise. Freshwater marshes could vary only slightly in area, while swamps could exhibit a 6% (64 ha) decline with a 50-cm rise; a 10% decline with a 1-m rise; and a 21% decline with a 2-m rise.

Padilla Bay

This site has extensive tidal flats and the most extensive diked and drained lowlands of any site studied. In the simulations we assumed that most of the dikes, which are protecting valuable croplands, including tulip farms, would be maintained through the next century. (Alternative simulations without maintenance of dikes yield similar results and suggest that the model is not sensitive to the presence of dikes in this area.)

The model predicts that a steady decline in tidal flats could occur with sea-level rise (Figures 11 and 12). It predicts a 46% decline in tidal flats with a 50-cm rise; a 71% decline with a 1-m rise; and an 87% decline with a 2-m rise. The large numbers of diving ducks and geese that use the tidal flats for feeding would

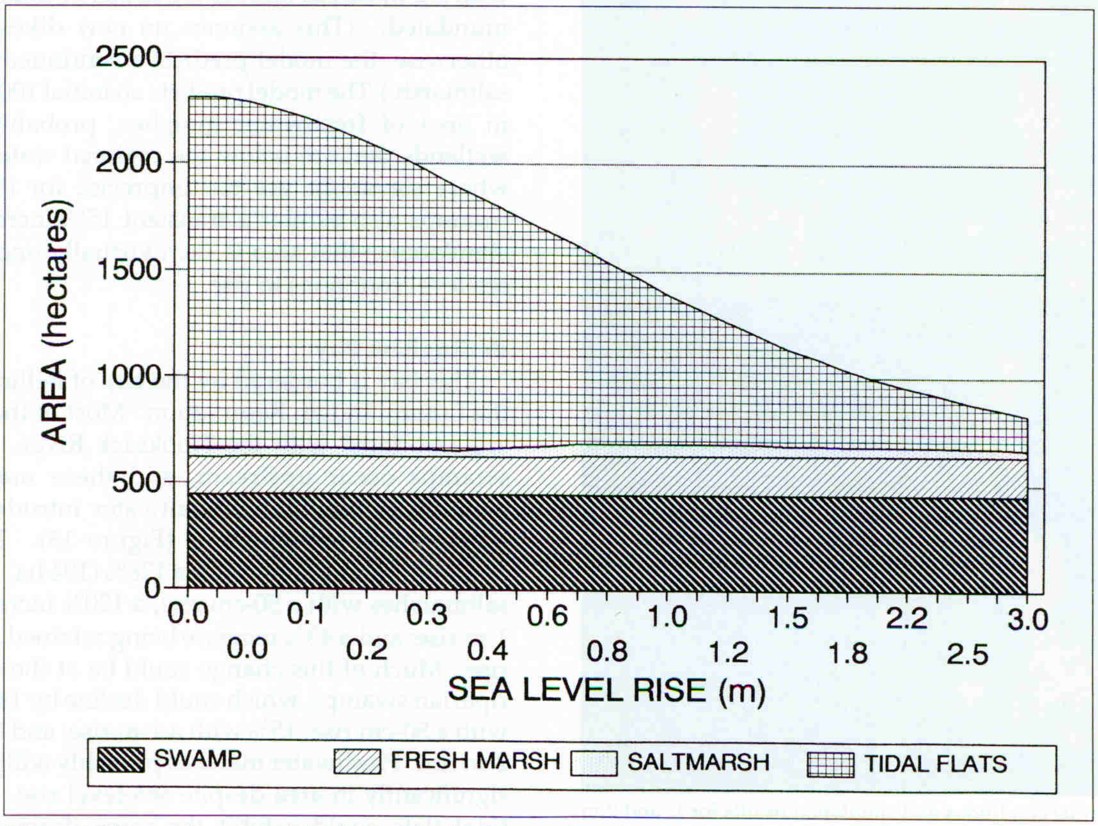

Figure 8 Changes in wetlands in the Port Orchard site with sea level rise to 3 m.

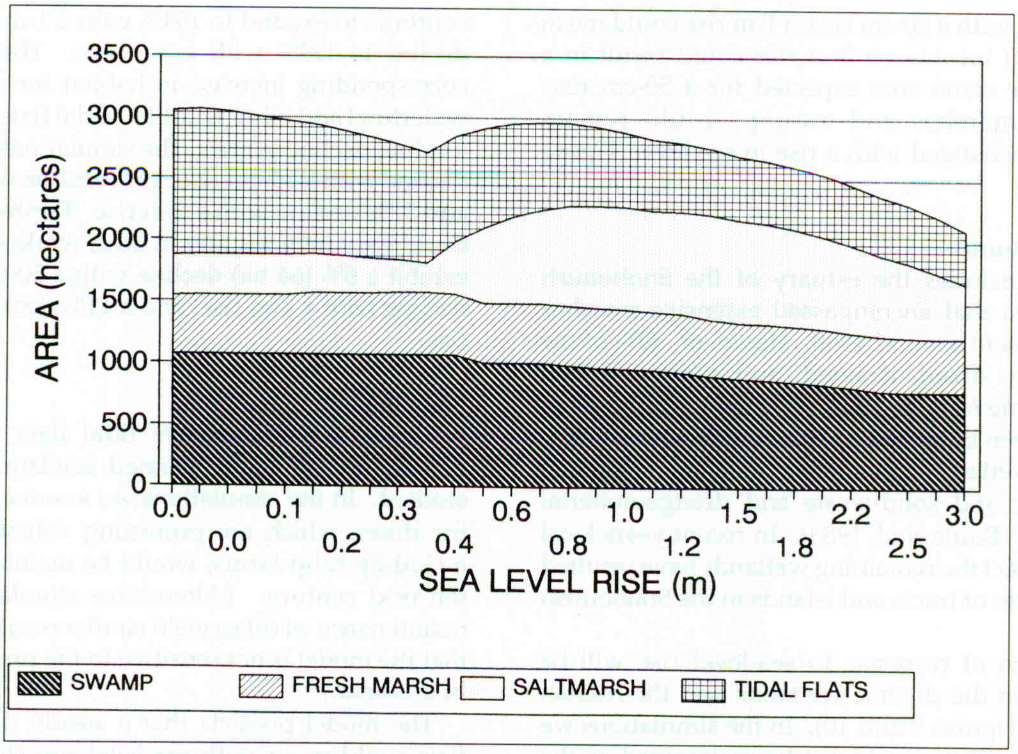

Figure 9 Changes in wetlands in the Possession Sound site with sea level rise to 3 m.

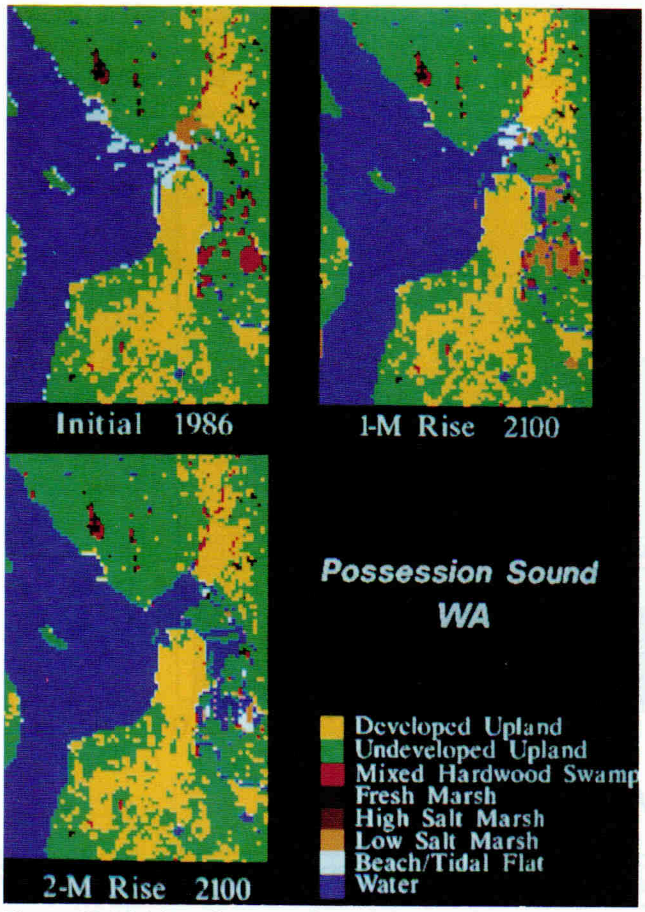

Figure 10 Initial conditions and simulation results for 1- and 2-m scenarios for Possession Sound.

suffer due to the loss of habitat. The model forecasts a 21% decline in saltmarshes with a 50-cm rise; a 10% increase with a 1-m rise; and a 30% (104 ha) increase with a 2-m rise as land at the heads of tidal sloughs is inundated. (This assumes no new dikes are built; otherwise, the model predicts a continued decline in saltmarsh.) The model predicts an initial 100% increase in area of freshwater marshes, probably drained wetlands that are below the regional water table (or where elevations are too imprecise for the model). Swamps also exhibit a transient 15% increase in the simulations; that area is then virtually unchanged as sea level continues to rise.

Bellingham Bay

This bay is bordered by the city of Bellingham and the Lummi Indian Reservation. Most of the wetlands are associated with the Nooksack River. Extensive swamps occur upstream, and these may convert partially to saltmarsh as saltwater intrudes into the estuary with sea-level rise (Figure 13). The model predicts that there could be a 126% (194 ha) increase in saltmarshes with a 50-cm rise; a 120% increase with a 1-m rise; and a 43% increase being retained with a 2-m rise. Much of this change could be at the expense of riparian swamps, which could decline by 14% (162 ha) with a 50-cm rise; 15% with a 1-m rise; and 16% with a 2-m rise. Freshwater marshes probably will not change significantly in area despite sea-level rise. However, tidal flats could exhibit the same dramatic decline

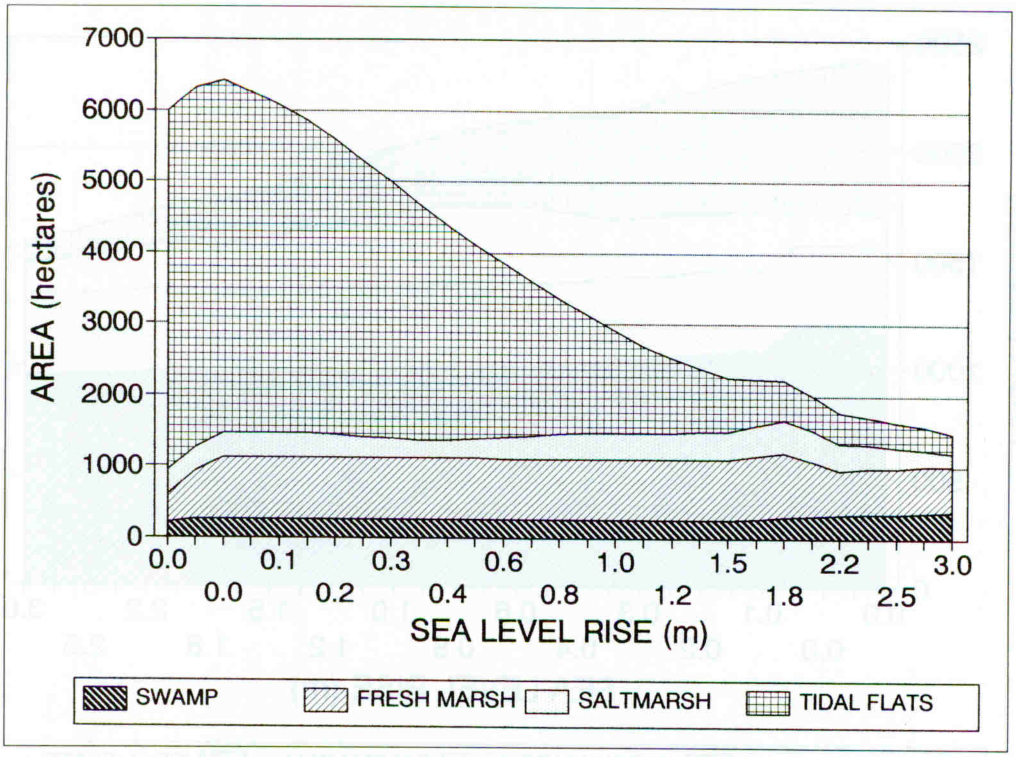

Figure 11 Changes in wetlands in the Padilla Bay site with sea level rise to 3 m.

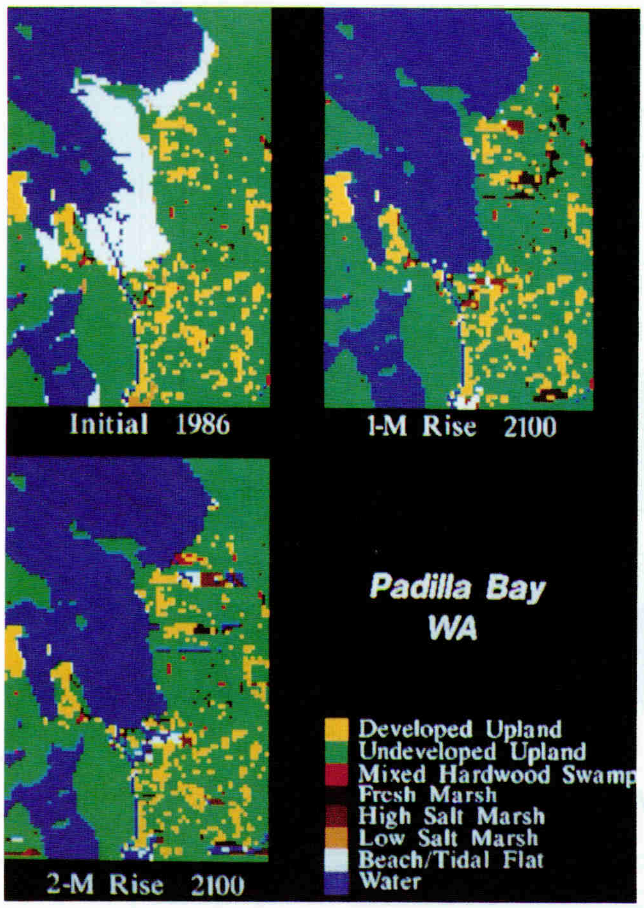

Figure 12 Initial conditions and simulation results for 1- and 2-m scenarios for Padilla Bay.

predicted for other sites, going from a 38% (260 ha) decline with a 50-cm rise, to a 56% decline with a 1-m rise, to a 74% decline with a 2-m rise.

Discussion and Conclusions

In conducting this remote sensing and simulation analysis, we have tried to consider the most likely management of coastal areas in response to accelerated sea-level rise on a site basis. Thus, in the simulations some dikes are allowed to fail and others are maintained. Some dikes are protecting saltmarshes for waterfowl in National Wildlife Refuges, and some are protecting valuable farmland. At one site there is a history of abandonment of dikes. In the absence of a uniform policy favoring wetlands, we anticipate a mixed response to sea-level rise by both humans and natural systems.

The most important impact of sea-level rise on coastal wetlands in the region probably will be to gradually inundate existing tidal flats. The site simulations exhibit a uniformly large loss of tidal flats with accelerated sea -level rise (Figure 14); this habitat loss could cause a significant decrease in shellfish, including oysters and clams; it could also lead to severe habitat loss for diving ducks and geese that feed on the flats. Recreational and commercial fisheries could also be affected, although they were not considered in this study. Dikes enclosing marshes may be breached in some areas, but in many areas continued maintenance

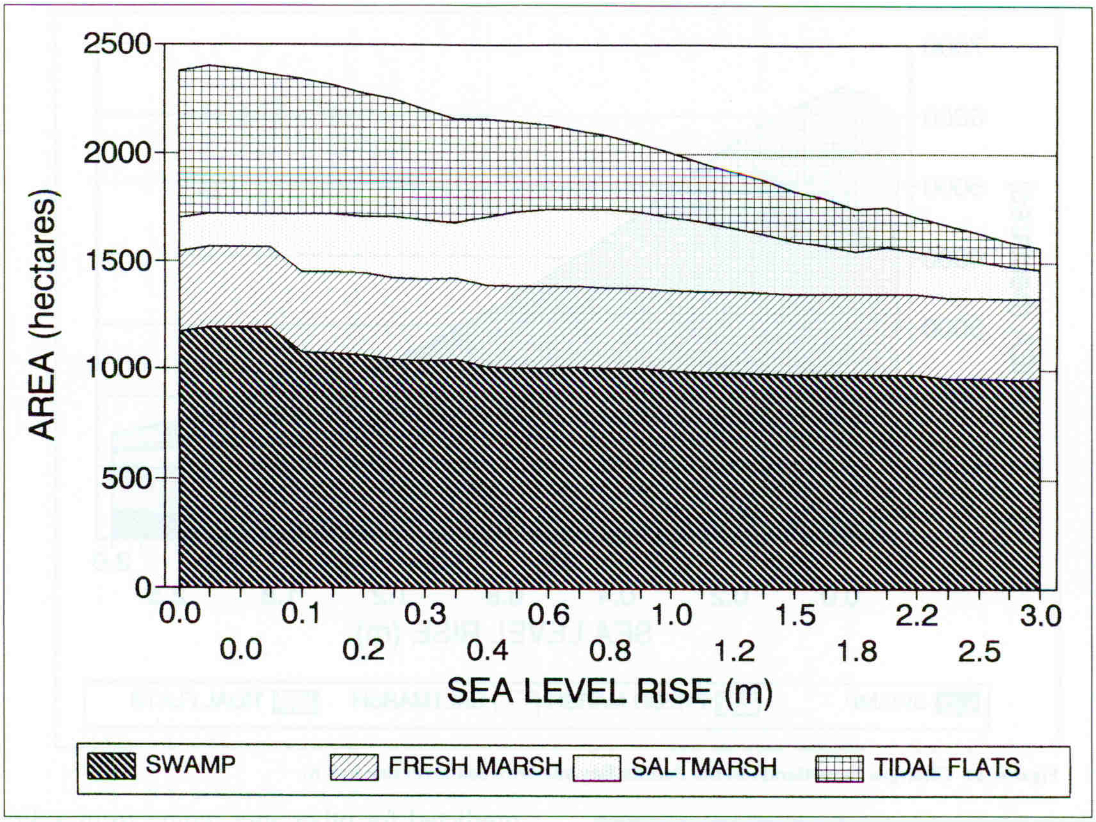

Figure 13 Changes in wetlands in the Bellingham Bay site with sea level rise to 3 m.

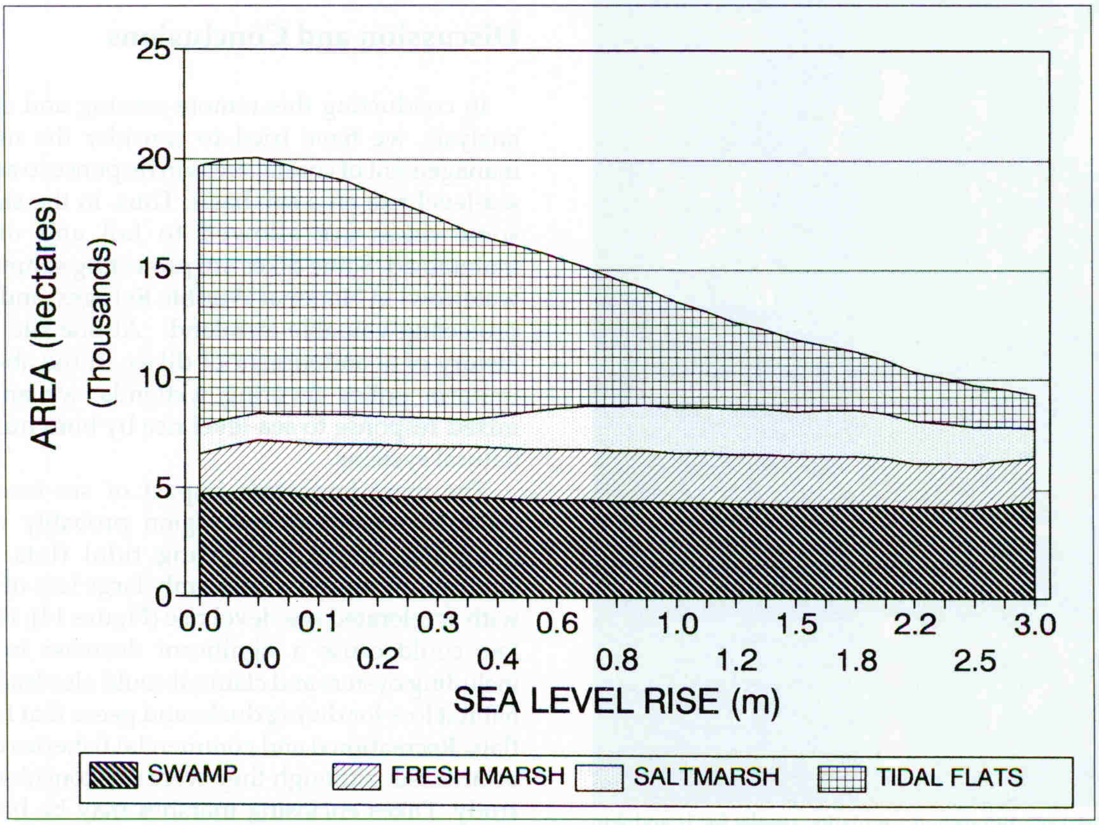

Figure 14 Composite response to sea-level rise of sites studied in Puget Sound.

of dikes could prevent tidal flats from migrating onto the adjacent vegetated wetlands. With a 50-cm to 2-m rise in sea level, 45% to 84% of the tidal flats studied could be lost by the year 2100.

If selected dikes are abandoned, saltmarshes could increase from 23% to 49 % in area, retaking land diked and drained for pasture. If dikes are maintained to protect waterfowl habitat in the enclosed marshes, such as at South Sound, sea-level rise will require elaborate tidal gates and pumping as the relative elevations of the marshes decrease. Small pocket marshes next to steep-sided inlets and marshes fringing more substantial or hardened dikes probably will be lost. Rising water tables along the shoreline could cause a 25 % increase in freshwater marshes, with minor impact on developed properties in the more urbanized areas. Swamps (forested wetlands) probably will decline 5% to 10% in area, although they may expand at some sites. Coastal wetlands in Puget Sound (and elsewhere on the West Coast) have been severely altered by diking in the past. Some of that environmental damage could be undone by a policy that would allow wetland creation to proceed as sea level rises.

Present Washington State policy regarding coastal wetlands is to prohibit new erosion control devices on the water-ward side of wetlands. Existing dikes are allowed to be maintained and strengthened as necessary for flood protection. Through the Coastal Erosion Management Strategy (Canning and Shipman 1993), Washington State is evaluating current erosion management policies and their environmental impact, and is formulating policy options for the future. Current sea-level rise policy options (Klarin *et al.* 1990) do not include maintenance or breaching of dikes; future studies should address this issue.

Whether wetlands would be allowed to retreat is problematical. At present, Washington State lacks a public policy addressing this question. On the river deltas, coastal wetlands are backed by agricultural development, and there will be strong sentiment on either side of the issue. Where coastal wetlands are backed by major infrastructure, such as railroads and interstate highways, or industrial facilities, the cost of relocation will be of paramount concern. Studies such as this one can help by providing a synoptic view of the present land uses and by showing the consequences of alternative policy options as conditions change.

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