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Potential Effects of Sea Level Rise on Washington State Wetlands

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for:
US Environmental Protection Agency

Report 97-98

Shorelands and Water Resources Program
Washington Department of Ecology
Olympia, WA 98504-7600

This document is a reprint of a report prepared for the Office of Policy Planning and Evaluation, US Environmental Protection Agency, in April 1992. This report was one of many prepared in support of EPA's Pacific Northwest Global Climate Change Case Study. Due to diminished funding and a change in priorities, the Case Study project was never completed. For further information about the Case Study, contact:

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PREFACE

This document is a reprint of a report prepared for the Office of Policy Planning and Evaluation, US Environmental Protection Agency, in April 1992. This report was one of many prepared in support of EPA's Pacific Northwest Global Climate Change Case Study. Due to diminished funding and a change in priorities, the Case Study project was never completed, nor was this report ever published by EPA.

The study reported on in this document was an investigation into the potential effect of sea level rise on Washington's coastal wetlands. Similar previous studies conducted by the principal investigator on Atlantic coast wetlands employed a statistically random selection of quadrangles[1] for selection of a sampling of coastal areas for analysis. Coastal wetlands in Washington State, however, are clumped at and near major river deltas. Therefore, for this study blocks of four or six quadrangles were selected by one of the study team (Canning) which represent coastal river delta locales.

This study is based upon an application of the third generation of the principal investigator's SLAMM computer model to remote sensing information. The intended field confirmation of "initial conditions" information could not be completed due to schedule conflicts, and was therefore based upon professional experience and comparison with recent aerial photography. No field studies to confirm modeling results have yet been conducted. The SLAMM model is a reliable predictor of sea level rise effect on coastal wetlands. However, this was the first application of the SLAMM model to the type of topography typical of Puget Sound: narrow river canyons incised in a coastal plateau. The SLAMM model was developed on Atlantic coast landscapes where broad coastal plains predominate. In Washington State this topography occurs only in the southwest part of the state near Willapa Bay and Grays Harbor. Readers of this report should be appropriately cautious in using and interpreting its information and conclusions.

Interest and concern over global climate change and sea level rise waned shortly after this study was completed in 1992. A resurgence of interest in 1997 prompted reissuance of this report.

Douglas J. Canning
May 1, 1997

[1] "Quadrangle" is the standard 7.5 minute US Geological Survey mapping quadrangle.

POTENTIAL EFFECTS OF SEA LEVEL RISE ON WASHINGTON STATE WETLANDS

Richard A. Park[1], Jae K. Lee[1], and Douglas J. Canning[2]

SUMMARY

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. The extensive flats in Willapa Bay, Washington, yielded over $9 million worth of oysters in 1989. The most important impact of sea level rise on coastal wetlands in the region will be to gradually inundate existing tidal flats, with the potential for a concomitant decline in the shellfish industry.

Historically, many of the coastal marshes were diked to prevent flooding during spring tides and to permit cattle grazing in the marshes (cf. Bortleson et al. 1980). Subsequently some of these marshes were drained and the 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. Dikes enclosing marshes may be breached, but those dikes will prevent tidal flats from migrating onto the adjacent vegetated wetlands in many areas. 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 (Figure 1). At the same time, 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 elevation of the marshes decreases. Small pocket marshes adjacent to steep-sided inlets and marshes fringing more substantial or hardened dikes will probably be lost.

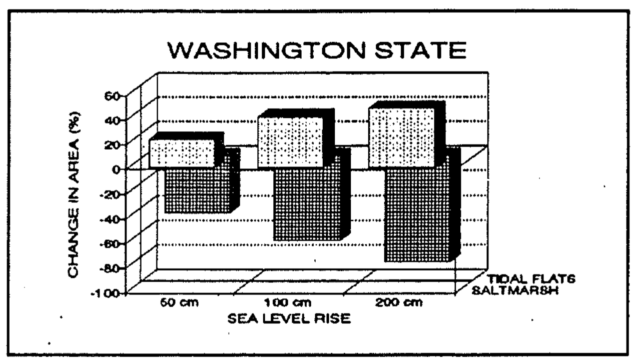

Figure 1. Changes in saltwater wetlands in Washington State for three scenarios of sea level rise.

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. Overall, swamps (forested wetlands) will probably decline 5% to 10% in area, although

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they may expand at some sites. The aggregate result of sea level rise could be to alter coastal wetlands significantly, to the detriment of the shellfish industry and possibly to the benefit of waterfowl and other wildlife.

INTRODUCTION

An important consequence of global warming may be accelerated sea level rise. Although estimates vary (Figure 2), many investigators believe that sea level may rise by 1 m by the year 2100 (Revelle, 1983, Thomas 1986, Robin 1986). Warming due to greenhouse gases already in the atmosphere could result in a 33-cm rise (IPCC 1990); the maximum rise anticipated by the year 2100 is 2 m (NRC 1985). An accelerated rise could have serious impacts on coastal wetlands and associated wildlife and fisheries. For much of the contiguous United States inundation and erosion probably will destroy at least half the existing coastal marshes and swamps (Park et al. 1989a). However, high tidal ranges, with corresponding broad elevational ranges for wetlands, and extensive modifications to historic wetlands in the Pacific Northwest suggest that the effects of sea level rise might be different for that region compared with those predicted for other coastal areas. A previous study using a 500-m grid and manually interpolated elevational data for modeling gave results that were suspect for Washington State (Park et al. 1989a); therefore, the present study was initiated.

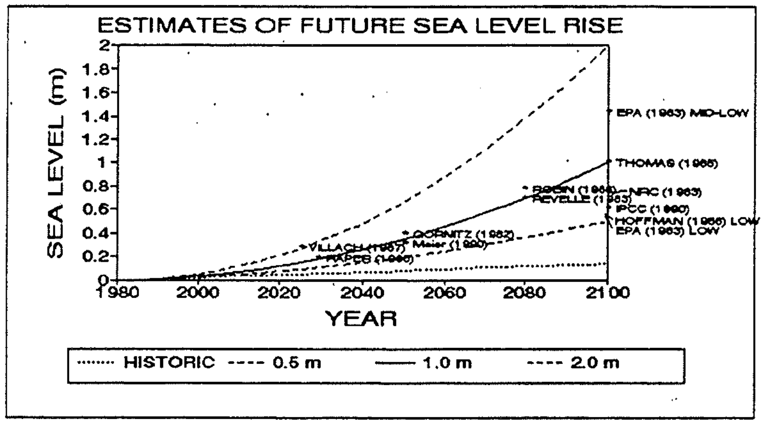

Figure 2. A comparison of various estimates of sea level rise, including the IPCC estimate of 66 cm by 2100 and the scenarios used in this study (Park 1991).

METHODS

The effects of sea level rise were projected using a rule-based simulation model (SLAMM3), remotely sensed land-cover data, and digitized elevational data.

SIMULATION MODELING

The model simulates the dominant processes involved in wetland conversions and shoreline reconfigurations during long-term sea level rise. A complex decision tree incorporating geometric and qualitative relationships is used to represent transfers among coastal classes (Figure 3). Each site is divided into cells of equal area (250 by 250 m for the Puget Sound sites and 500 by 500 m for the Willapa Bay site), and each class existing 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.

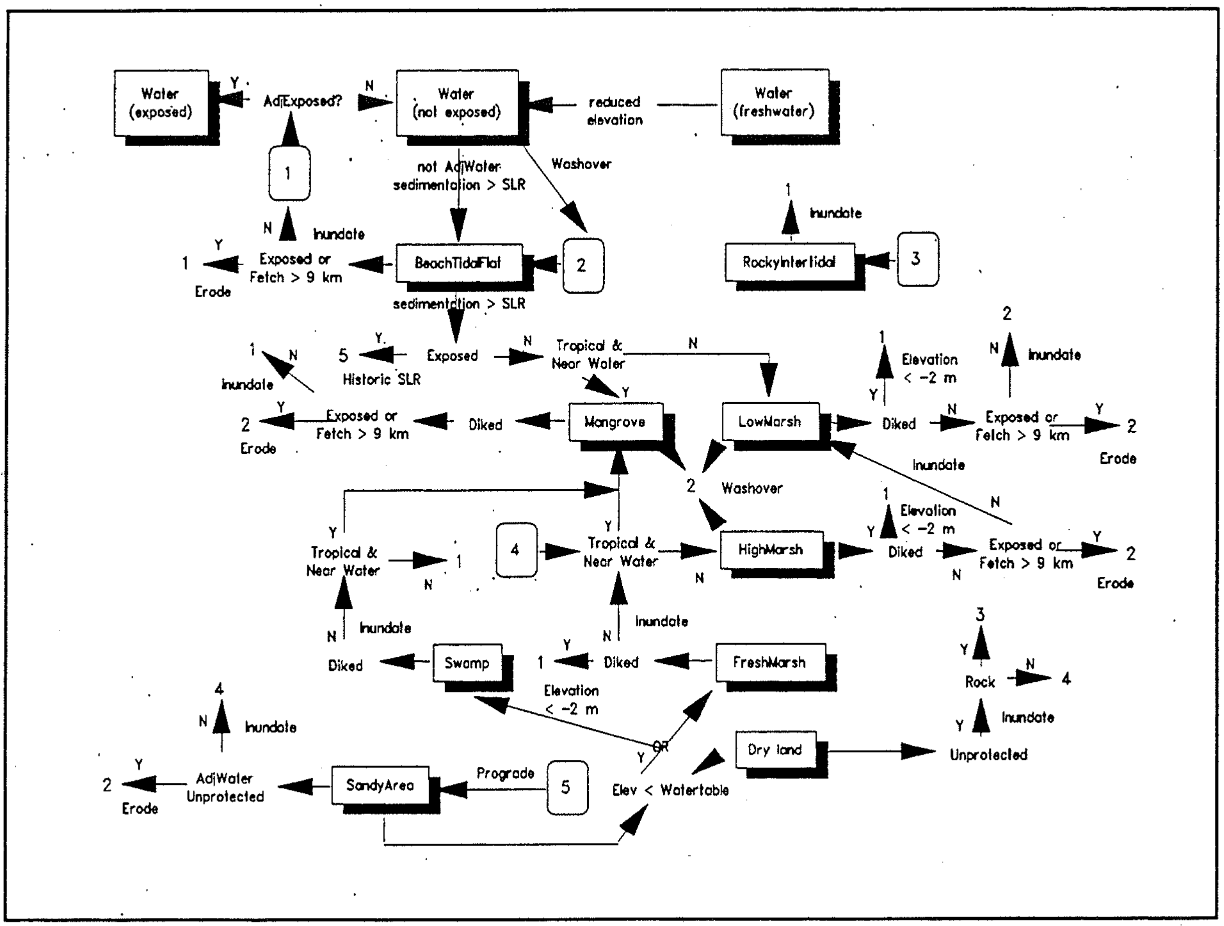

Figure 3. Logic embodied in the SLAMM simulation model.

Relative sea level change is computed for each site for each time step; it is the sum of the historic eustatic trend (assumed to be 1.2 mm/yr), the site-specific rate of change of elevation due to subsidence and isostatic adjustment, and the accelerated rise depending on the scenario chosen. Sea level rise may be offset by sedimentation and accretion. In the absence of site-specific data, average values are used, depending on the extent of existing marshes (the assumption being that extensive marshes indicate higher accretion rates). The values used in this study were 5 mm/yr for Padilla Bay and 2 mm/yr for the other sites. Marshes not adjacent to water are assumed to have rates half those adjacent to water (cf. Gosselink 1984). Sedimentation rates for tidal flats and open water areas are taken to be half the accretion rates. The model is not sensitive to these assumptions for higher sea level rise scenarios (Park et al. 1989b), but the predicted changes in wetlands for a 50-cm rise in an area such as Puget Sound with low subsidence could vary by as much as 50% 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 on the basis of 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 are only slowly converted to unvegetated tidal flats.

If a cell is protected by a dike or levee it is not permitted to change. 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.

In addition to the effects of inundation represented by the simple geometric model described above, second-order effects occur due to changes in the spatial relationships among the coastal elements. In particular, the model computes exposure to wave action; if the fetch (the distance across which wind-driven waves can be formed) is greater than 9 km, the model assumes moderate erosion. If a cell is exposed to open ocean, severe erosion of wetlands is assumed. Beach erosion is modeled using a relationship reported by Bruun (1962, 1986) whereby 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. This could seriously underestimate the availability of sediment to replenish wetlands where accelerated bluff erosion could be expected to occur. 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.

REMOTELY SENSED DATA

To generate land-cover data, Landsat Multispectral Scanner (MSS) digital data were used. First, the Landsat MSS data were geometrically rectified based on the Universal Transverse Mercator (UTM) coordinates. Bilinear interpolation was applied for the resampling of gray value. The bilinear interpolation is a reasonable compromise of computational time and image distortion (Gonzalez and Wintz 1987).

The geocorrected MSS data were then transformed into normalized difference vegetation index (NDVI) and principal component data for data enhancement and reduction. The NDVI is known to be a good indicator of marsh types and saltmarsh biomass (Gross et al. 1987). Only the first two principal components of the four-band MSS data were used with the NDVI data because the two components explained over 95% of the variance in the original data. Thus, the three-band transformed MSS data were used for classification to generate land-cover/land-use data for the seven sites on Puget Sound. The Willapa Bay site was analyzed in a prior study (Park et al. 1989a) using a slightly different approach.

An unsupervised classification of MSS data was performed. The spectral values of the transformed digital MSS data were grouped together to generate spectrally homogeneous classes through cluster analysis. One hundred classes were generated in the initial clustering analysis, then these were reduced to a manageable number of classes based on the statistical information of each cluster and ground truth data. The final classes were then associated with each land-cover and land-use class to assign the name to each class. All this processing was done on the Earth Resource Data Analysis System (ERDAS).

For the final processing, a verification of the spectral classification and editing of misclassification were performed over the classified MSS data, based on the digitized National Wetland Inventory (NWI) data. The digitized NWI data were available in Digital Line Graph-3 (DLG3) format in 1:24,000 scale and converted to ARC/INFO polygon coverage on pc-ARC/INFO system. Each polygon within the files was associated with attribute data indicating land-use/land-cover class in the Fish and Wildlife Service classification system (Cowardin et al. 1979). The only vector polygons of interest, marshes and swamps, were reselected from the files. The reselected wetland polygons were graphically overlaid over the classified MSS data using ERDAS-ARC/INFO Live Link. Based on the overlaid NWI data, misclassified pixels of MSS data were corrected and reassigned to new classes. Finally, the classified images were checked against prior field transects and maps. Many of the small marshes were not detected by the coarse-grained (57-m) MSS data, thus the need for using the NWI data as well. The only other serious misclassifications that were detected truth were the identification of large log booms as tidal flats and of ships as islands.

DIGITAL ELEVATION DATA

Where available, USGS 7.5-minute Digital Elevation Model (DEM) data were used for the sites. These data consist of a regular array of elevations referenced horizontally in the UTM coordinate system (USGS 1990) with a 30-meter sampling interval. However, DEM data were available for only parts of four sites; only Elliott Bay was completely covered. For the other areas, elevational contours were manually digitized from the USGS 7.5-minute topographic maps, and computer interpolation was used to generate DEM data comparable to and of the same format as the USGS DEM data. The DEM data from these two sources were merged to create continuous elevational data over the sites. All maps in the study area have 20-ft contour intervals, but 5- and 10-ft supplemental contours exist for extensive lowland areas such as adjacent to Padilla Bay. The potential for inundation could be predicted more precisely if better elevational data were available. The most serious error detected in the initial simulations was inundation of the shore of

Lake Washington due to the lake elevation being given as 0 in the USGS DEM data! That elevation was manually corrected, and the simulations were run again. The model was modified to provide automatic checks for consistency between elevation above tidal datum and cover class, as determined from remote sensing and National Wetland Inventory data; this resulted in a marked improvement in the realism of the simulations.

INTERFACING DATA WITH THE MODEL

The class and digital elevation data were further processed for simulation modeling. In this study, the model grid size selected for simulation modeling was 250 m. Thus, all the input data were aggregated at the size of the grid cell. Class data were aggregated and stored as percent cover for each 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.

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.

All the data processing was performed on a 80386-based personal computer. For efficient data processing and modeling on the desktop computer, the simulation model, SLAMM3, was linked with a geographic information systems (GIS) and image processing systems. 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 were written in FORTRAN 77 to interface the two systems with the SLAMM3 model. The input data were read into SLAMM3, and the simulation results were written to GIS files for generation of maps.

SITE DESCRIPTIONS AND RESULTS

Coastal wetlands of Puget Sound are clumped at major river deltas and other locations, not widely distributed. Therefore, 7.5-minute quadrangle fourplex sets were selected for specific areas in Puget Sound (Figure 4): 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. As originally conceived, this study addressed only Puget Sound; Willapa Bay was added to provide representation of the Pacific coast. Initial and simulation maps are contained in the Appendix.

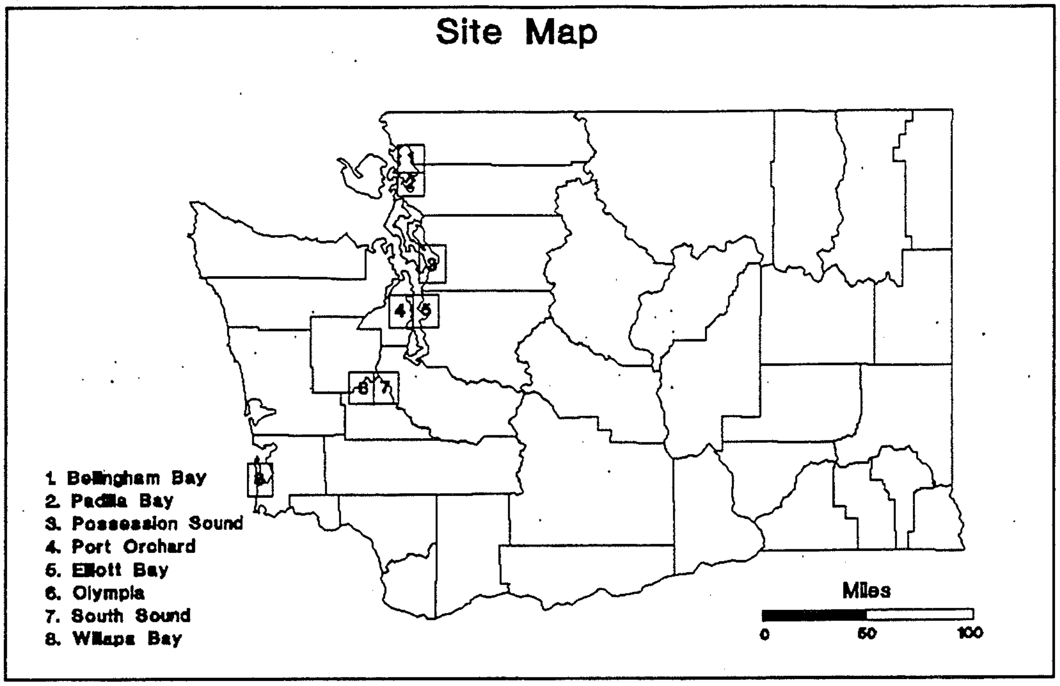

Figure 4. Location of sites on the Washington coast.

SOUTH SOUND

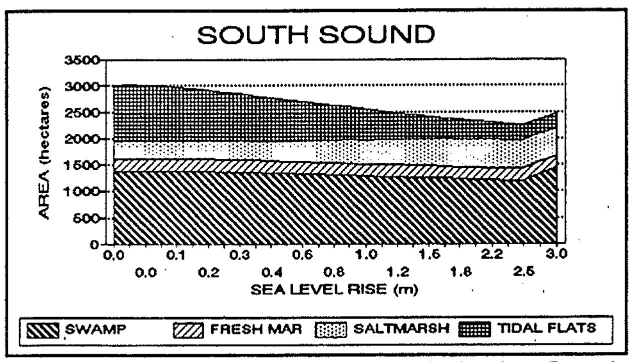

Figure 5. Changes in wetlands in the South Sound site with sea level rise to 3 m.

Located at the south end of Puget Sound, this site includes the Nisqually River delta, which 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 a majority of the delta was acquired for the new Nisqually National Wildlife Refuge. Subsequent to 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 for the foreseeable future. Similar to other sites that have been diked, tidal flats cover a larger area than saltmarsh at the present time.

The model predicts (Figure 5) that saltmarsh will expand gradually from 12% (43 ha) with a 50-cm rise by 2100 to 56% with a 2-m rise as the diked wetlands are supplemented by additional inundation of lowland. Concurrently, tidal flats would 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 would decline by 11% with a 2-m rise, but then expand with a 2.5-m rise. Freshwater marshes would 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 important wetlands, covering three times as much area as the vegetated wetlands combined.

Because of the shoreline topography, tidal flats and saltmarshes will steadily decline with sea level rise (Figure 6). With a 50-cm rise, 28% (477 ha) of tidal flats will 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 would 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 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.

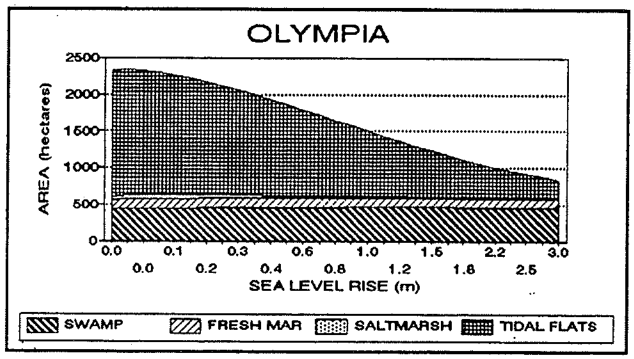

Figure 6. Change in wetlands in the Olympia site with sea level rise to 3 m.

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.

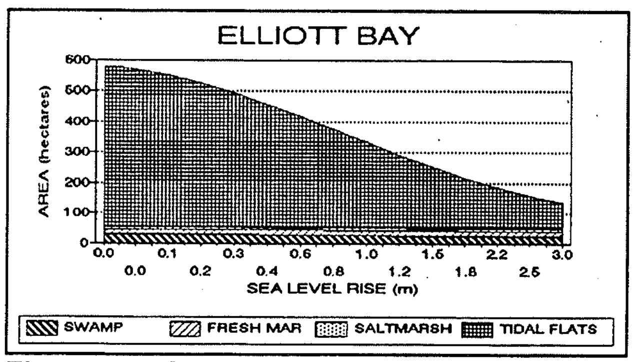

Figure 7. Change in wetlands in the Elliott Bay site with sea level rise to 3 m.

The more extensive tidal flats would 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 would be unchanged; swamps would decline by about 19% with a 2-m rise.

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 indicate that the tidal flats will gradually decline with increasing sea level; with a 50-cm rise a 34% decline could occur; with 1 m a 57% decline could occur; a 2-m rise could result in 80% of the tidal flats being lost. Saltmarshes could expand 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 would remain essentially unchanged with a rise in sea level (Figure 8).

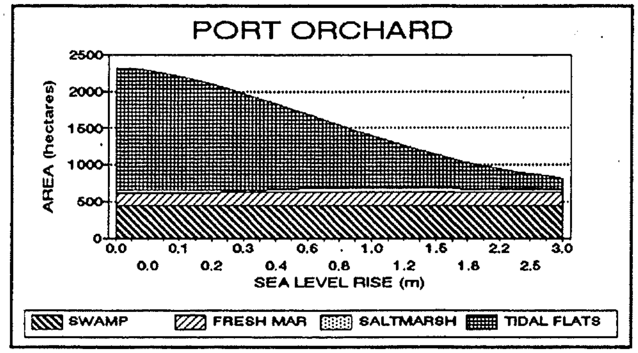

Figure 8. Changes in wetlands in the Port Orchard site with sea level rise to 3 m.

POSSESSION SOUND

This site includes the estuary of the Snohomish River, an area that encompassed extensive marshes prior to 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 (Boulé 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.

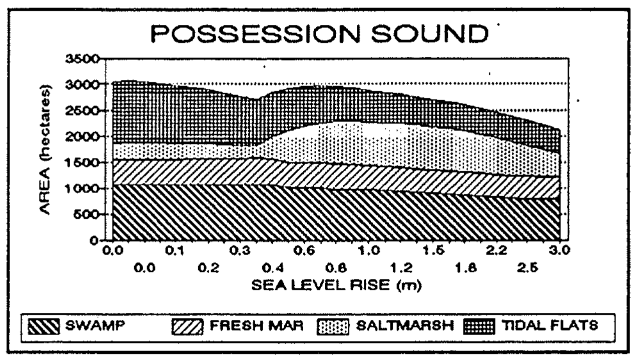

Figure 9. Changes in wetlands in the Possession Sound site with sea level rise ro 3 m.

The pattern of response to sea level rise will be complex given the diverse wetlands and the human disturbance (Figure 9). In the simulations we assumed that dikes would not be maintained as the seas encroached. 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 would 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 would 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 the most extensive diked and drained lowlands of any site studied, and it is second only to Willapa Bay in the extent of tidal flats. In the simulations we assumed that most of the dikes would be maintained through the next century, but that new dikes would not be constructed to protect additional farmland located at the heads of tidal sloughs. (Alternative simulations without maintainance of dikes yield similar results and suggest that the model is not sensitive to the presence of dikes in this area.)

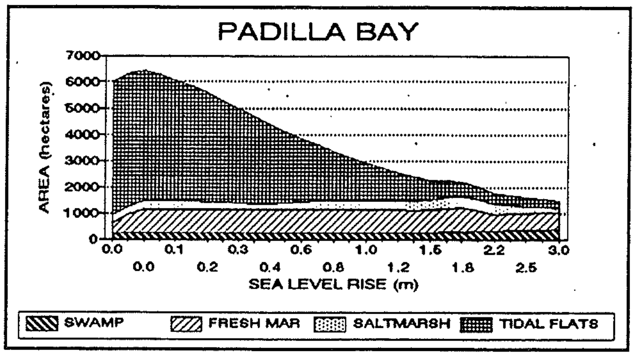

Figure 10. Changes in wetlands in the Padilla Bay site with sea level rise to 3 m.

The model predicts that a steady decline in tidal flats will occur with sea level rise (Figure 10). 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 brants that utilize the tidal flats would suffer accordingly. 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. It 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 and then maintain that area with little variation 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 be partially converted to saltmarsh as saltwater intrudes into the estuary with sea level rise (Figure 11). The model predicts that there will 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 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.

WILLAPA BAY

This large bay is located on the southwestern coast of Washington. The bay is over twenty miles in length and is separated from the Pacific Ocean by North Beach Peninsula, a long spit occupied by several towns. More than half the bay is tidal flats. In recent years 45% of the oysters of Washington State have been harvested from this area; in 1988 those oysters were worth $78 million (Department of Fisheries 1988). Prior to settlement, marshes were extensive, but settlers and diking districts diked and drained 3,500 acres of wetlands to create agricultural land; another 650 acres were filled for urban and industrial use (Boulé et al. 1983).

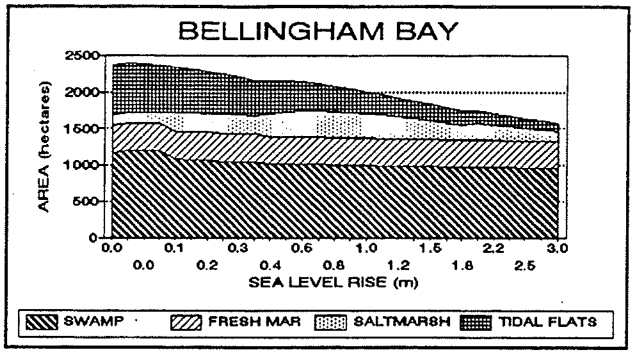

Figure 11. Changes in wetlands in the Bellingham Bay site with sea level rise to 3 m.

This site was studied as part of a national study (Park et al. 1989a). Although the data were not comparable in quality to those obtained specifically for this study and a grid size of 500 m was used, the site is so important that the simulations were redone with the SLAMM3 model and are included in this report. In the simulations, the assumption was made that the dikes will be maintained despite accelerated sea level rise; these preclude migration of saltwater wetlands within much of the basin.

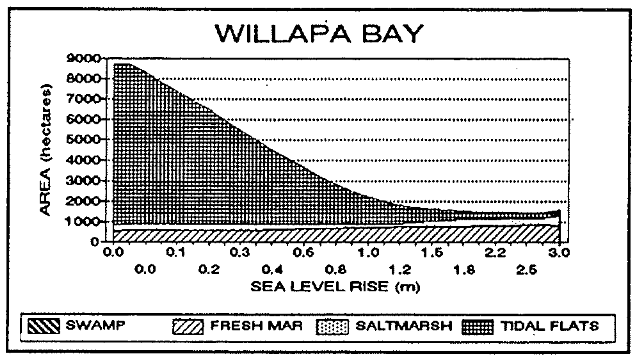

Figure 12. Changes in wetlands in the Willapa Bay site with sea level rise to 3 m.

With a 50-cm rise by 2100, 59% (4,682 ha) of tidal flats could be lost; with a 1-m rise, 83% of tidal flats could be lost; and a 2-m rise could result in loss of over 95% (Figure 12). In the absence of increased tidal flushing, which is likely, the newly created subtidal areas could continue to support the oyster fishery; otherwise, even the low rise scenario could be a severe blow to the local economy. The model predicts that 19% (65 ha) of saltmarshes could be lost with a 50-cm rise; 47% with a 1-m rise; but that a 2-m rise would cause an expansion, making up for area lost with prior rises in sea level, and resulting in a 7% (25 ha) increase. A rise in sea level will also result in a steady increase in freshwater marshes, with a 36% increase accompanying a 1-m rise.

CONCLUSIONS

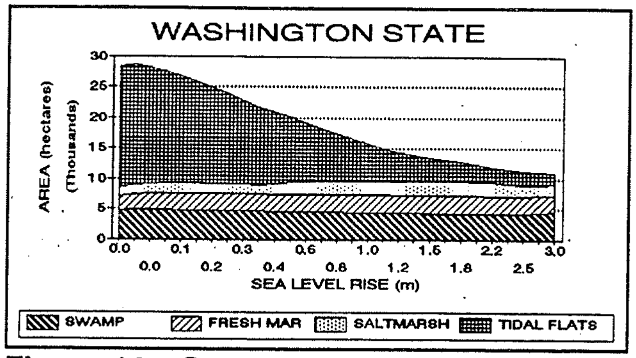

Figure 13. Composite response of sites studied to sea level rise.

The sites exhibit a uniformly large loss of tidal flats with accelerated sea level rise (Figure 13); this could cause a significant decrease in shellfish, including oysters and clams, with serious consequences for that industry; it could also lead to severe habitat loss for diving ducks and brants. In contrast, if the small dikes enclosing most of the former salt- and brackish marshes are allowed to deteriorate, saltmarshes will gradually reclaim those lowlands. This spread of saltmarshes will benefit chinook salmon and some waterfowl, but at the expense of agricultural lands that occupy those areas now. If the dikes are strengthened, saltmarshes will disappear in large part along with the tidal flats. Freshwater marshes and swamps could exhibit a slight increase in area with accelerated sea level rise, provided they are not artificially drained.

LITERATURE CITED

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APPENDIX

Site maps follow.

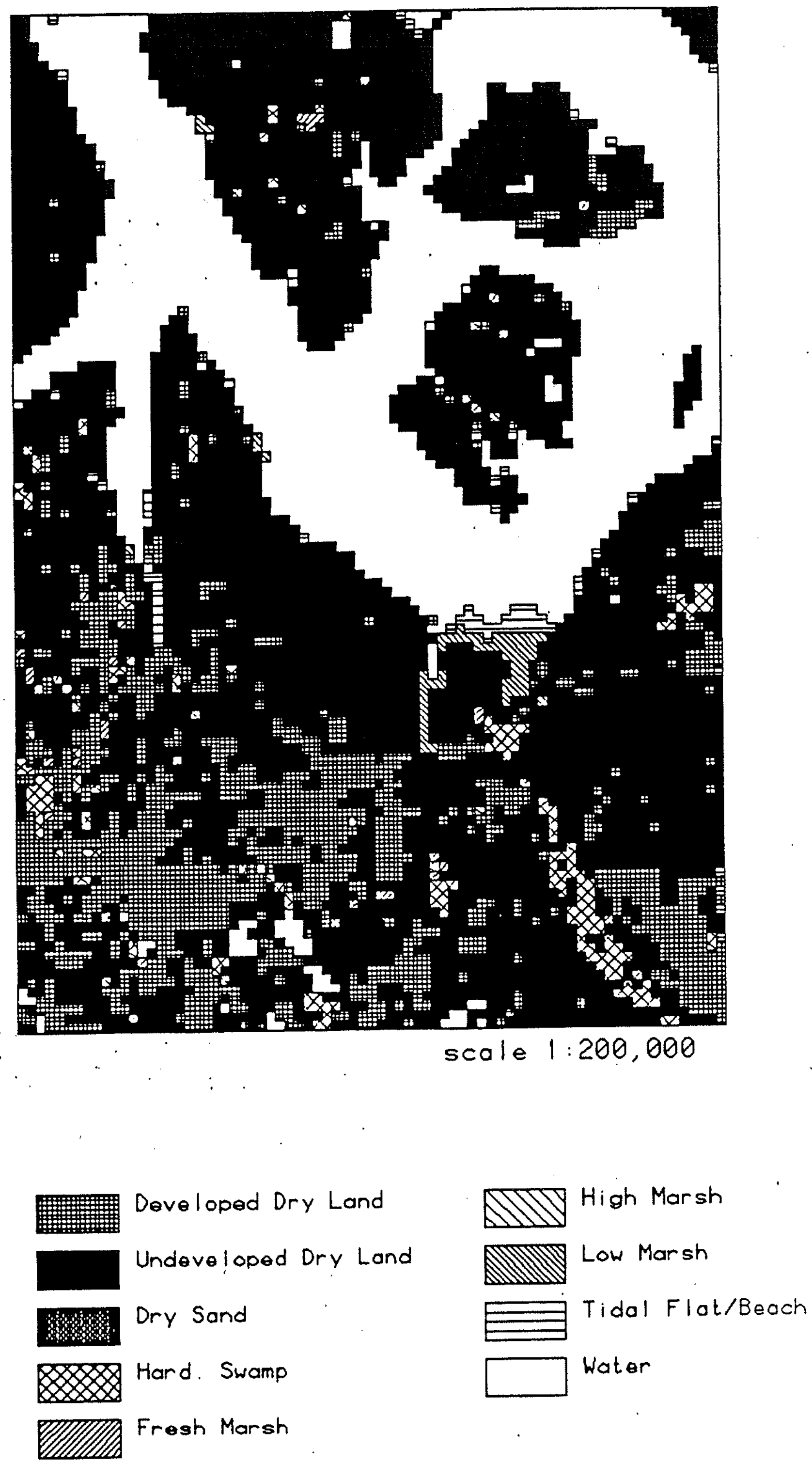

Figure 1. South Sound initial conditions based on 1986 Landsat imagery.

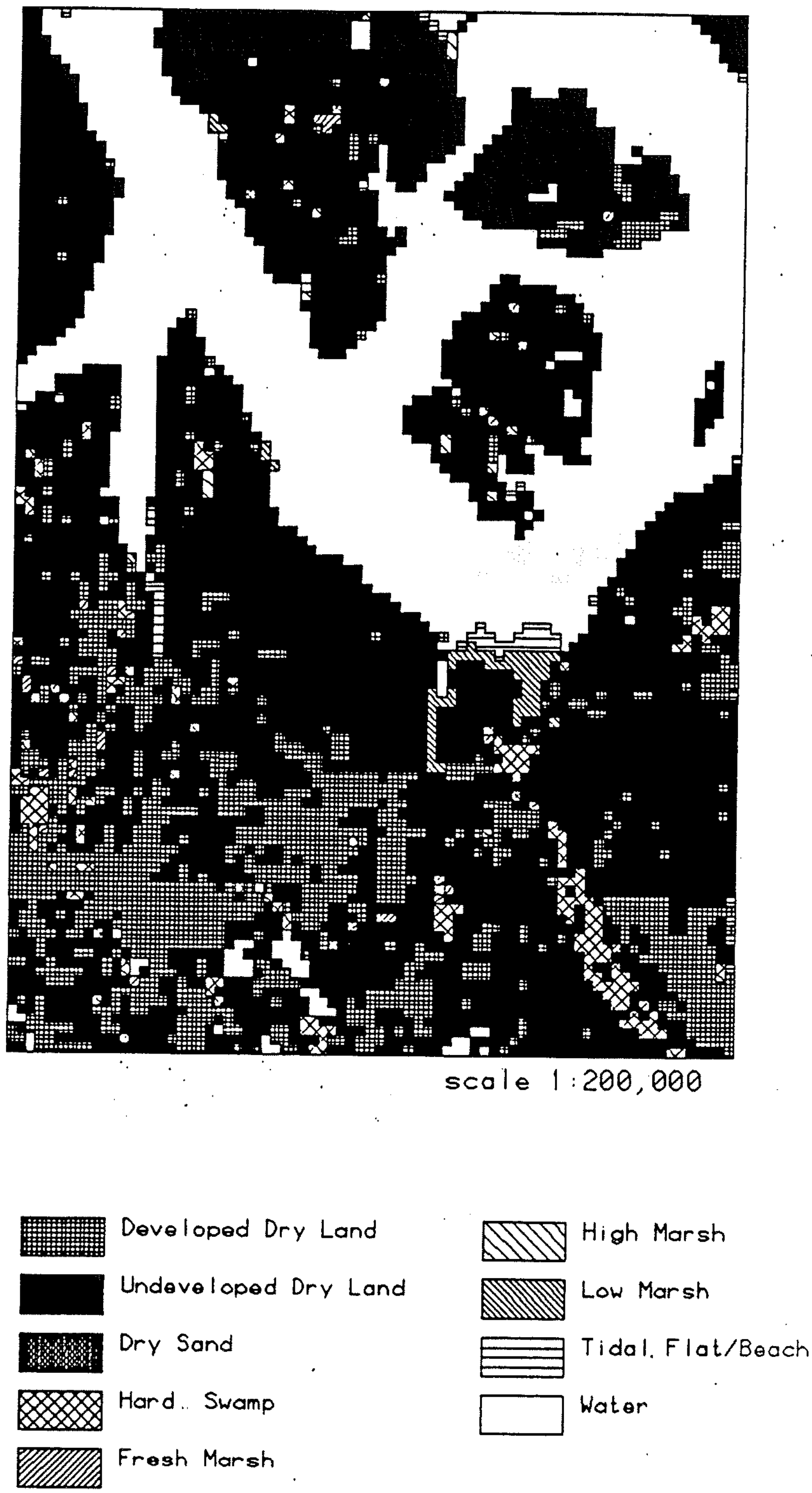

Figure 2. South Sound predicted conditions for the year 2100 with a 14-cm increase in eustatic sea level.

Figure 3. South Sound predicted conditions for the year 2100 with a 50-cm increase in eustatic sea level.

Figure 4. South Sound predicted conditions for the year 2100 with a 1-m increase in eustatic sea level.

Figure 5. South Sound predicted conditions for the year 2100 with a 2-m increase in eustatic sea level.

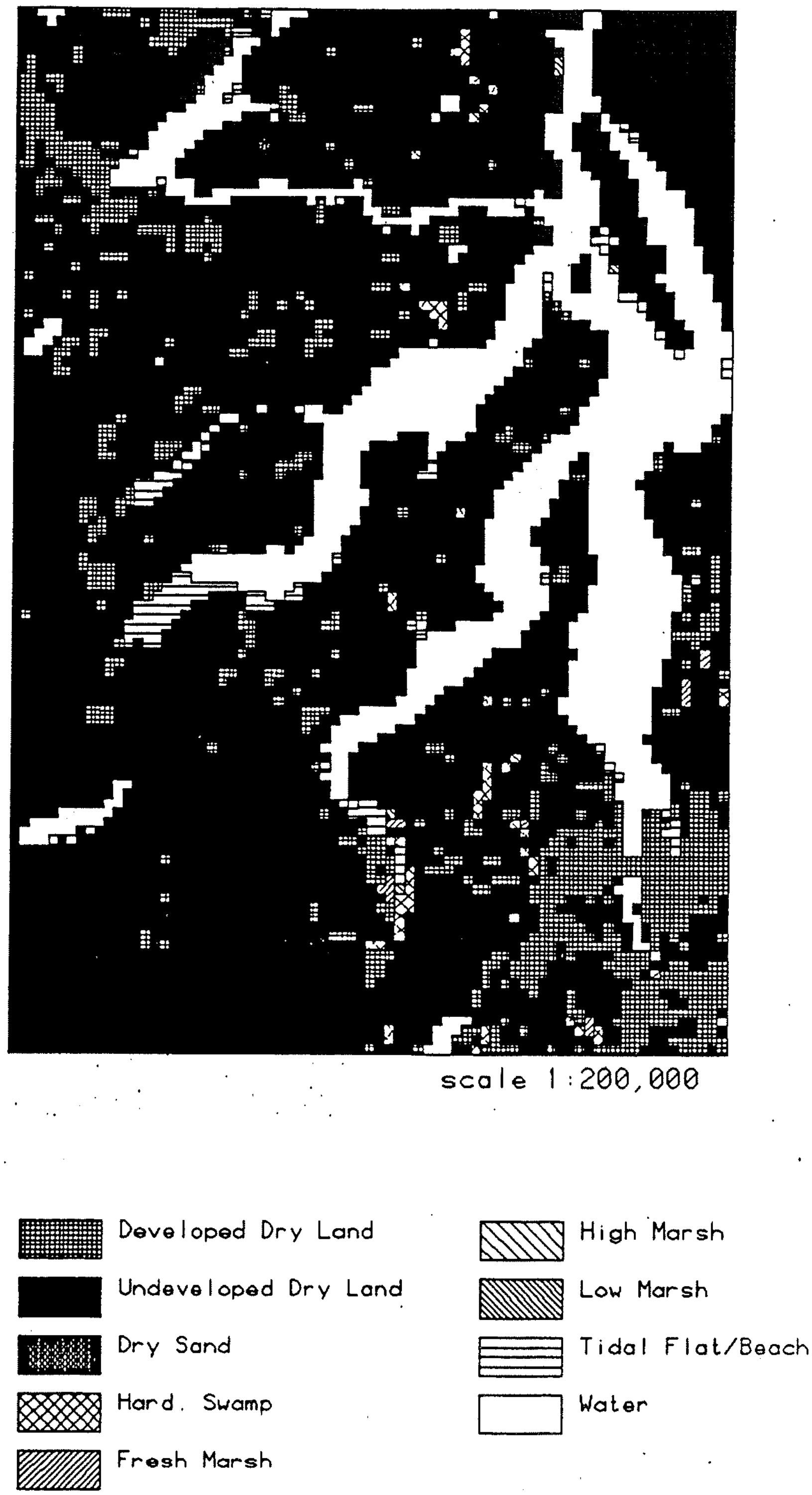

Figure 6. Olympia initial conditions based on 1986 Landsat imagery.

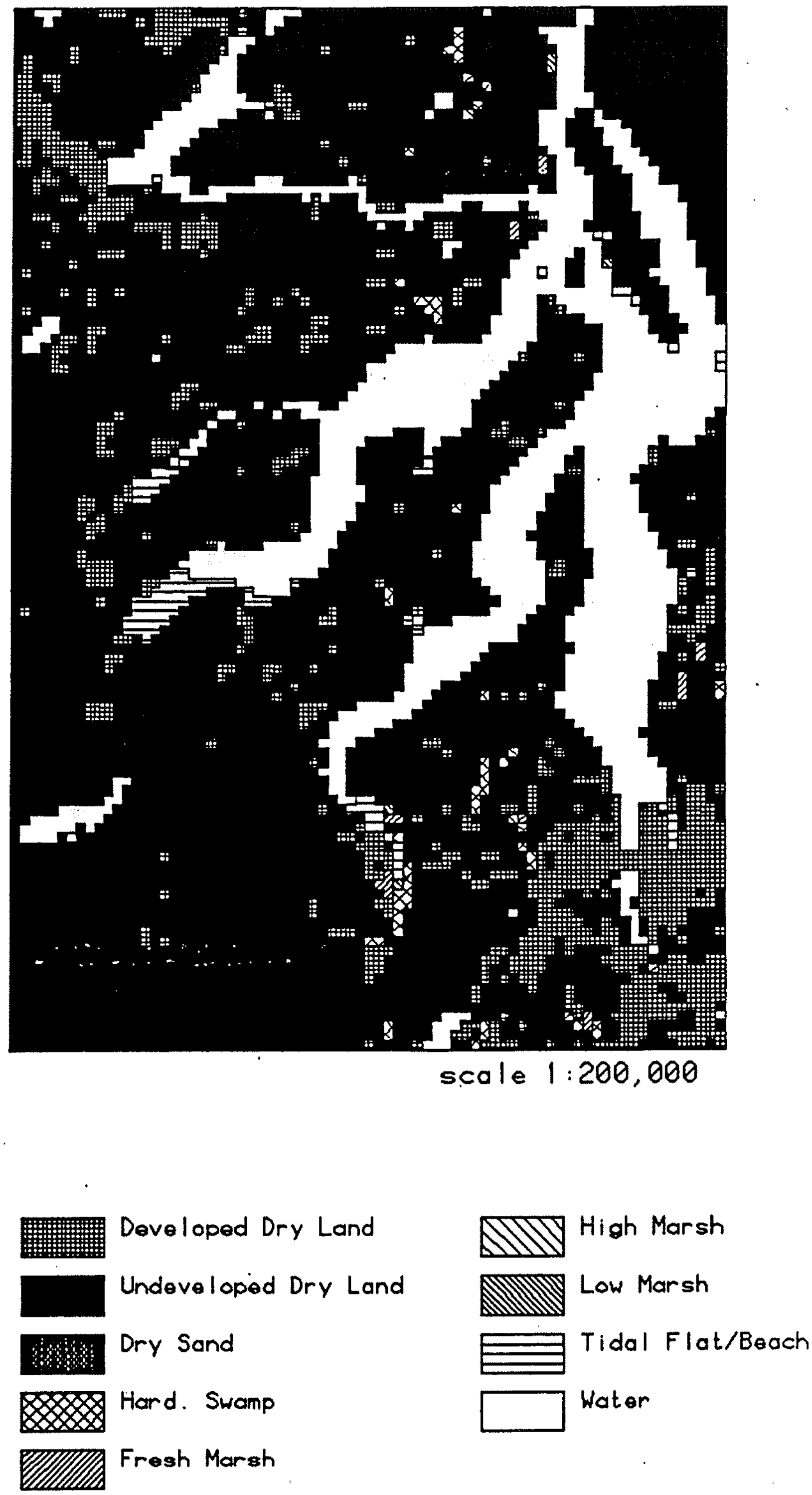

Figure 7. Olympia predicted conditions for the year 2100 with a 14-cm increase in eustatic sea level.

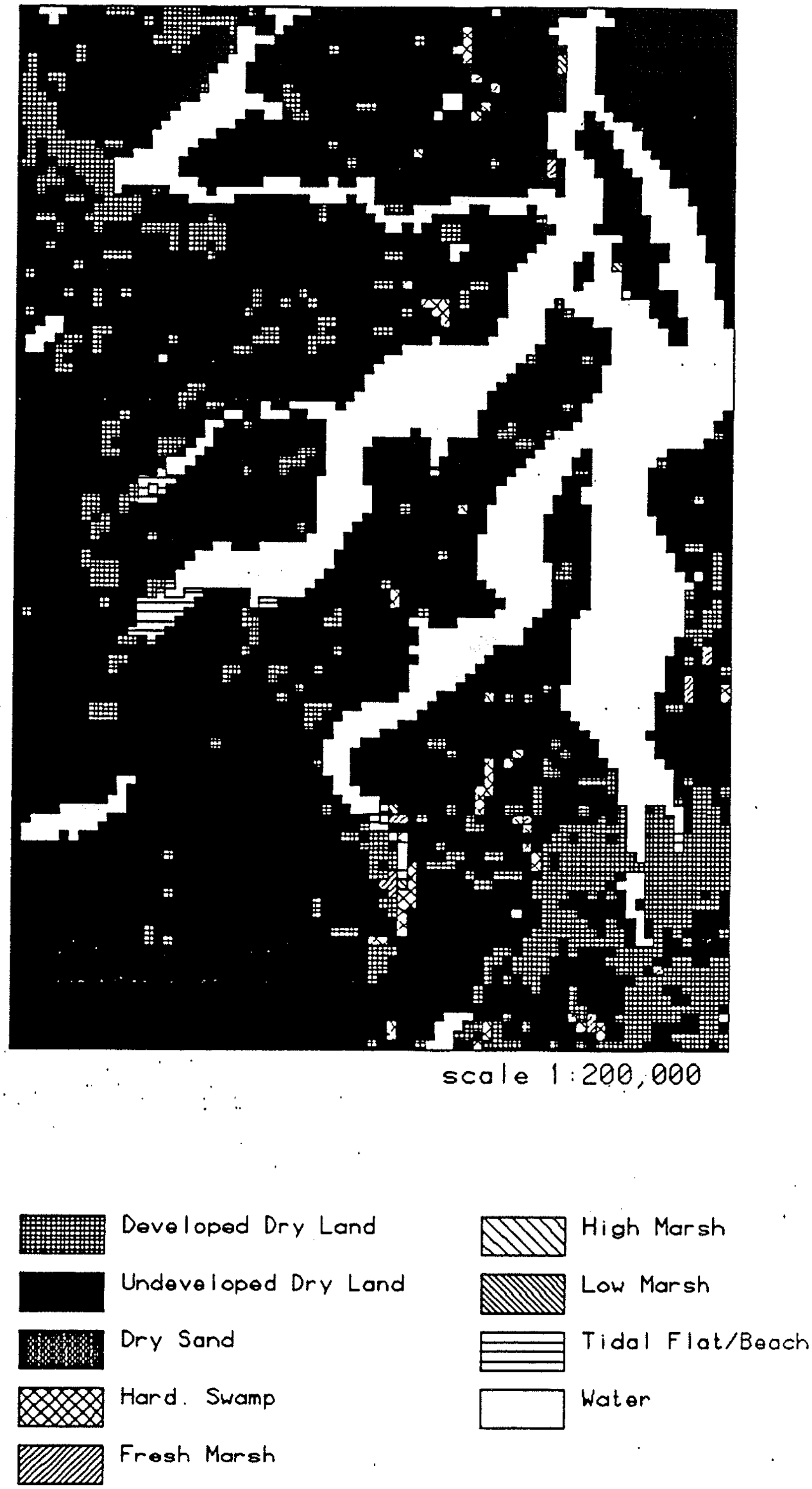

Figure 8. Olympia predicted conditions for the year 2100 with a 50-cm increase in eustatic sea level.

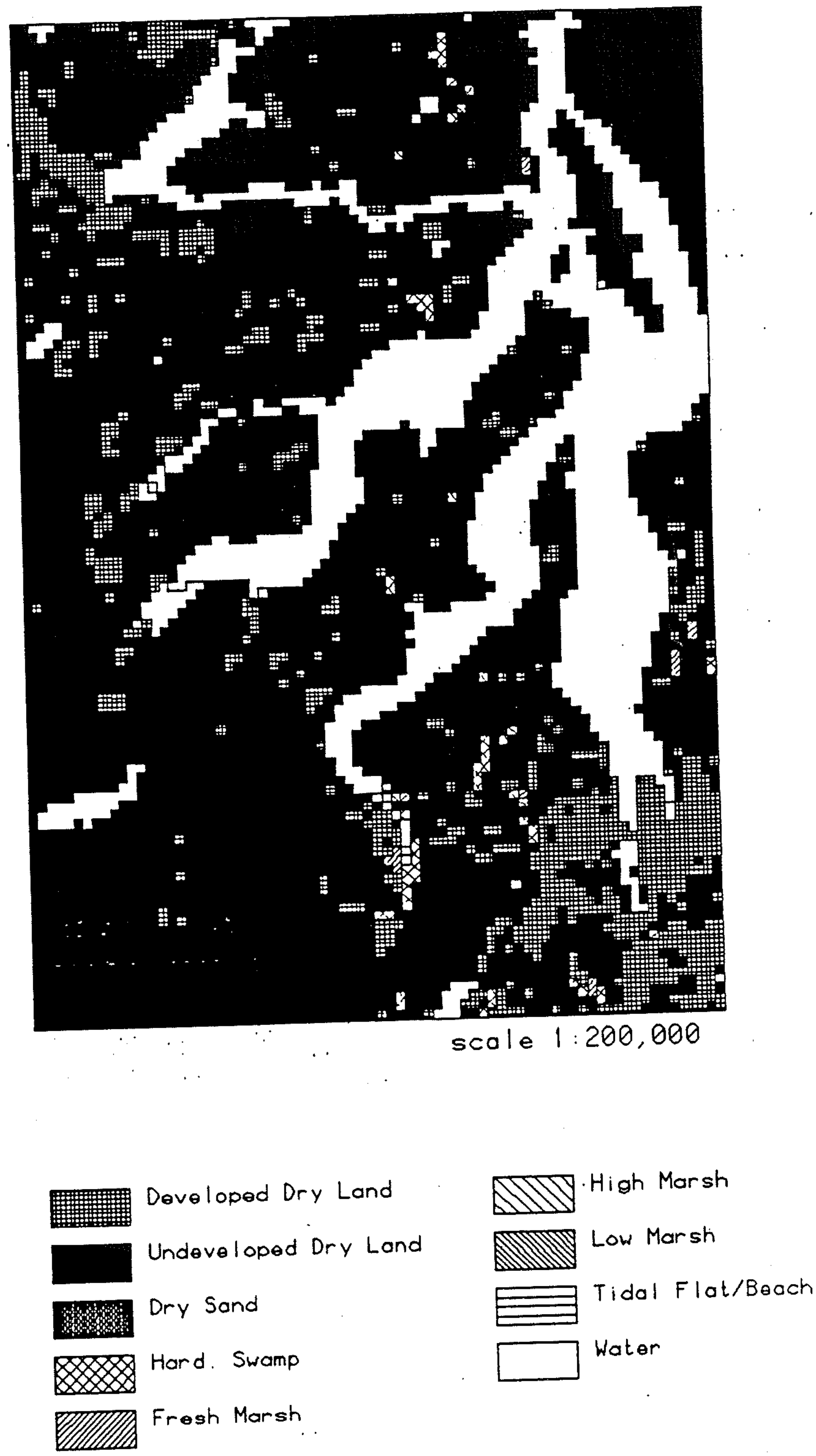

Figure 9. Olympia predicted conditions for the year 2100 with a 1-m increase in eustatic sea level.

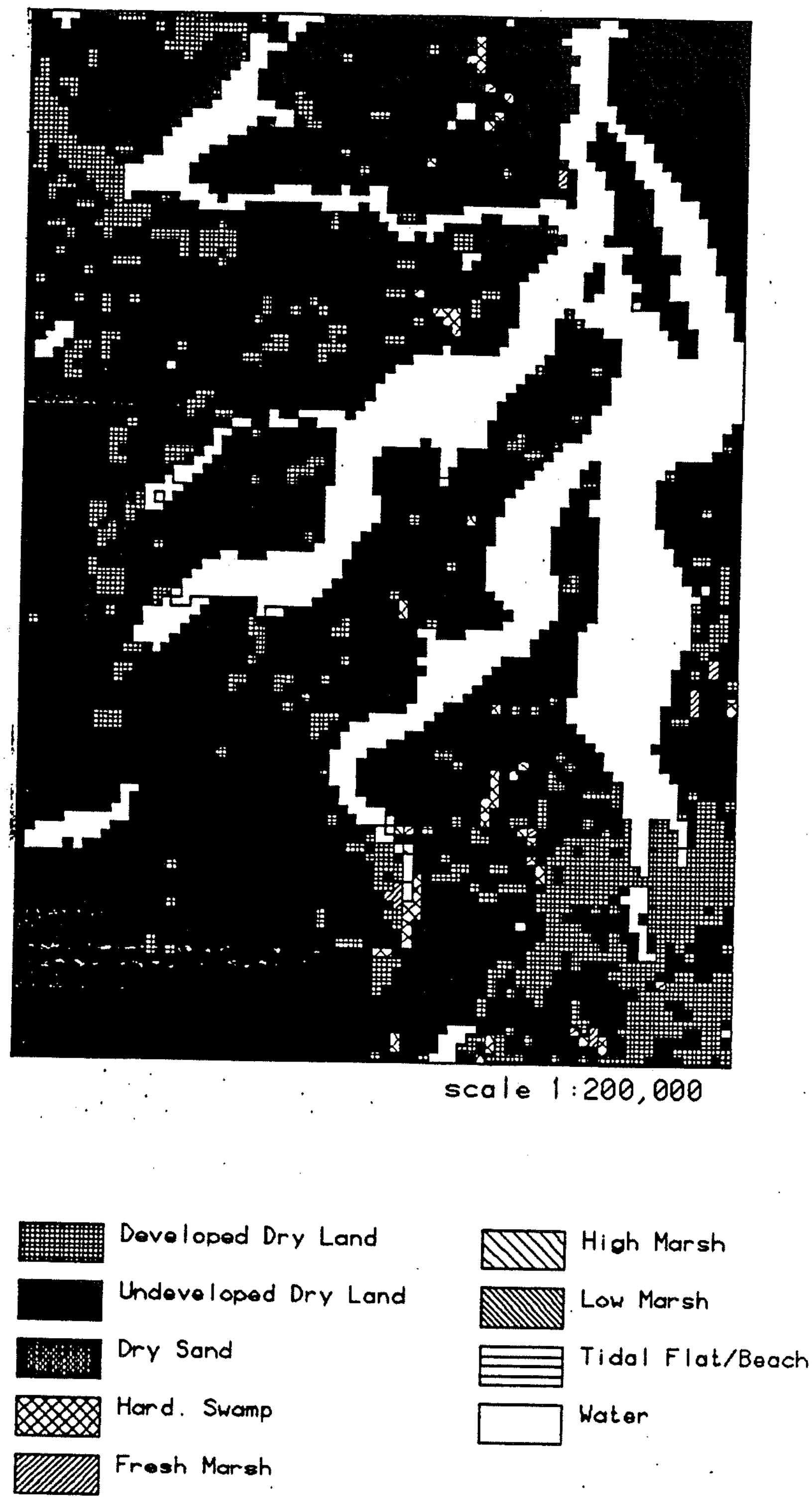

Figure 10. Olympia predicted conditions for the year 2100 with a 2-m increase in eustatic sea level.

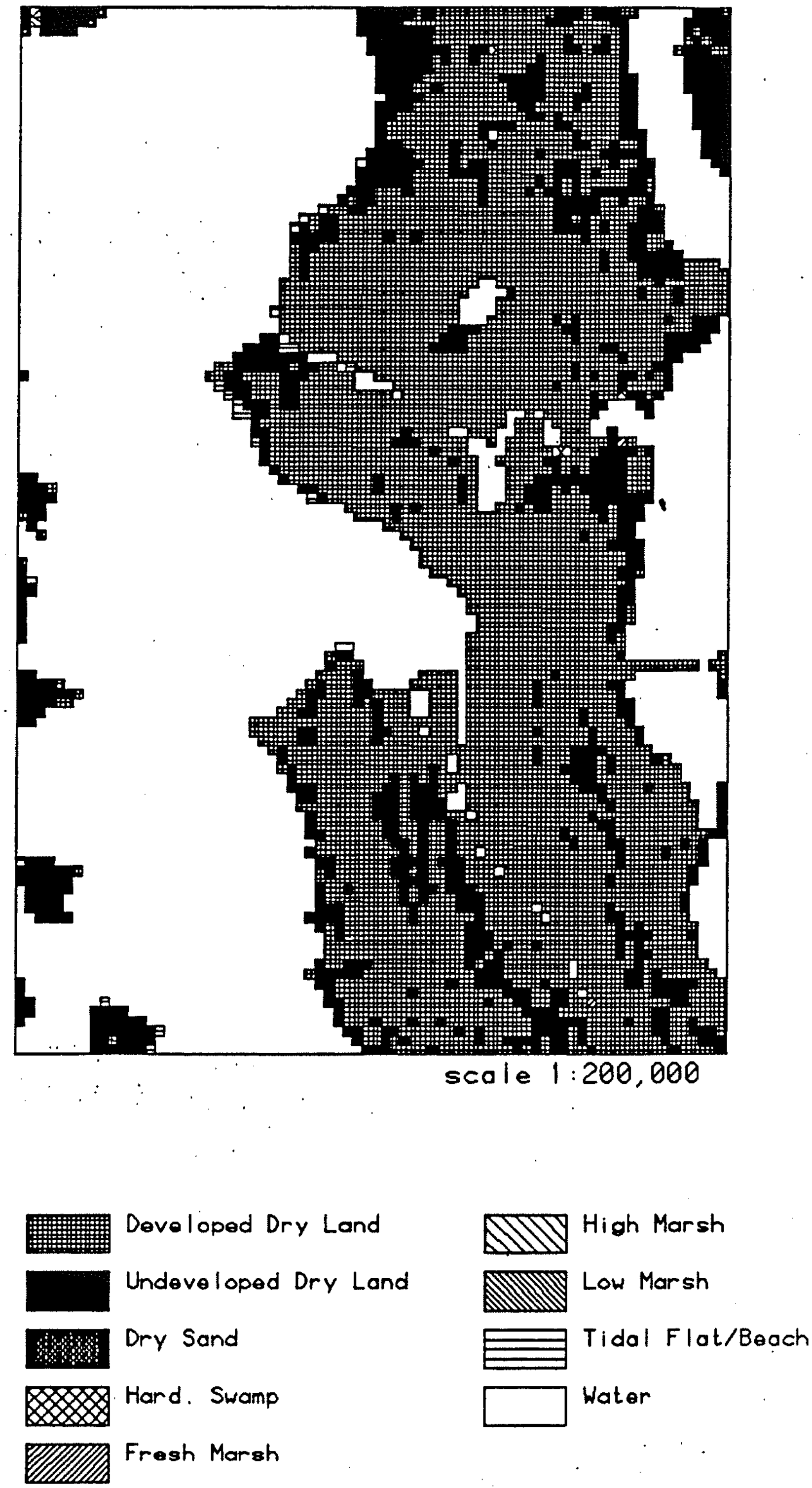

Figure 11. Elliott Bay initial conditions based on 1986 Landsat imagery.

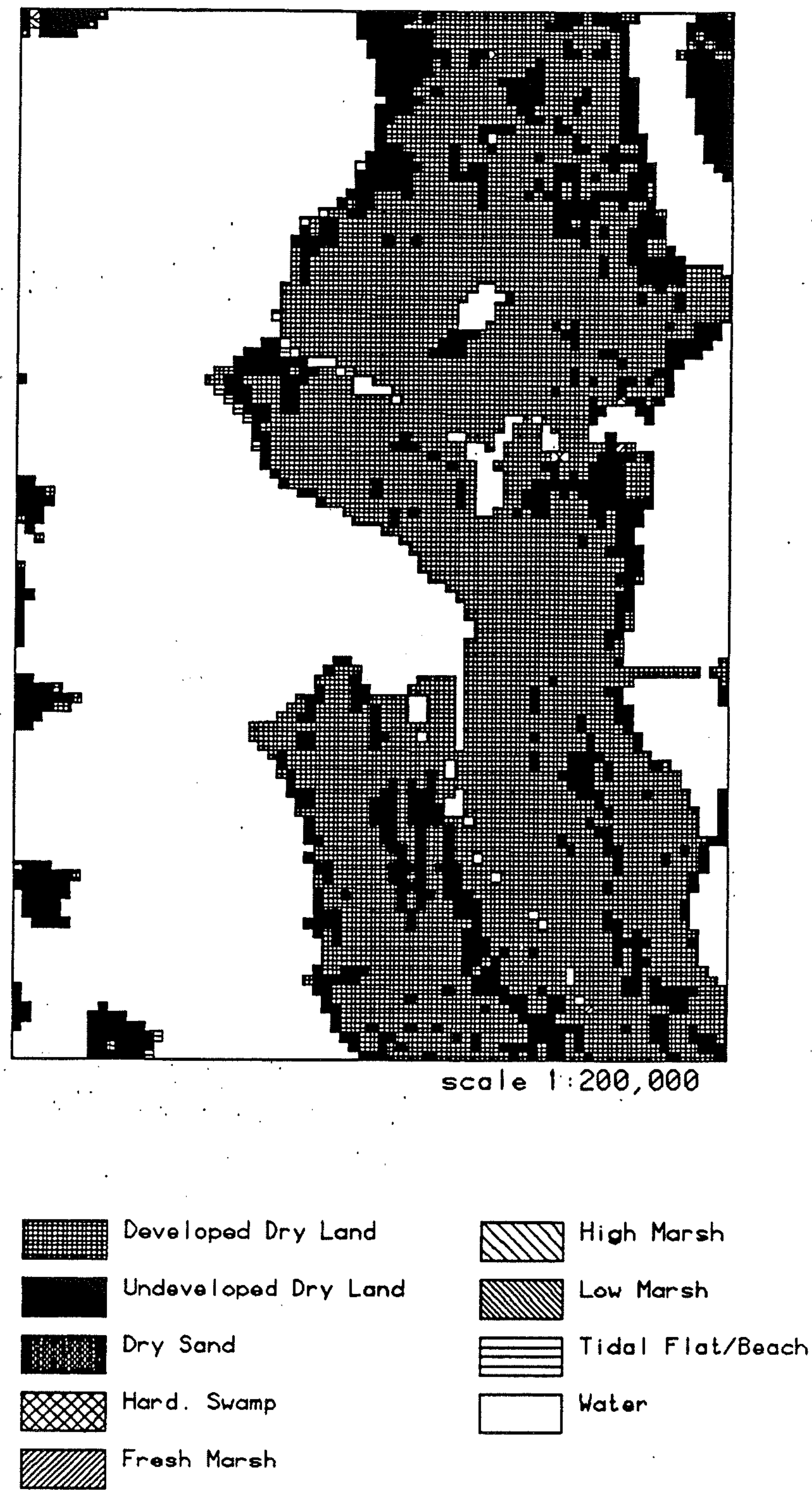

Figure 12. Elliott Bay predicted conditions for the year 2100 with a 14-cm increase in eustatic sea level.

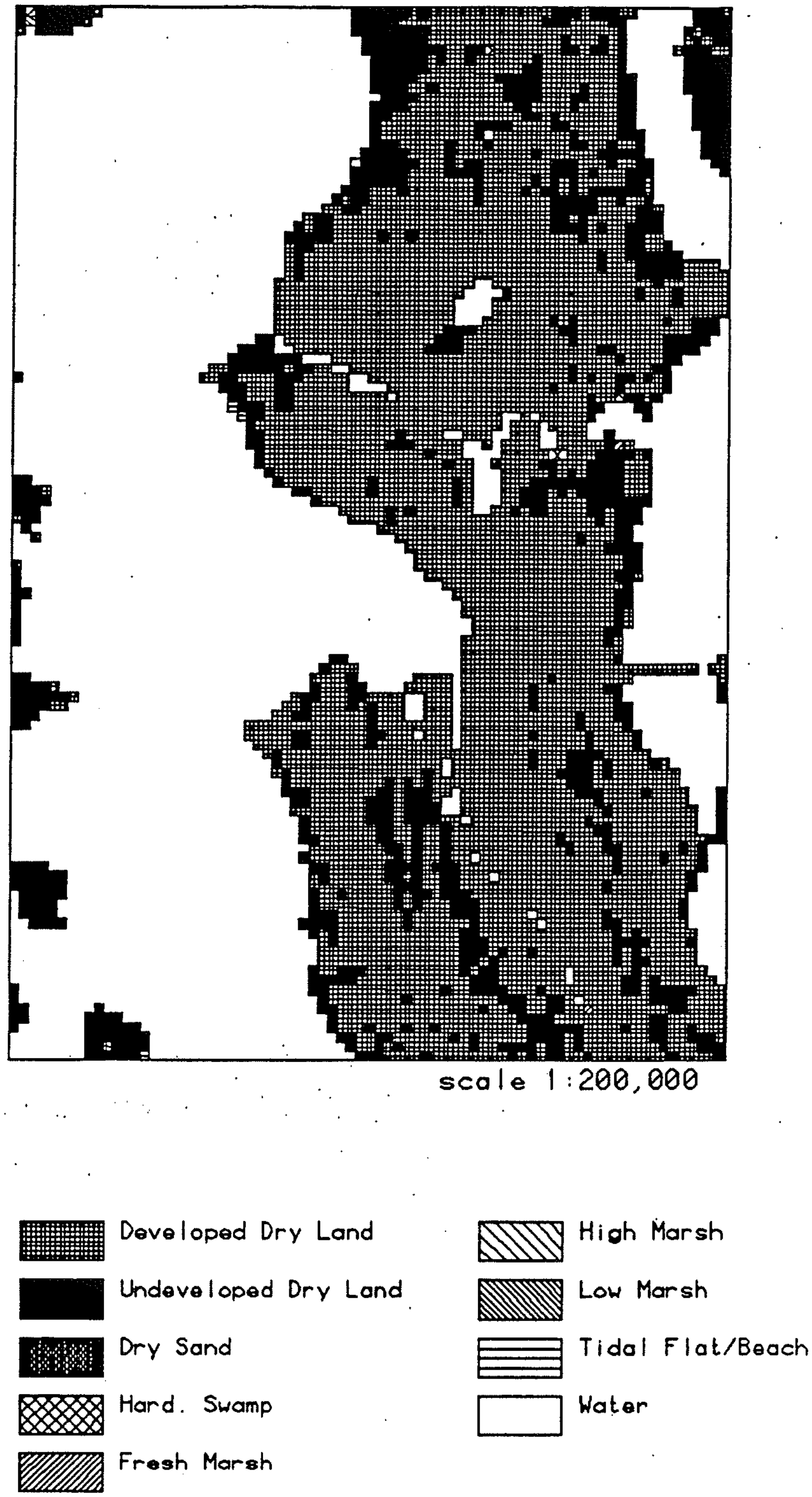

Figure 13. Elliott Bay predicted conditions for the year 2100 with a 50-cm increase in eustatic sea level.

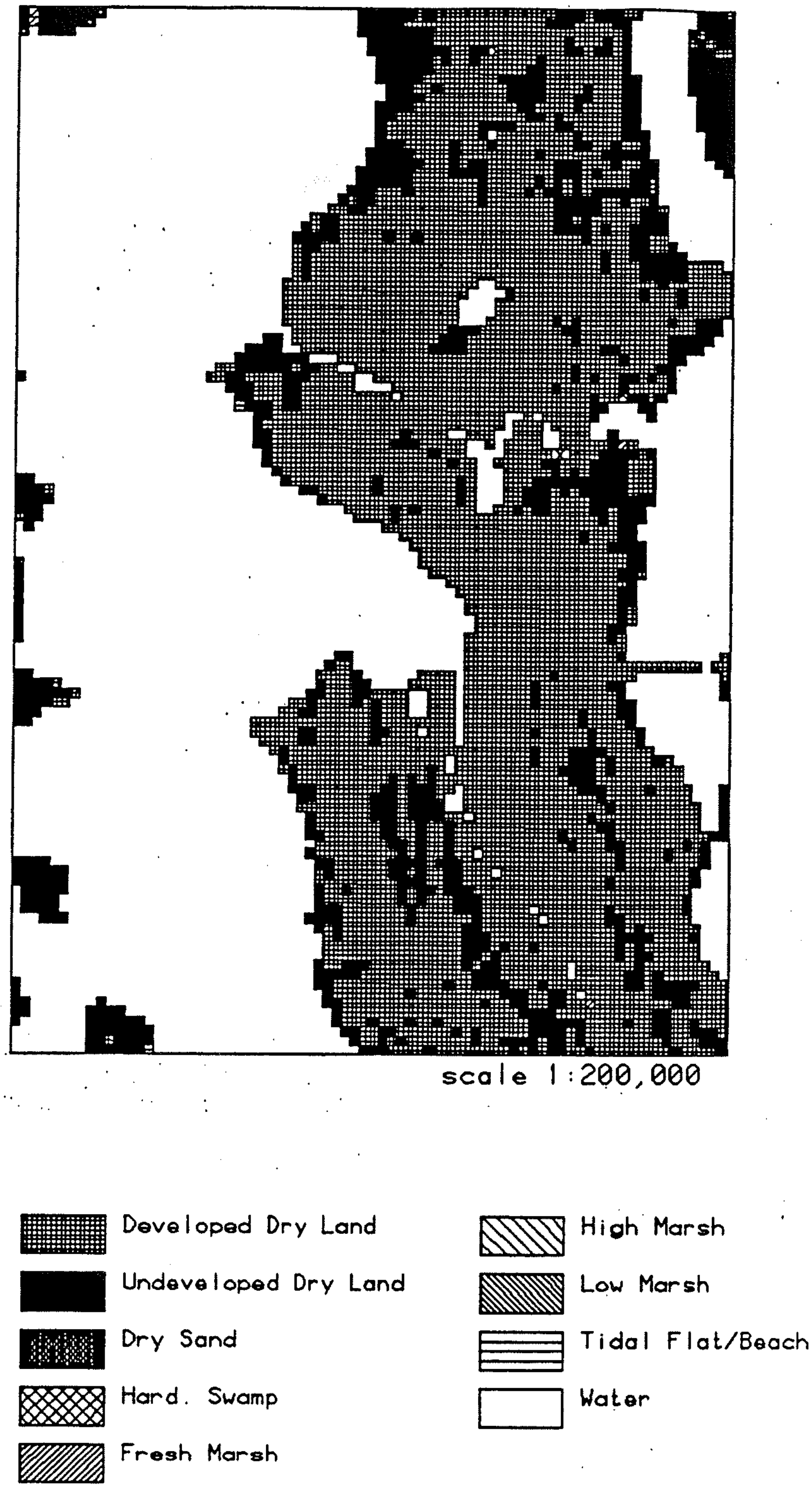

Figure 14. Elliott Bay predicted conditions for the year 2100 with a 1-m increase in eustatic sea level.

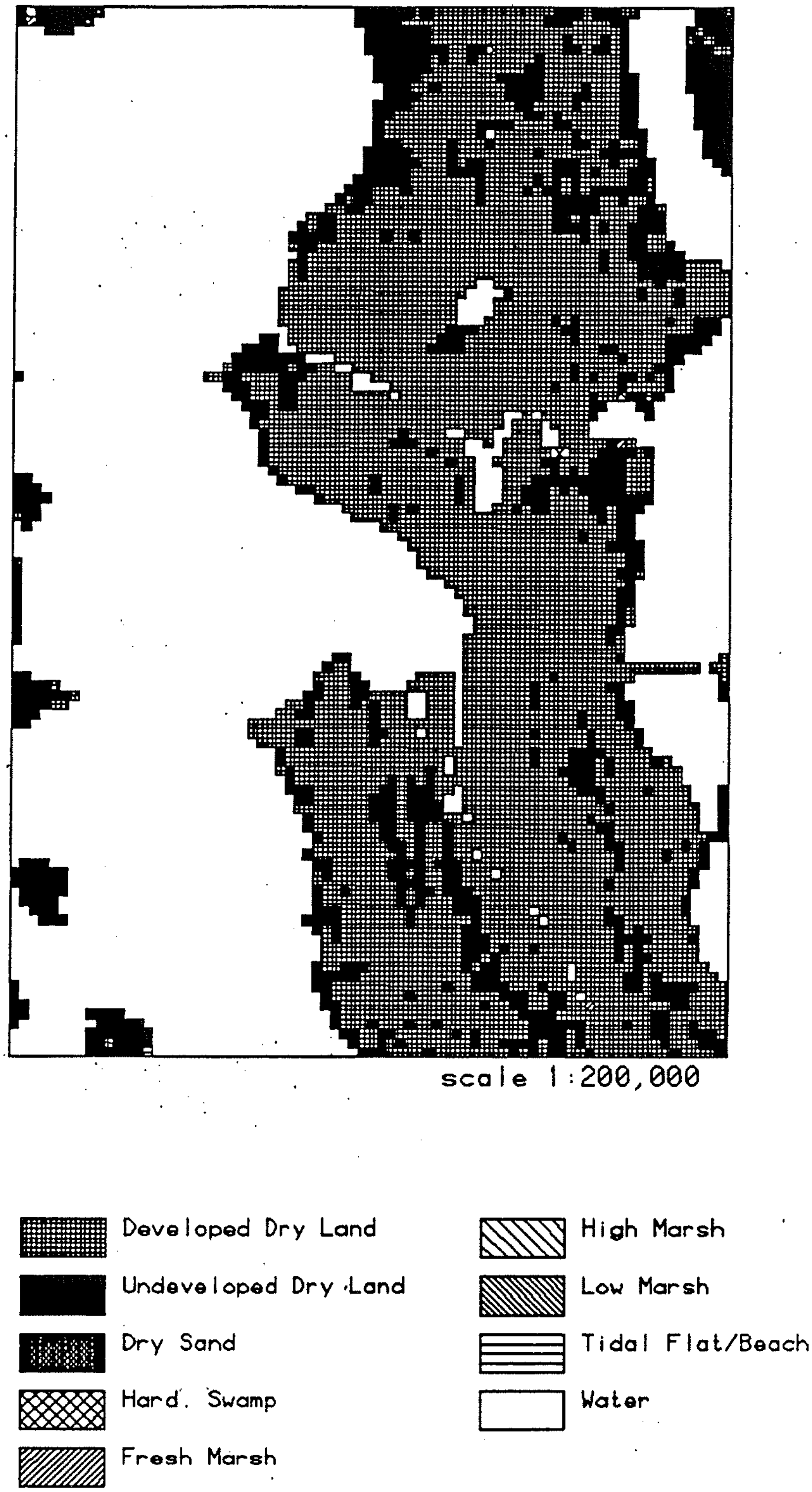

Figure 15. Elliott Bay predicted conditions for the year 2100 with a 2-m increase in eustatic sea level.

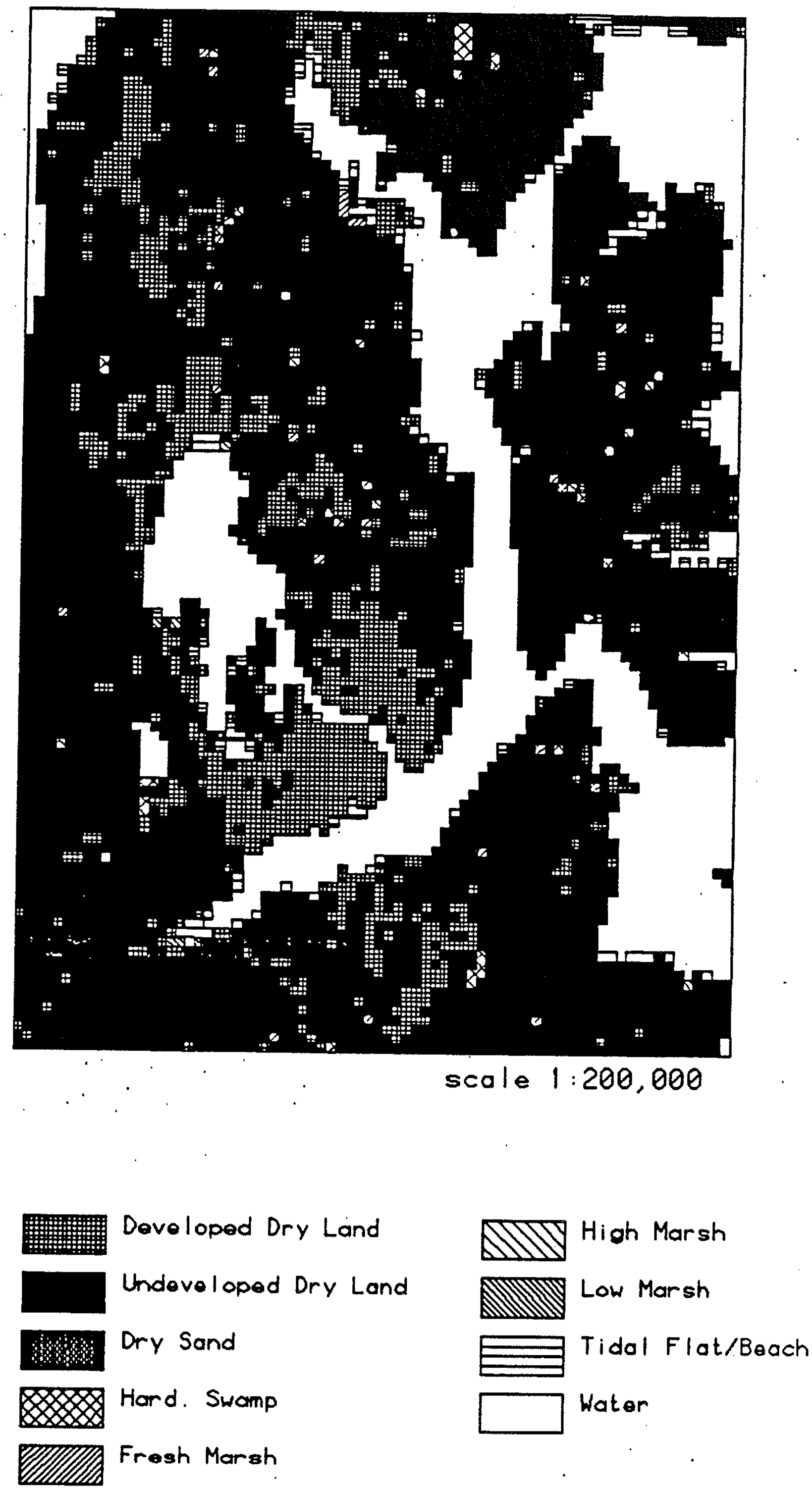

Figure 16. Port Orchard initial conditions based on 1986 Landsat imagery.

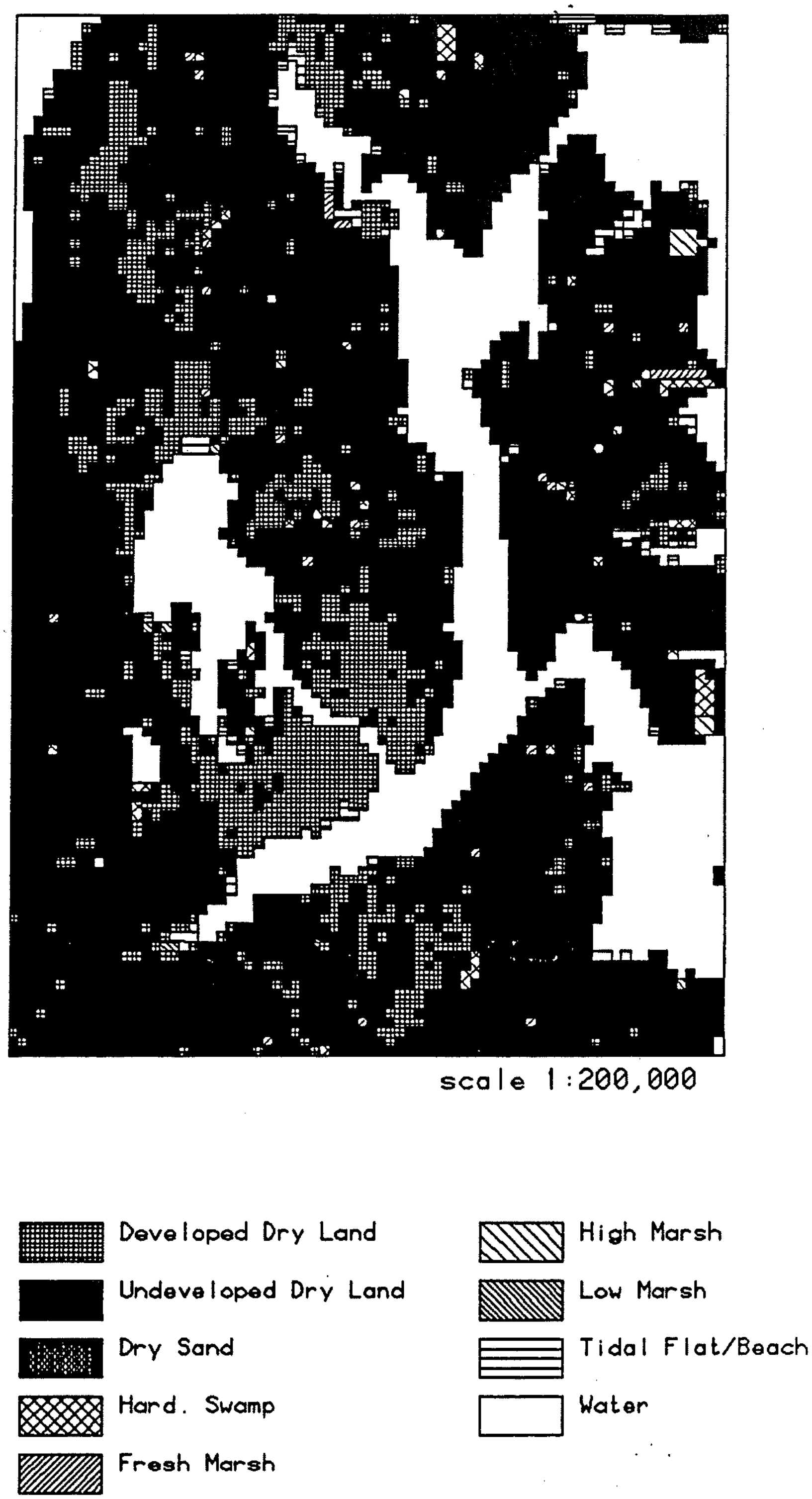

Figure 17. Port Orchard predicted conditions for the year 2100 with a 14-cm increase in eustatic sea level.

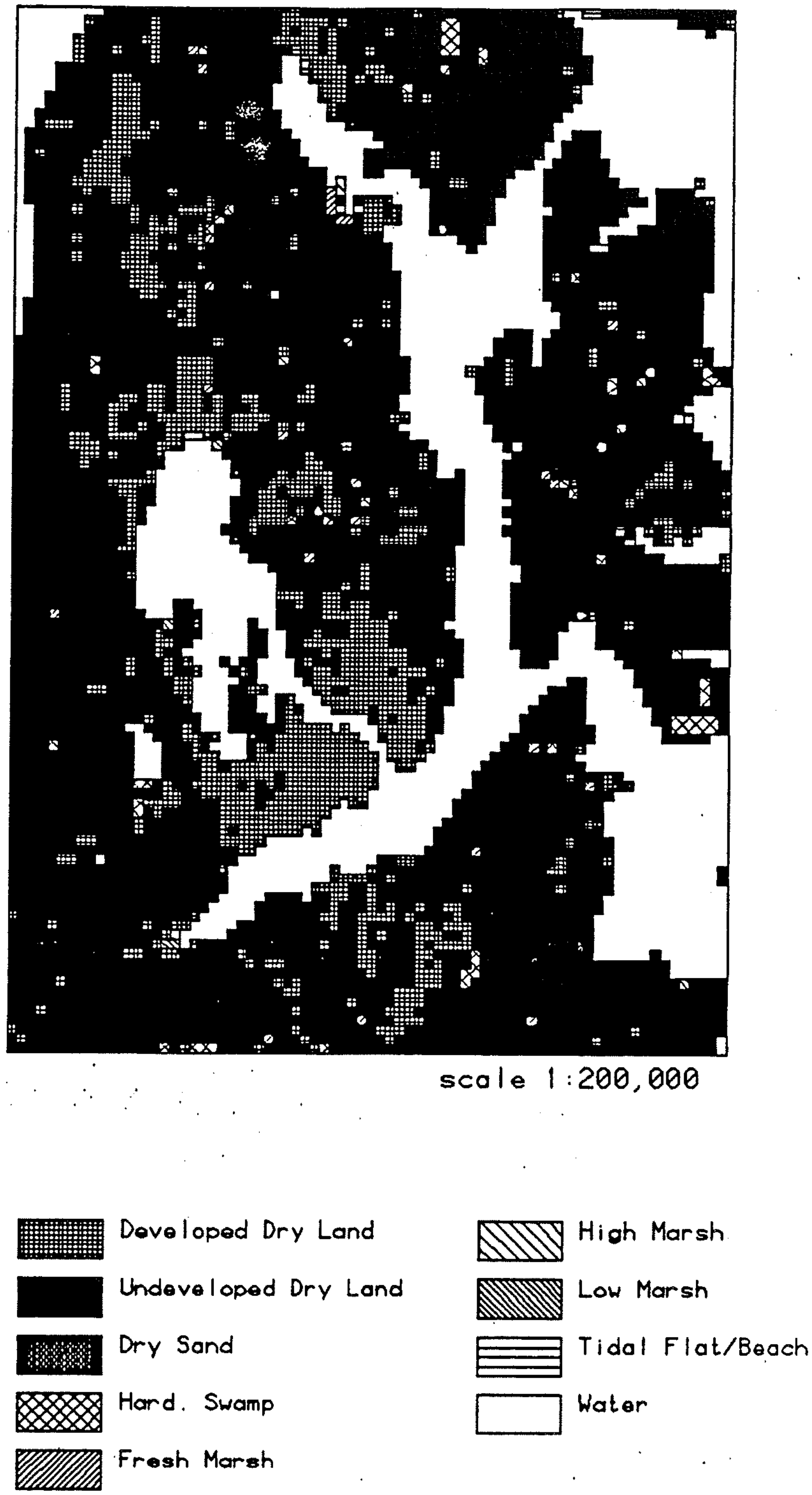

Figure 18. Port Orchard predicted conditions for the year 2100 with a 50-cm increase in eustatic sea level.

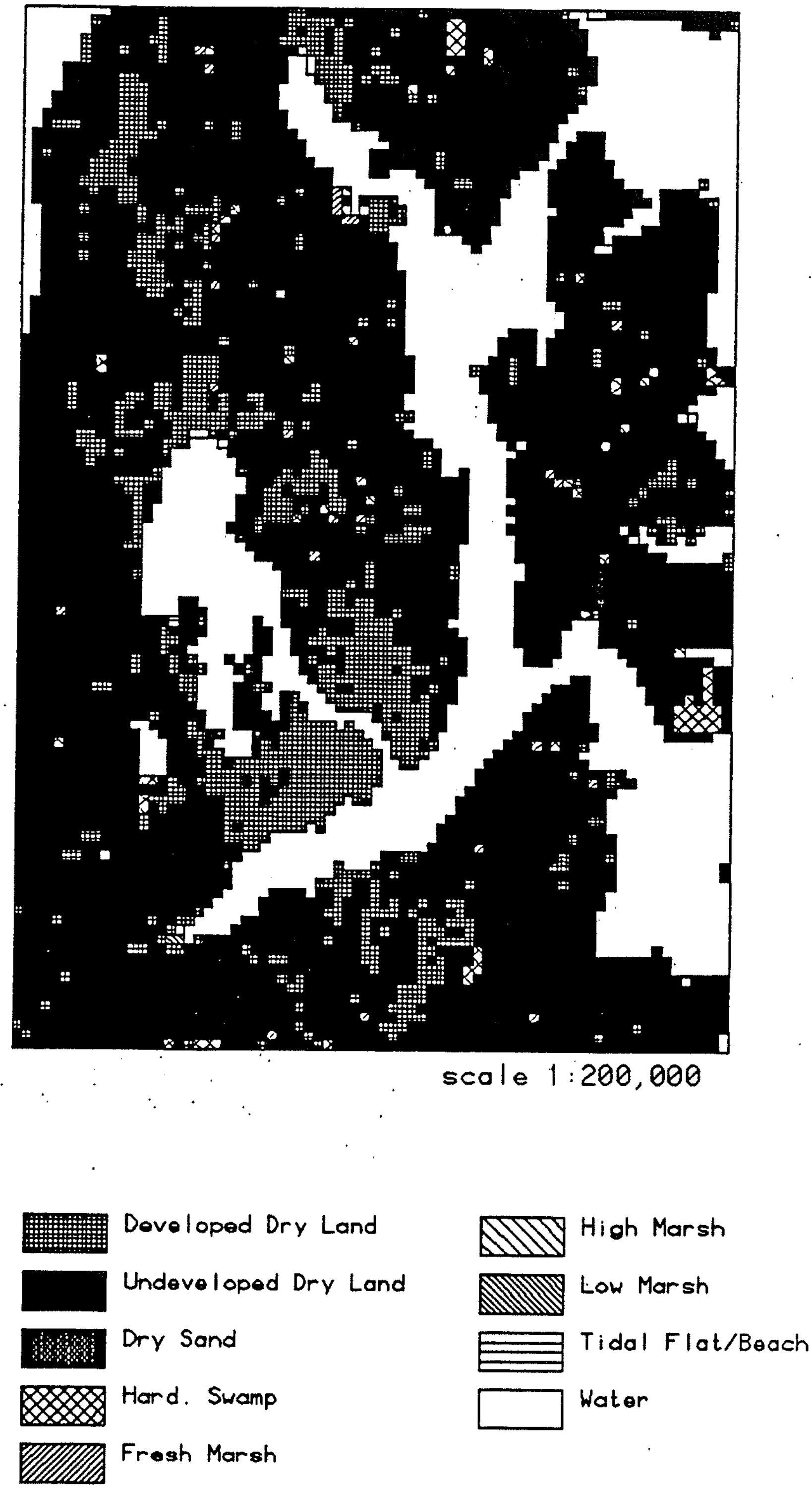

Figure 19. Port Orchard predicted conditions for the year 2100 with a 1-m increase in eustatic sea level.

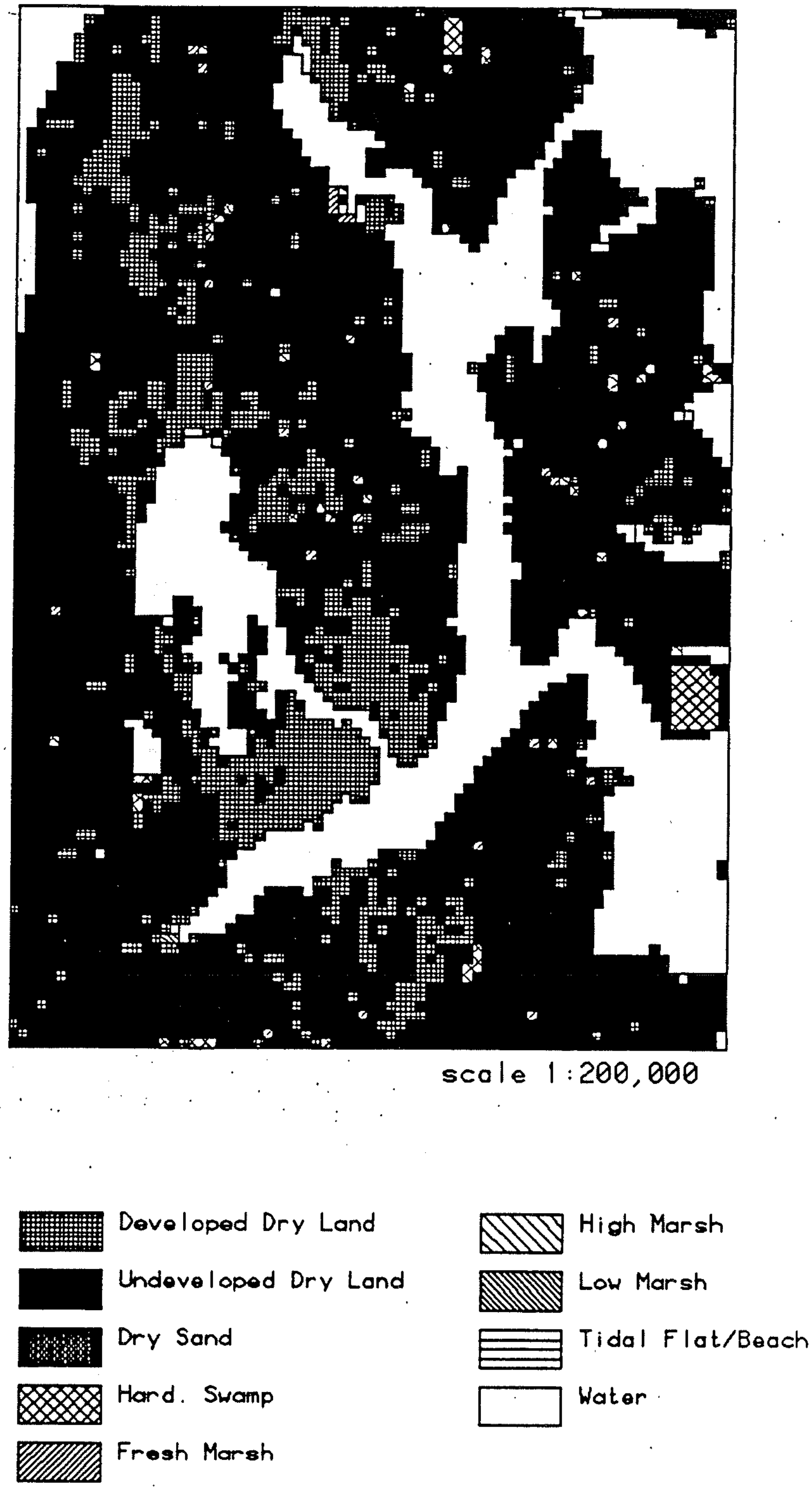

Figure 20. Port Orchard predicted conditions for the year 2100 with a 2-m increase in eustatic sea level.

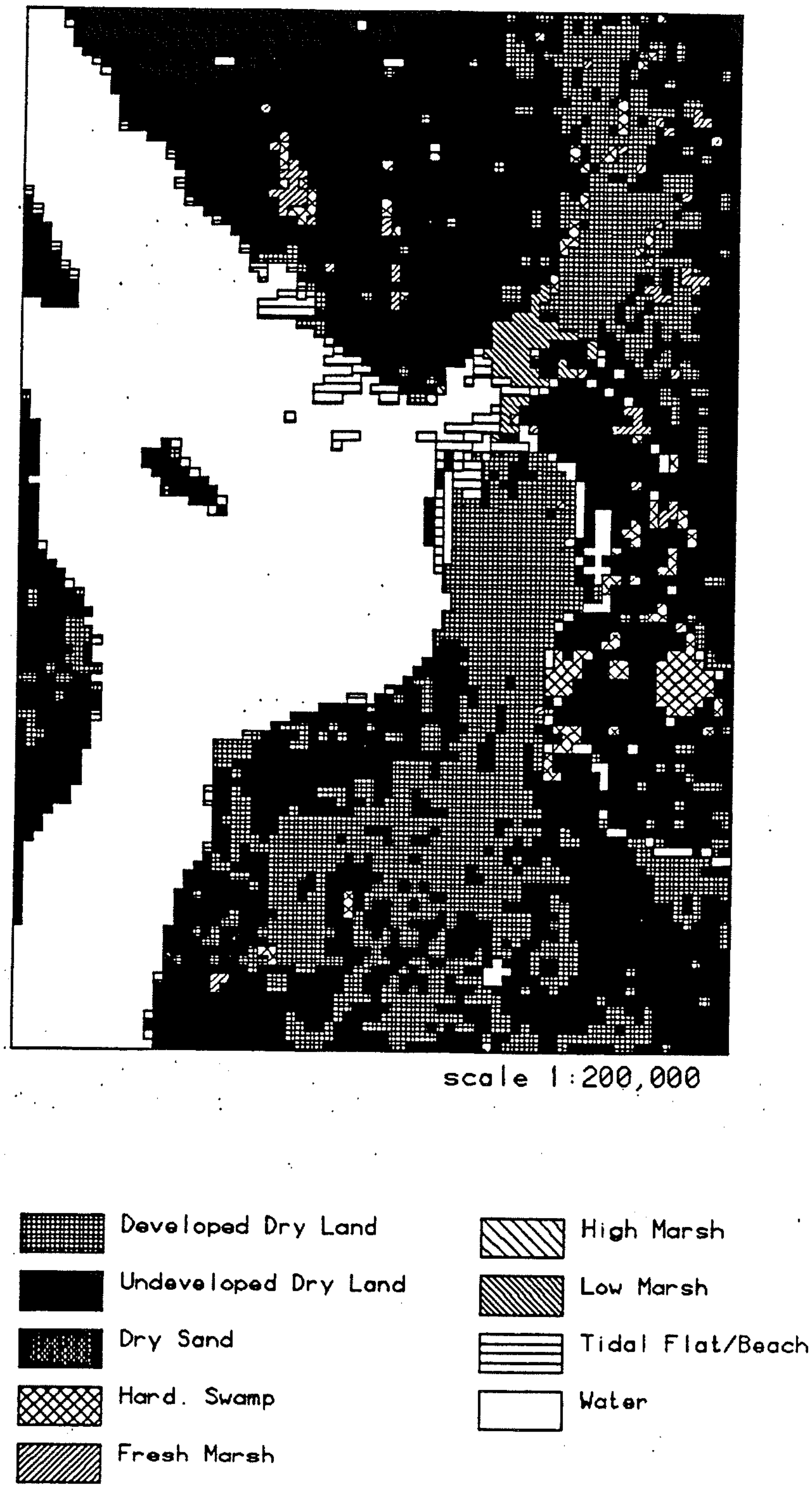

Figure 21. Possession Sound initial conditions based on 1986 Landsat imagery.

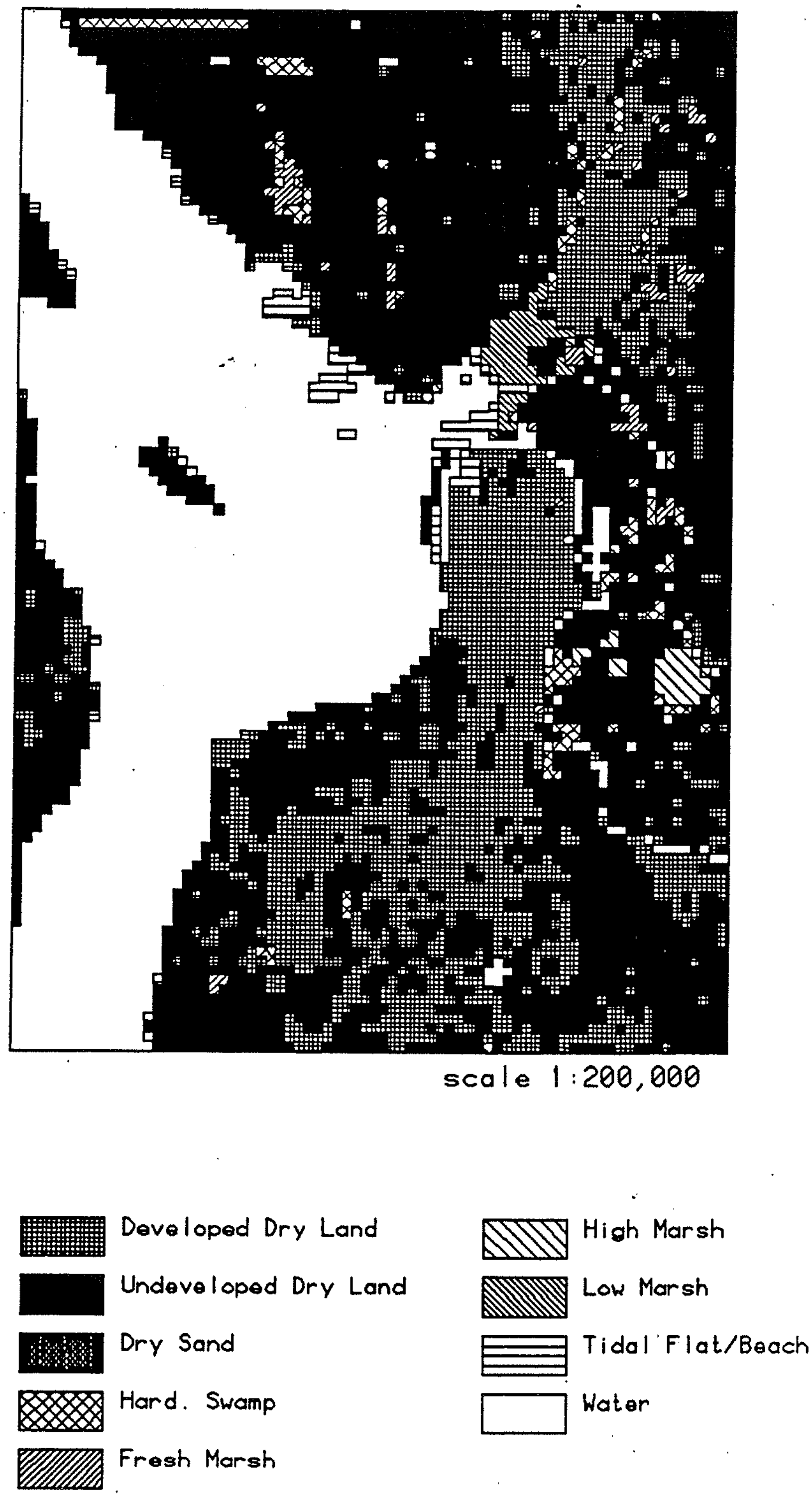

Figure 22. Possession Sound predicted conditions for the year 2100 with a 14-cm increase in eustatic sea level.

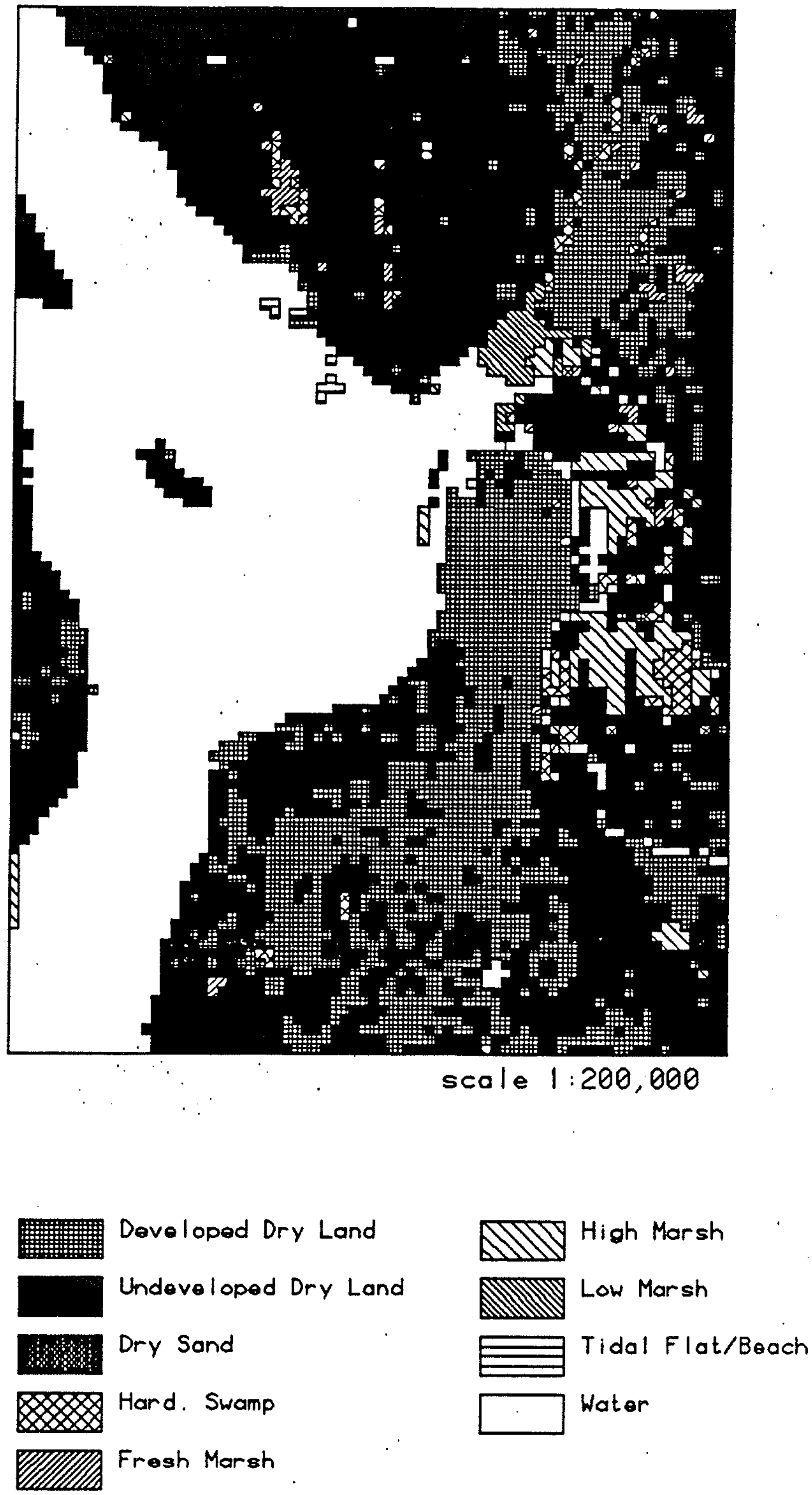

Figure 23. Possession Sound predicted conditions for the year 2100 with a 50-cm increase in eustatic sea level.

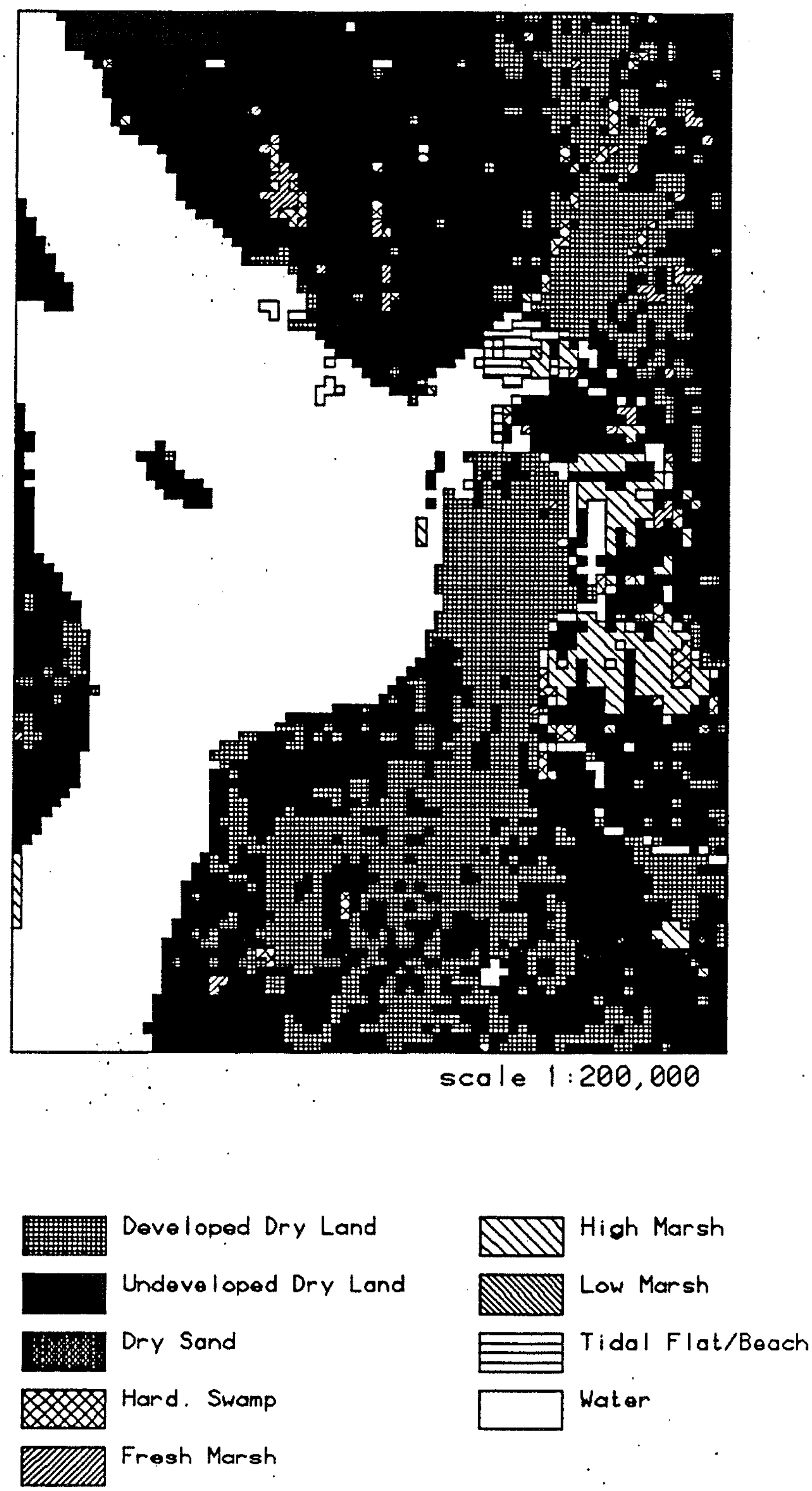

Figure 24. Possession Sound predicted conditions for the year 2100 with a 1-m increase in eustatic sea level.

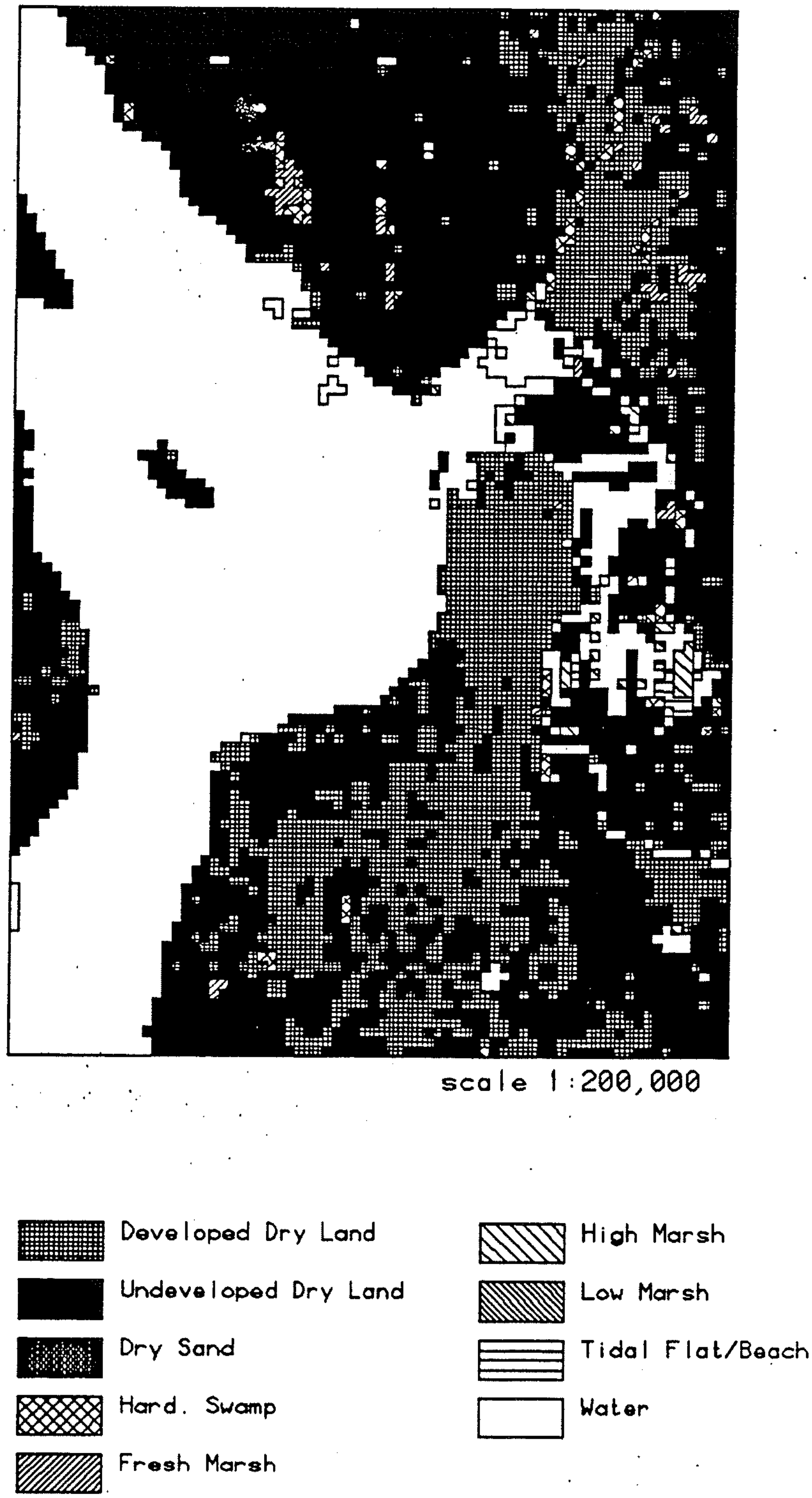

Figure 25. Possession Sound predicted conditions for the year 2100 with a 2-m increase in eustatic sea level.

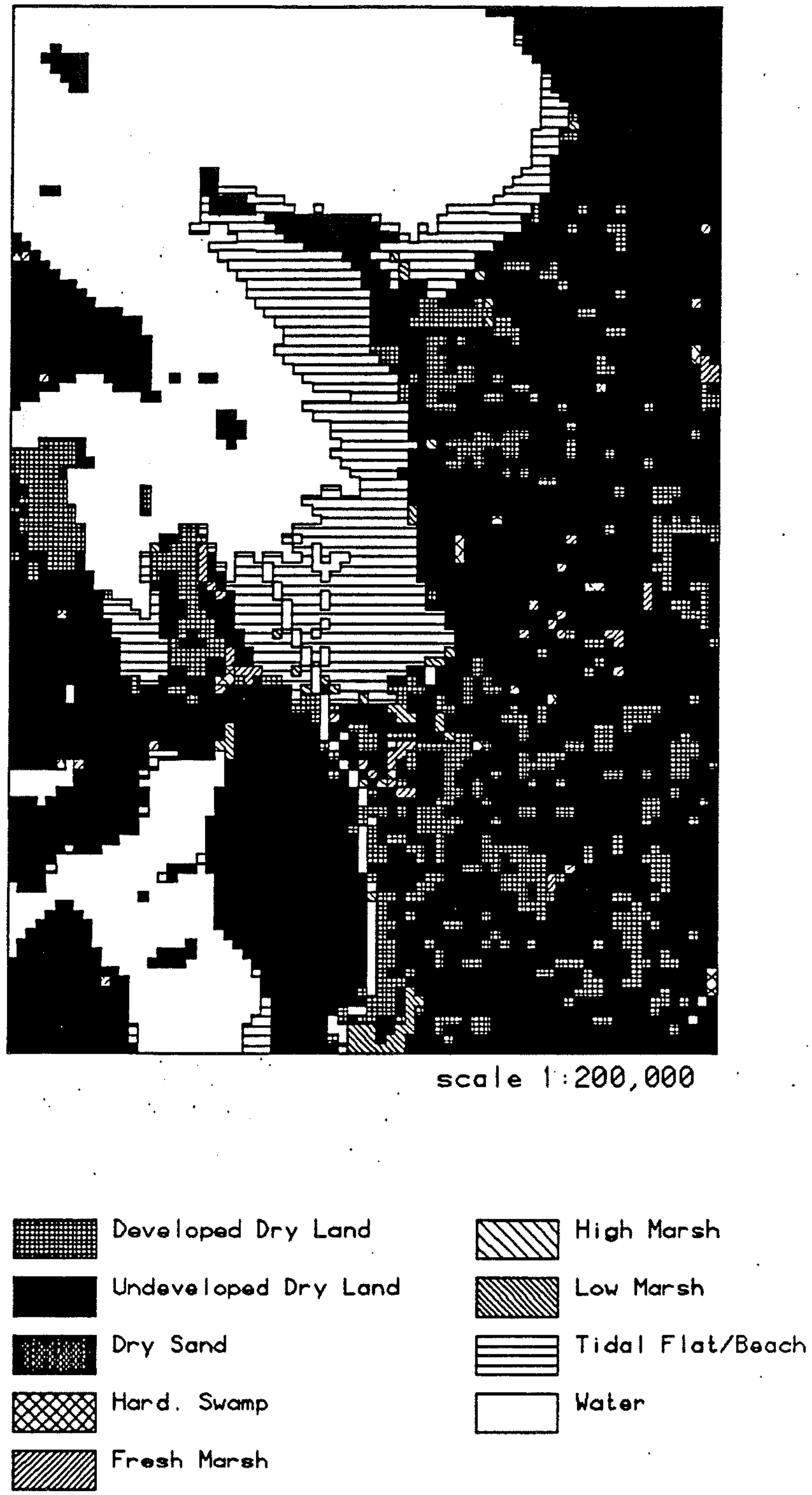

Figure 26. Padilla Bay initial conditions based on 1986 Landsat imagery.

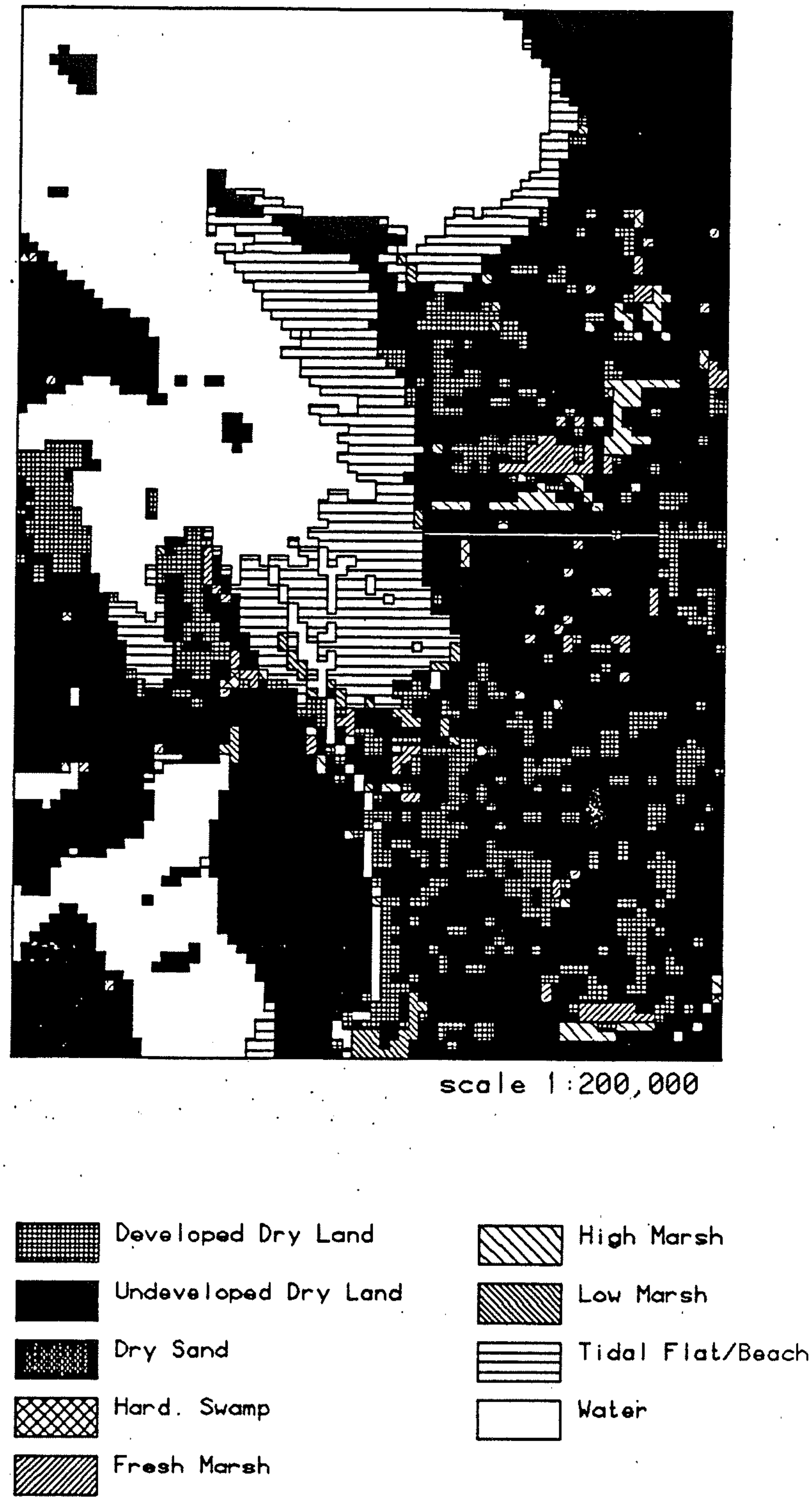

Figure 27. Padilla Bay predicted conditions for the year 2100 with a 14-cm increase in eustatic sea level.

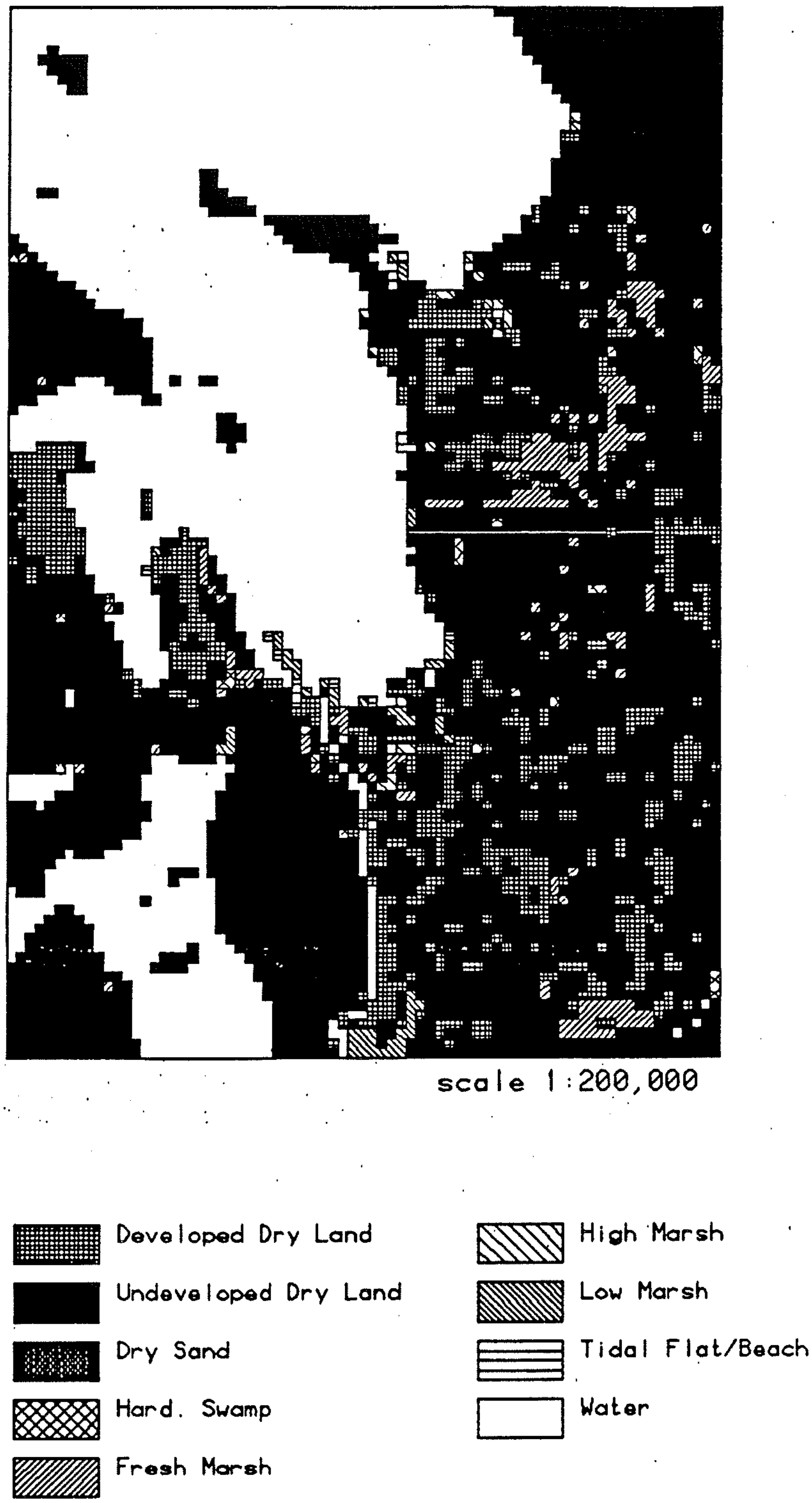

Figure 28. Padilla Bay predicted conditions for the year 2100 with a 50-cm increase in eustatic sea level.

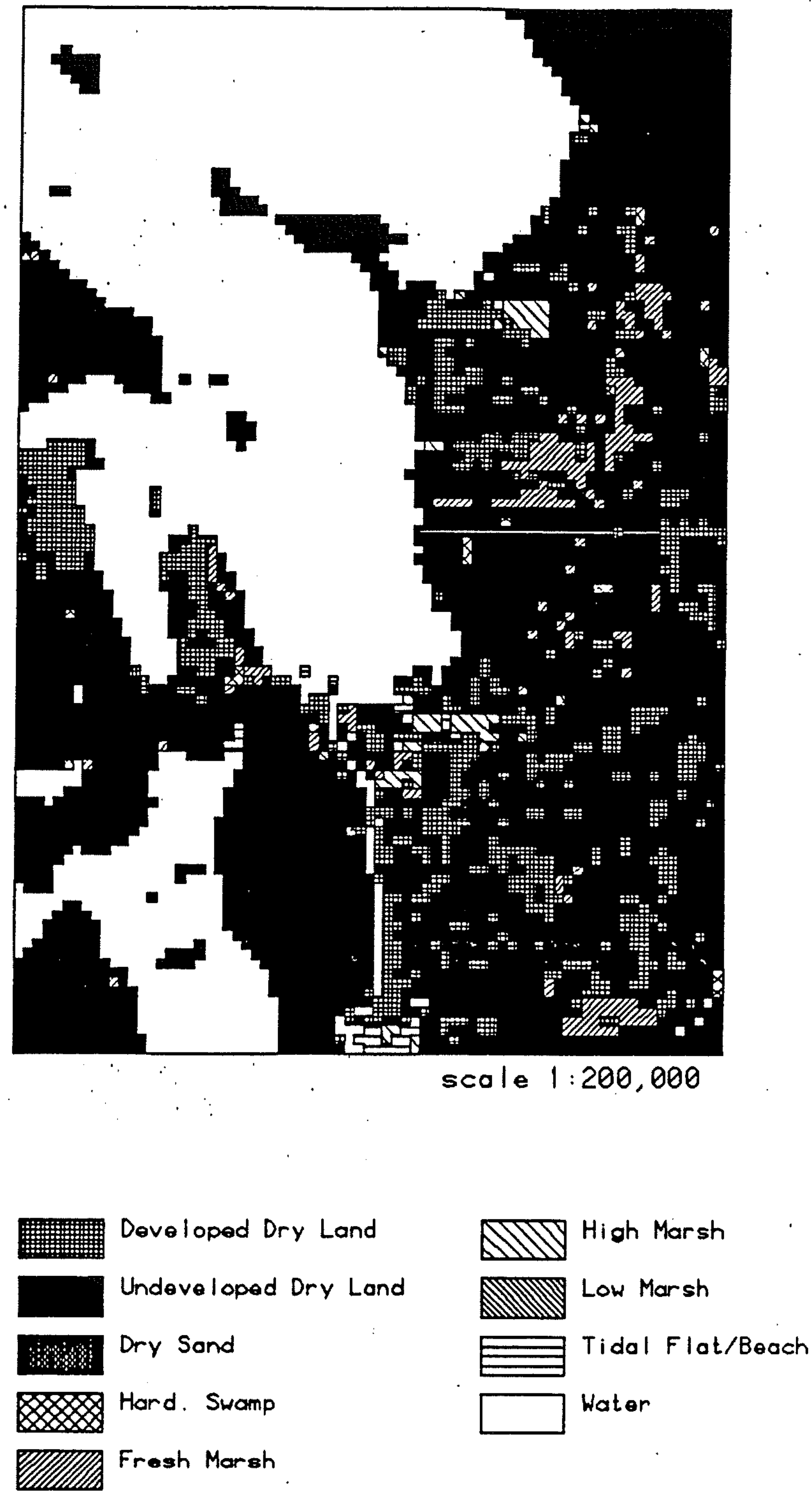

Figure 29. Padilla Bay predicted conditions for the year 2100 with a 1-m increase in eustatic sea level.

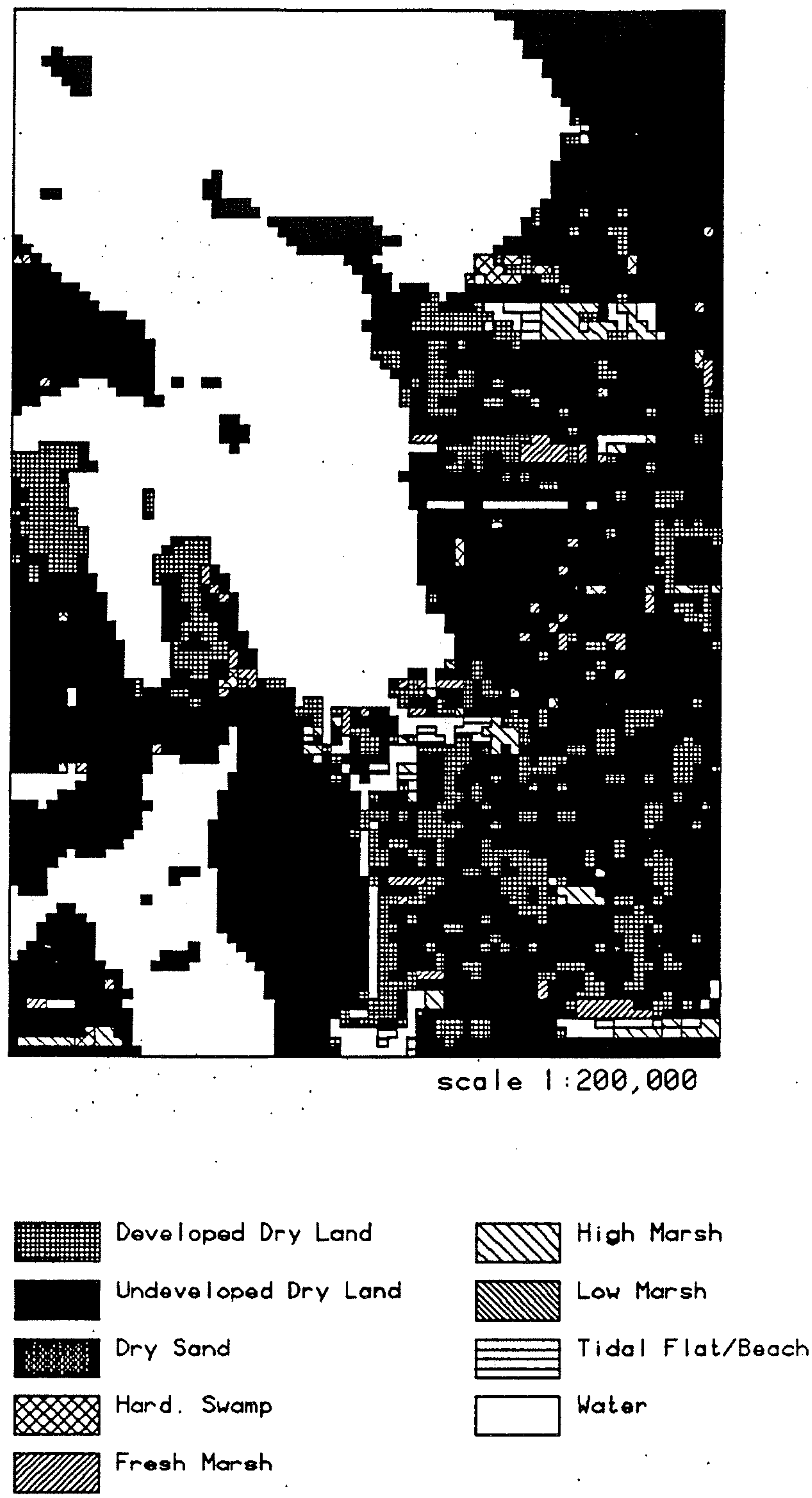

Figure 30. Padilla Bay predicted conditions for the year 2100 with a 2-m increase in eustatic sea level.

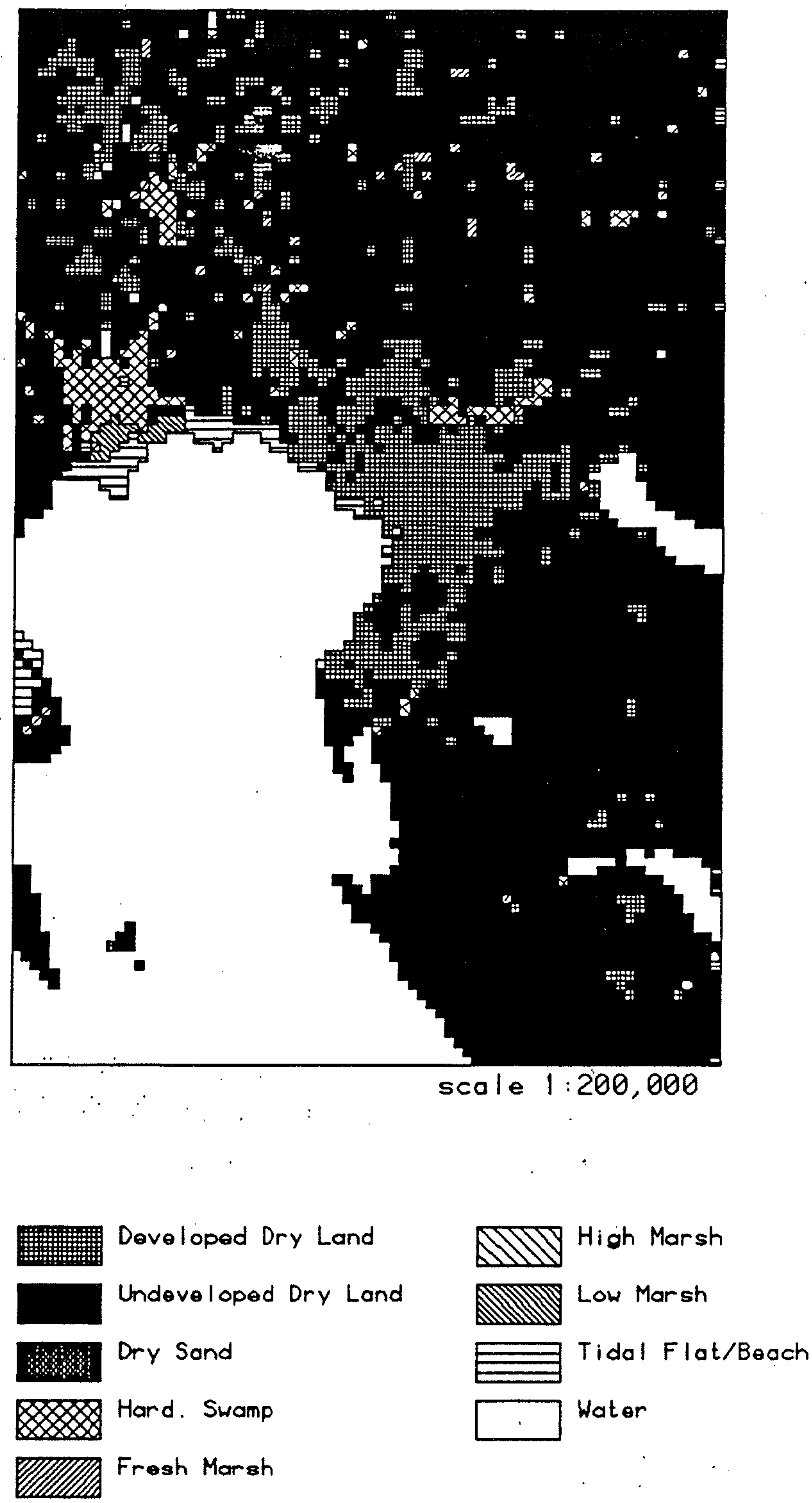

Figure 31. Bellingham Bay initial conditions based on 1986 Landsat imagery.

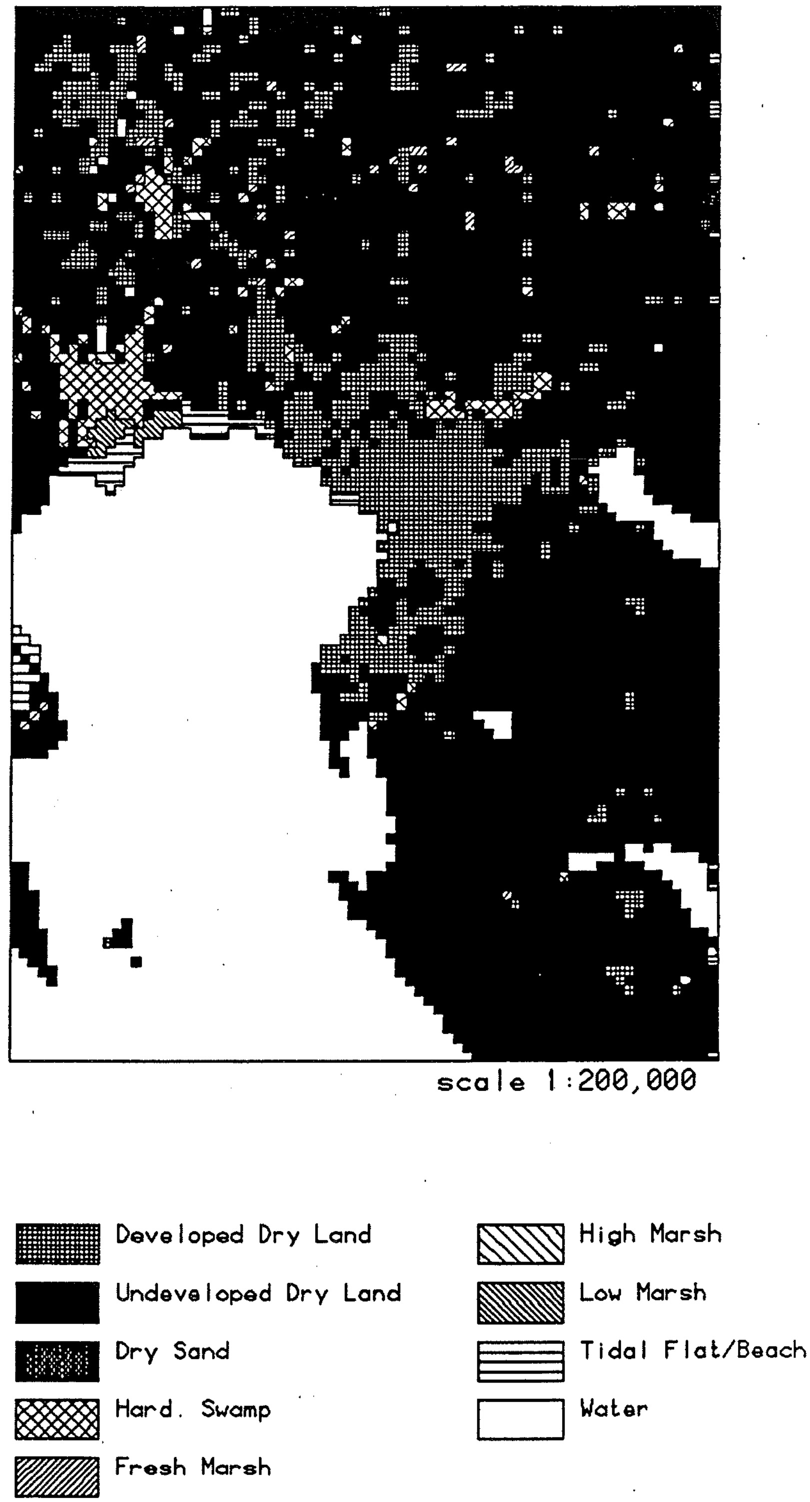

Figure 32. Bellingham Bay predicted conditions for the year 2100 with a 14-cm increase in eustatic sea level.

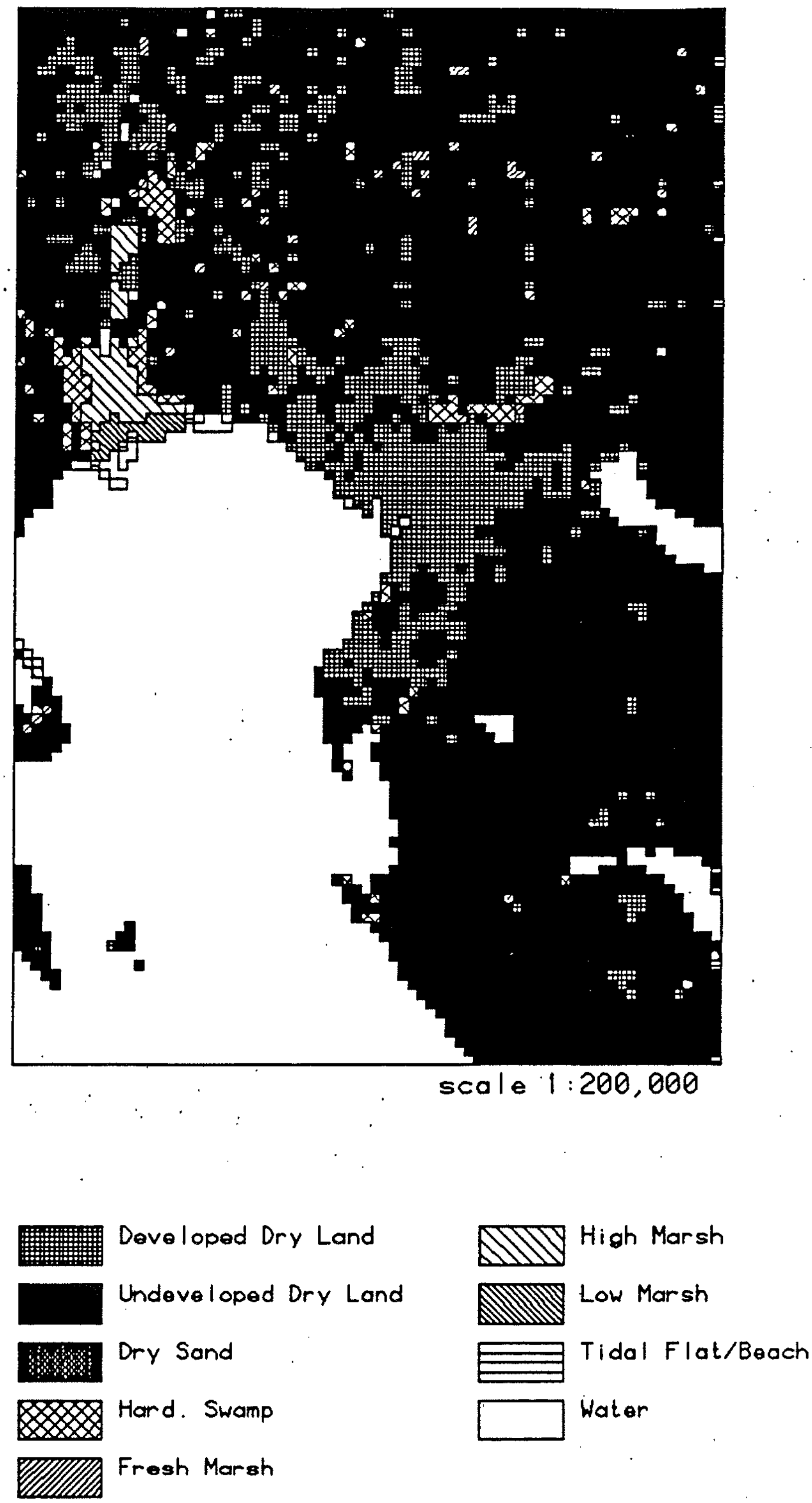

Figure 33. Bellingham Bay predicted conditions for the year 2100 with a 50-cm increase in eustatic sea level.

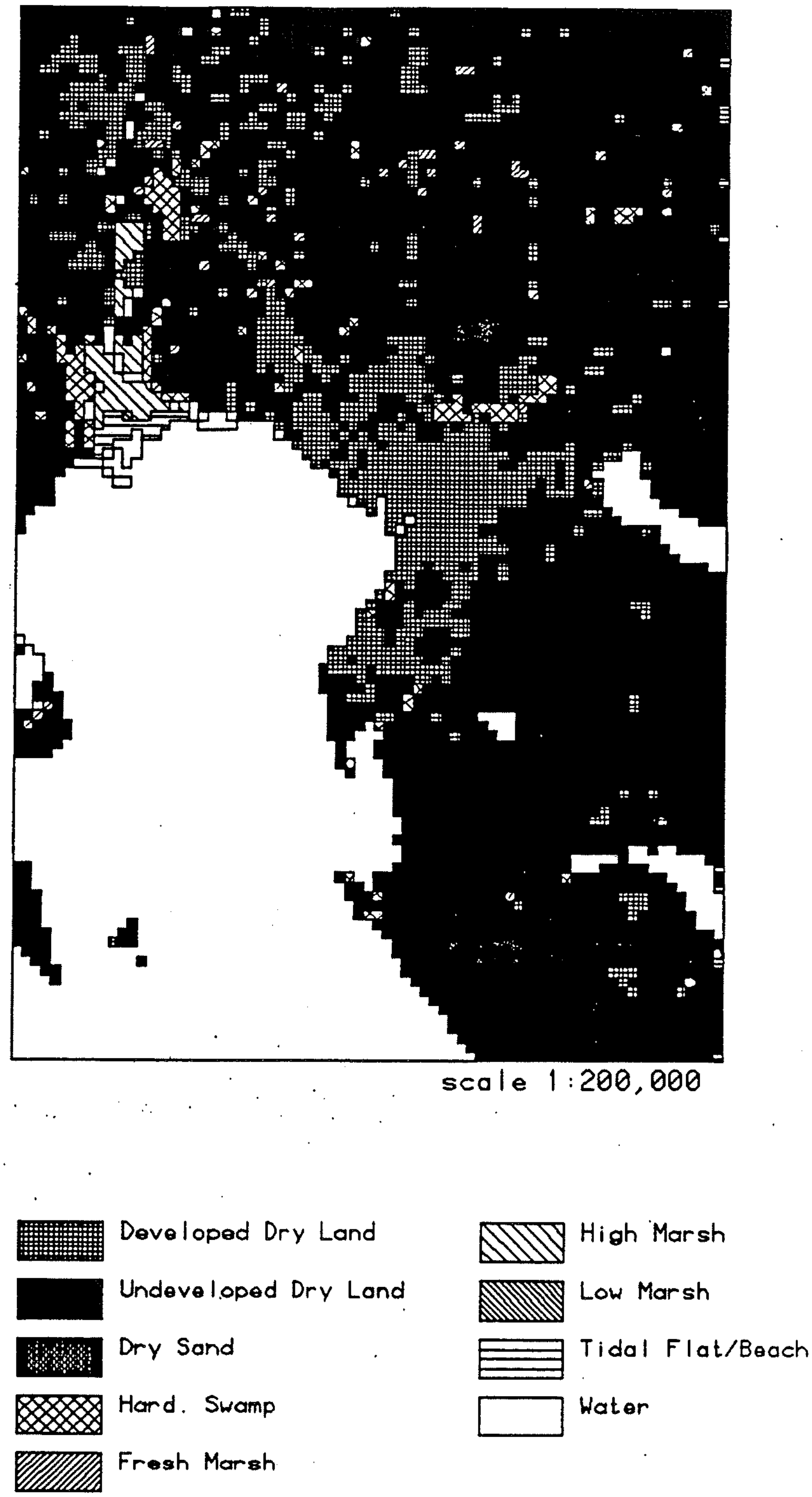

Figure 34. Bellingham Bay predicted conditions for the year 2100 with a 1-m increase in eustatic sea level.

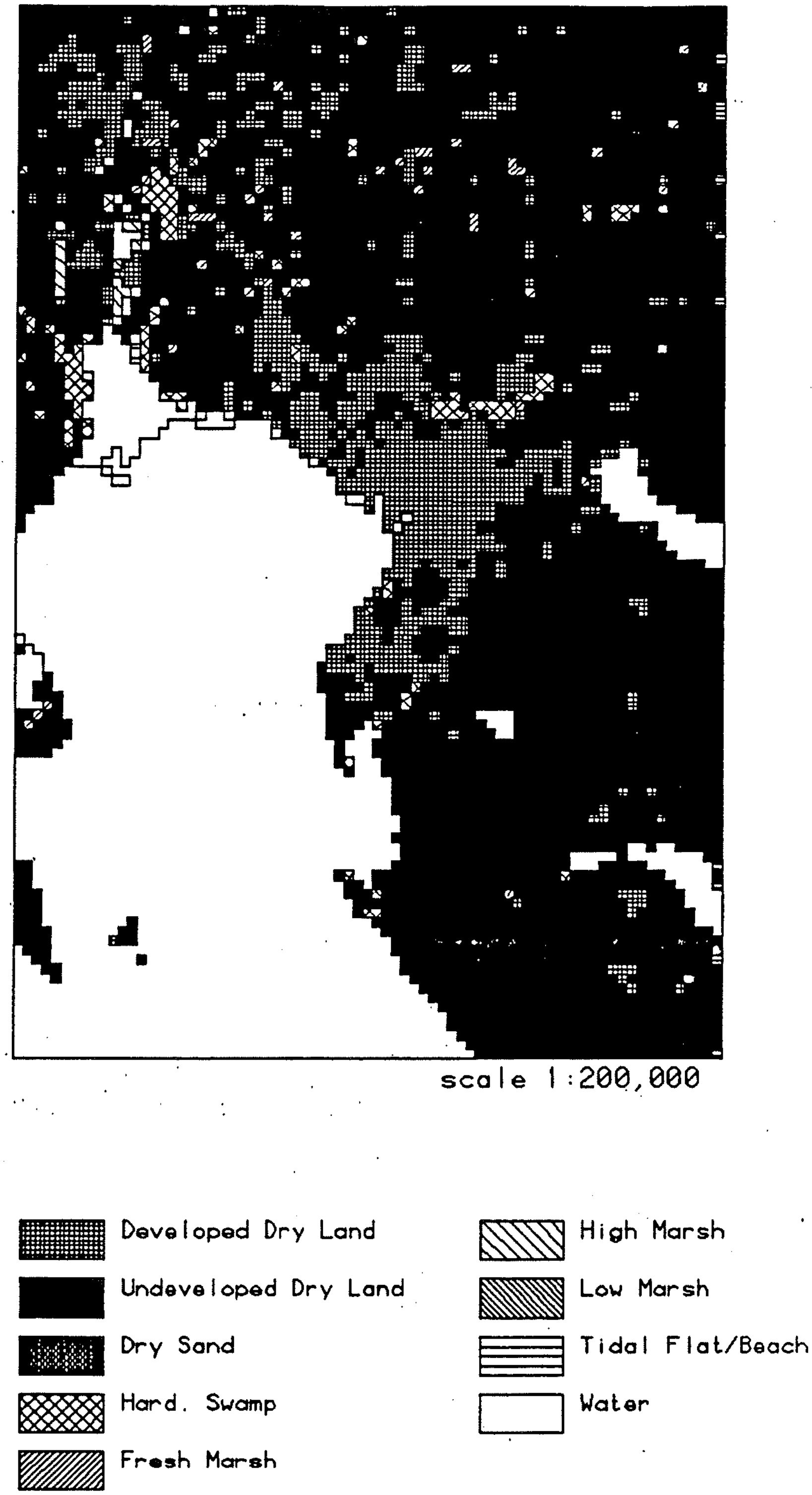

Figure 35. Bellingham Bay predicted conditions for the year 2100 with a 2-m increase in eustatic sea level.

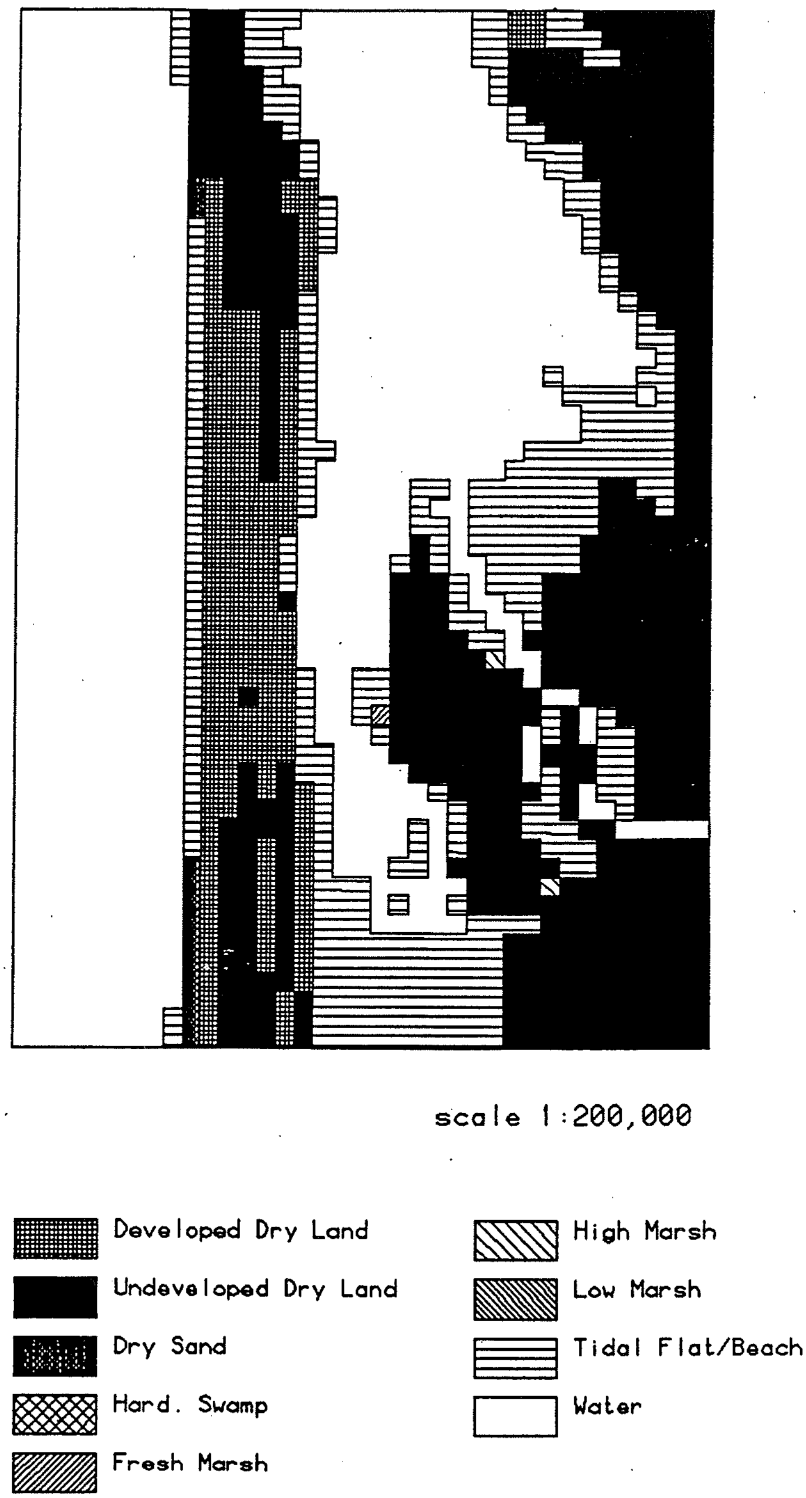

Figure 36. Willapa Bay initial conditions based on 1986 Landsat imagery.

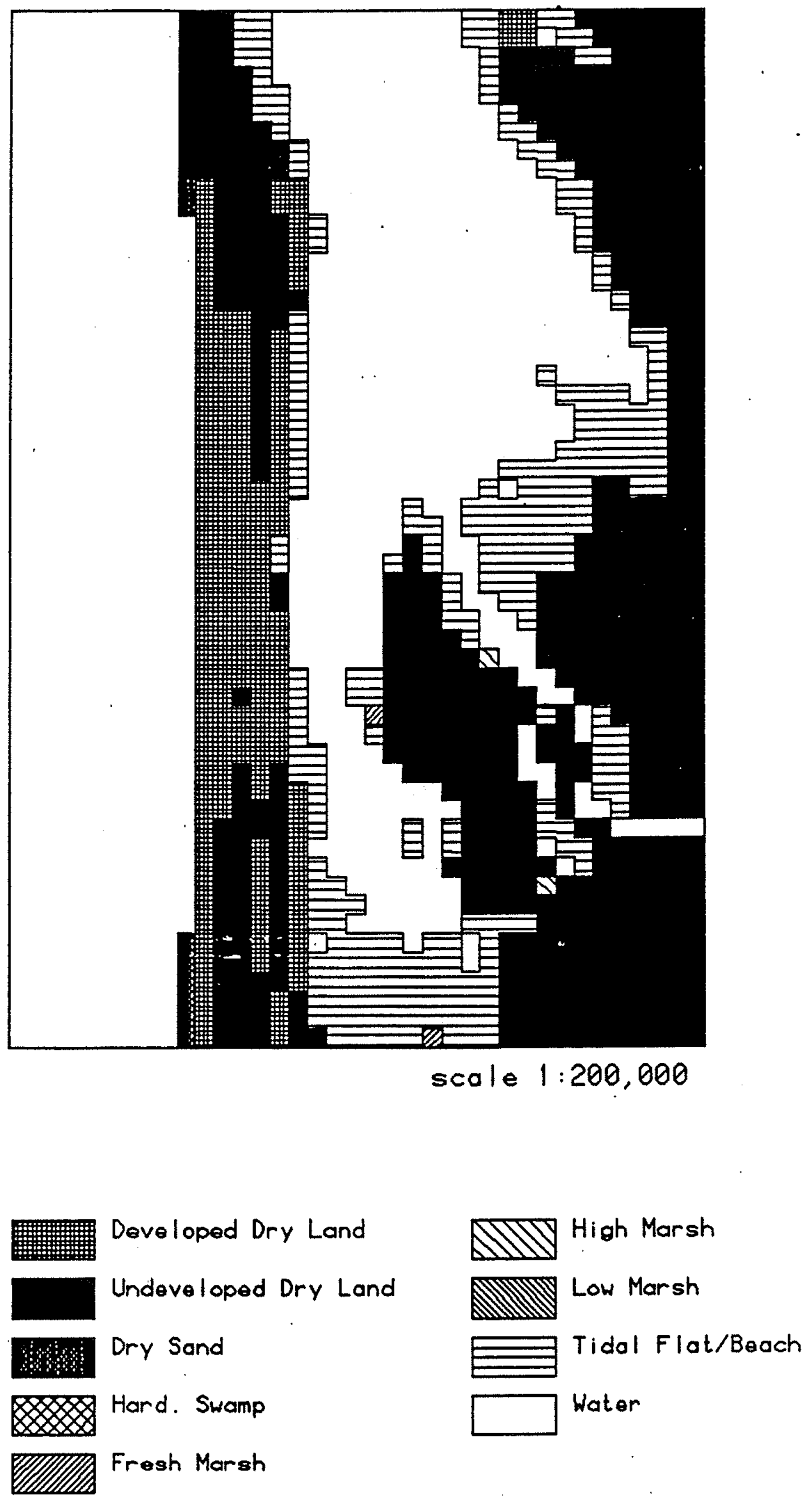

Figure 37. Willapa Bay predicted conditions for the year 2100 with a 14-cm increase in eustatic sea level.

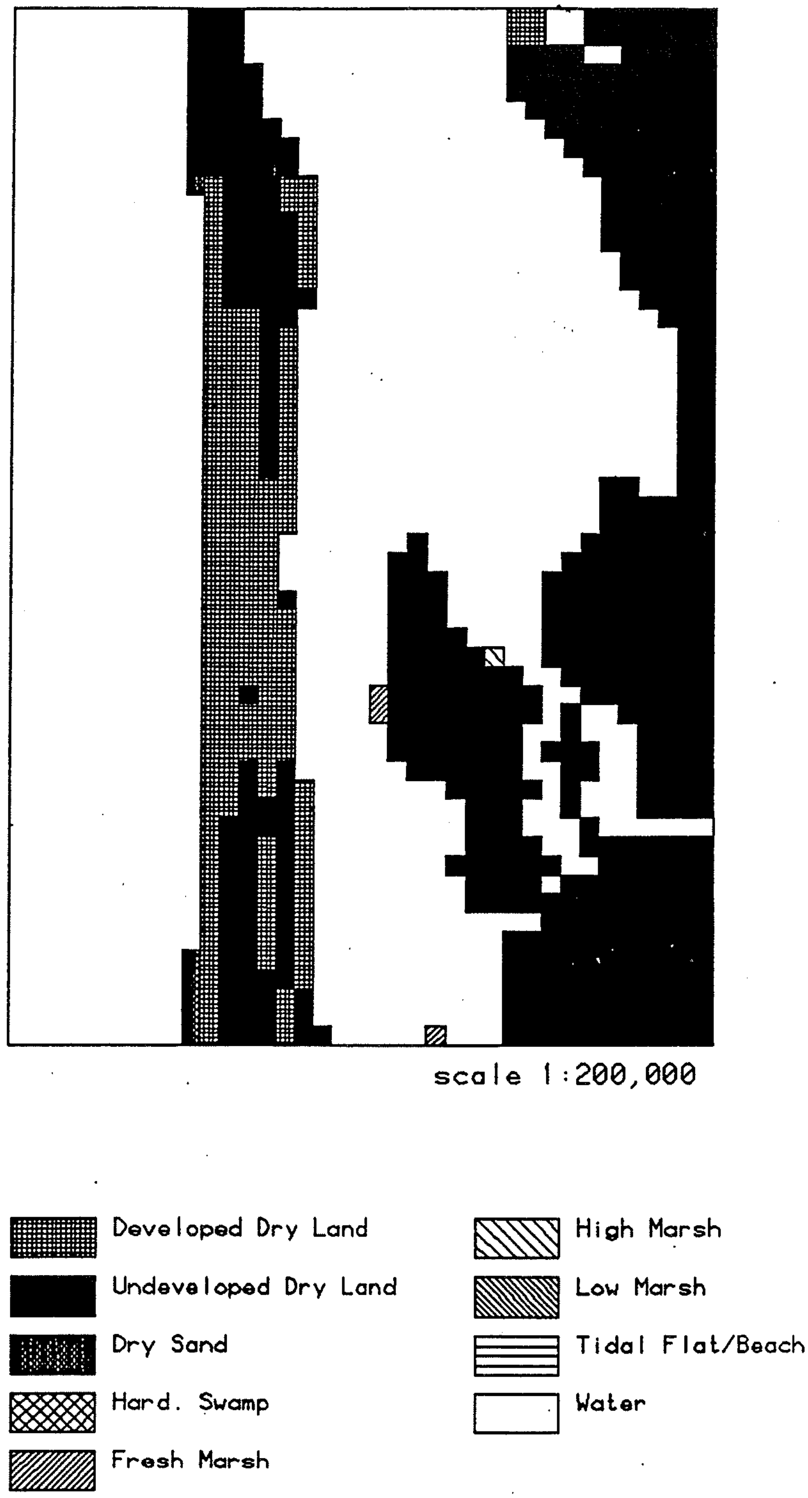

Figure 38. Willapa Bay predicted conditions for the year 2100 with a 50-cm increase in eustatic sea level.

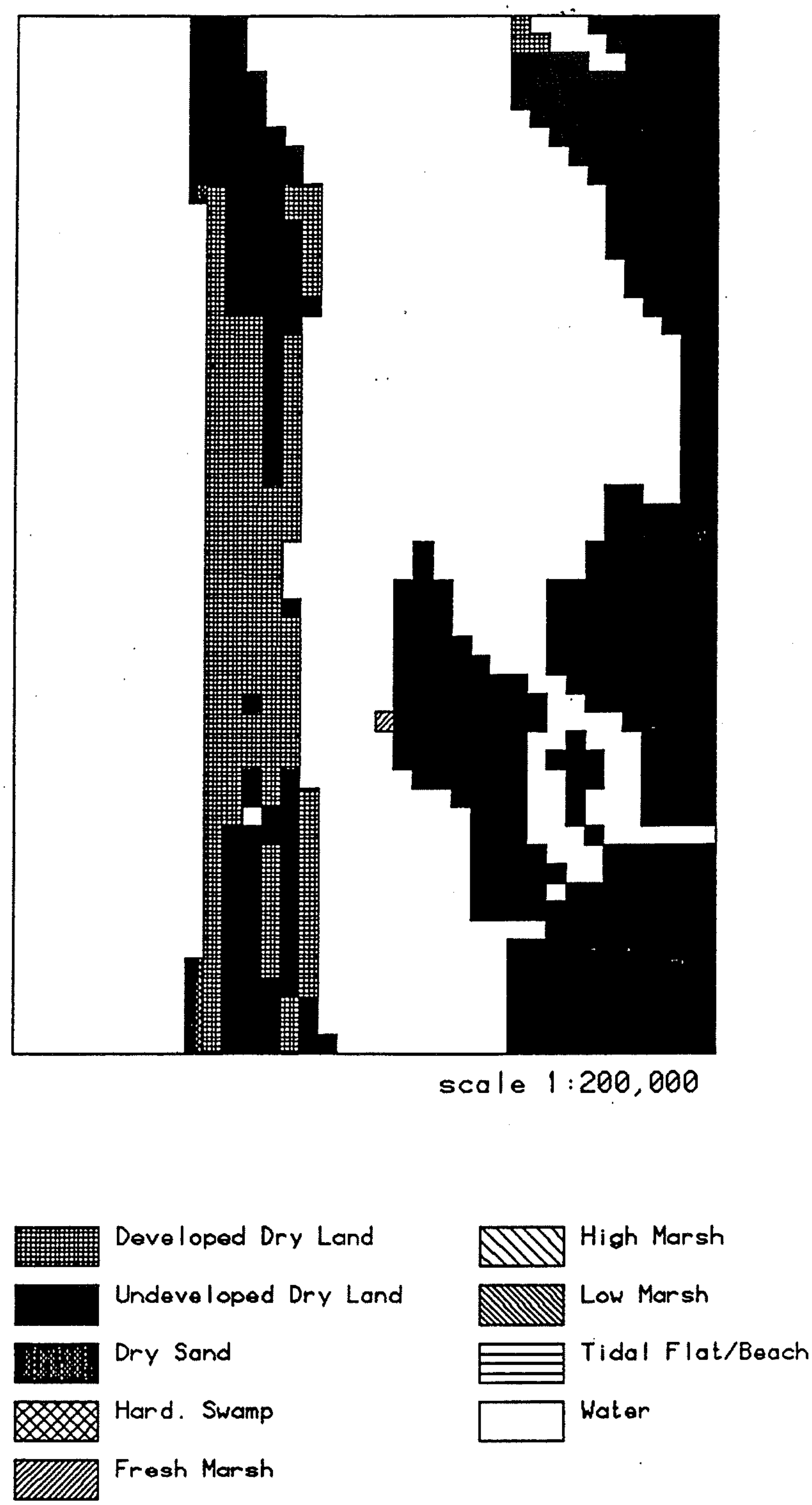

Figure 39. Willapa Bay predicted conditions for the year 2100 with a 1-m increase in eustatic sea level.

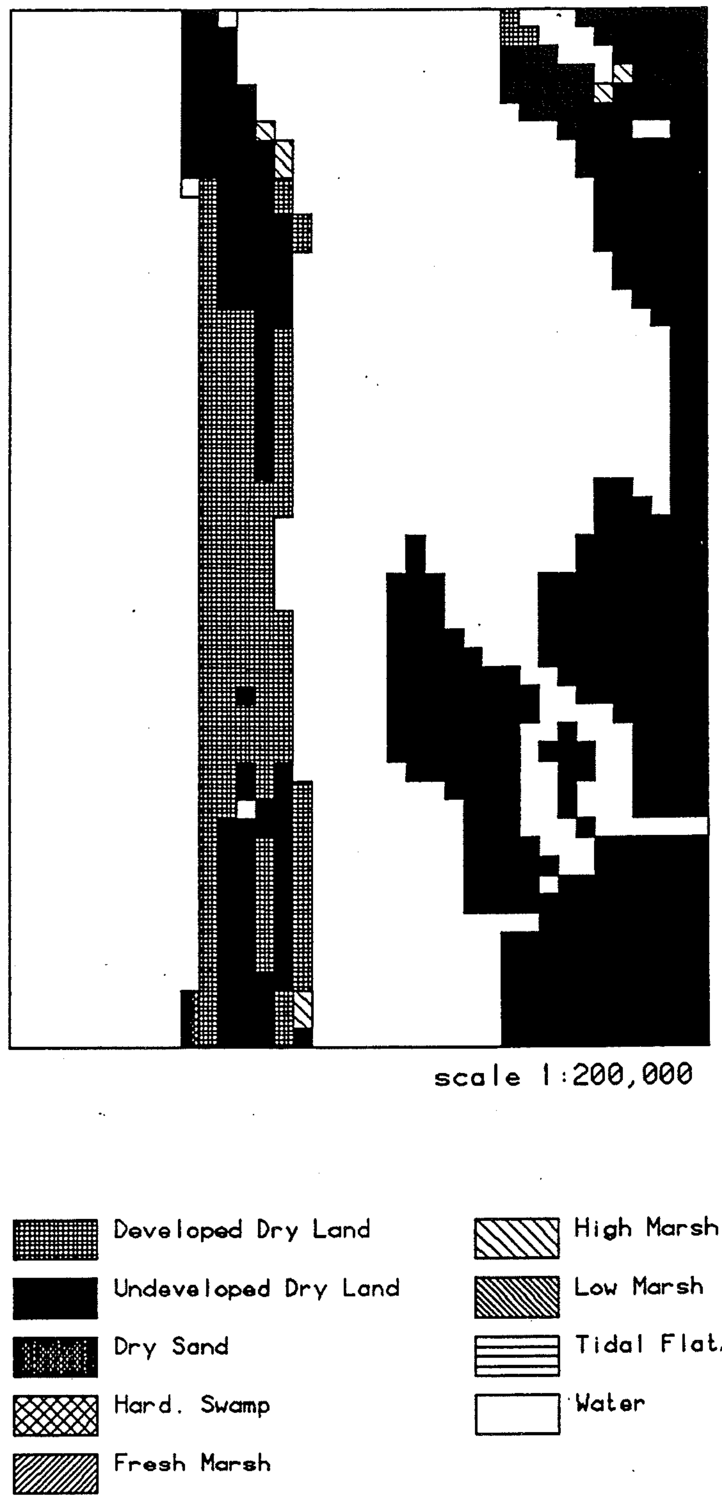

Figure 40. Willapa Bay predicted conditions for the year 2100 with a 2-m increase in eustatic sea level.