US Army Corps
of Engineers ®
Portland District

Tillamook Bay and Estuary, Oregon
General Investigation Feasibility Report

February 2005

ABBREVIATIONS AND ACRONYMS

Corps	U.S. Army Corps of Engineers
cfs	cubic feet per second
ESA	Endangered Species Act
FEMA	Federal Emergency Management Agency
GI	General Investigation
LWD `	large woody debris
NEP	National Estuary Project
NRCS	Natural Resources Conservation Service
ODFW	Oregon Department of Fish and Wildlife
OWRD	Oregon Water Resources Department
PWA	Philip Williams and Associates, Ltd.
RM	river mile(s)
TBHEID	Tillamook Bay Habitat and Estuary Improvement District
TCSWCD	Tillamook County Soil and Water Conservation District
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
USFWS	U.S. Fish and Wildlife Service

Executive Summary

The Tillamook Bay and Estuary, Oregon, General Investigation study was authorized by a U.S. Senate Committee Resolution on June 5, 1997. The purpose of the study is to evaluate flood damage reduction and ecosystem restoration in the Tillamook Bay watershed in Tillamook County in northwestern Oregon. The feasibility report describes the progression of the study and the activities that have been completed to date. It provides a status of the potential alternatives evaluated, including initial modeling results and preliminary cost estimates. The feasibility report is the final response to the study authority.

A Feasibility Cost Sharing Agreement was executed in July 1999 with Tillamook County Soil and Water Conservation District. Tillamook County requested to become the formal sponsor, which the District agreed to on February 17, 2000. A Feasibility Study Advisory Council was established to provide local public oversight for the study.

Five major rivers enter into Tillamook Bay and estuary. The lower valleys of three of these rivers (Wilson, Trask and Tillamook) merge to form a broad alluvial plain to the east and south of the bay on which the City of Tillamook is located. Declared a federal disaster area because of the February 1996 flood, Tillamook County suffered over $53 million in damage, which is the equivalent of 148% of the county's annual budget. The lower portions of the rivers overflow frequently because channel capacity is inadequate to handle heavy flows during severe rainstorms when combined with high tides. The resulting flooding cut off access to U.S. Highway 101, the major north-south arterial along the Pacific Coast, and inundated residential, commercial, and pasture areas. No vehicular access was possible between the north and south portions of the county.

Designated as a significant tidal estuary in the National Estuary Program and a component of the Oregon Coastal Salmon Restoration Initiative (*Oregon Plan*), Tillamook Bay and its watershed are economically and ecologically valuable to the State of Oregon. An extensive analysis of the watershed was conducted under the National Estuary Program, which resulted in the identification of four goals that were consistent with the Corps' study authority. These goals included: (1) restoration of critical habitat for salmonid species; (2) reduction of sedimentation for salmonid spawning and rearing habitat; (3) reduction of bacterial contamination; and (4) reduction of magnitude, frequency, and impact of flood events.

Fifty-nine potential alternative measures were initially considered. During the process to prioritize and narrow the measures, the sponsor decided to support only those alternatives providing both ecosystem restoration and flood damage reduction benefits, as well as having overall public support. This reduced the number of alternative measures to 33. Further evaluation with an area of focus in and around the City of Tillamook, and based on engineering and biological evaluation, further reduced this number to 14 potential alternatives.

A one-dimensional, hydrodynamic model of the five rivers was developed as the primary evaluation tool for screening the 14 potential alternatives. Preliminary model runs were performed to increase the understanding of the system and to aid in the process of prioritization and narrowing of alternatives. From the modeling results, it appeared that some of the potential alternatives would not provide many benefits for flood damage reduction. The sponsor decided that these alternatives would no longer be considered for further evaluation. The Wetland Acquisition/Swale and Hall Slough alternatives were evaluated further because they had the greatest potential to provide both ecosystem restoration and flood reduction benefits.

The Hall Slough alternative consists of reconnection of tidal flows in the historic slough, high flow flushing from the Wilson River, and setback levees with riparian plantings. It is a high priority ecosystem restoration action and would eliminate flooding in the Highway 101 business district up to approximately the 2-year flood event. Because the sponsor indicated that they do not have adequate funds for implementation at this time, the alternative was not developed further.

The Wetland Acquisition/Swale alternative would restore tidal marsh/wetlands with actions to offset flood increases. It is a high priority ecosystem restoration action and would reduce flooding for lower flood events. However, the sponsor requested that remaining study funds focus on developing the Modified Wetland Acquisition alternative endorsed by the Tillamook Bay Habitat and Estuary Improvement District. The Modified Wetland Acquisition alternative meets ecosystem restoration requirements without causing an increase in flood elevations, meets the requirements of the sponsor, and is acceptable to the community. After initial evaluation and modeling, the sponsor requested that the Modified Wetland Acquisition alternative be transferred to either the Continuing Authorities Program or to Section 536 of the Water Resources Development Act of 2000 (Public Law 106-541) for further evaluation and implementation.

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General Investigation Feasibility Report

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1. INTRODUCTION

1.1. PURPOSE AND NEED

The purpose of the Tillamook Bay and Estuary, Oregon, General Investigation (GI) study is to evaluate flood damage reduction and ecosystem restoration in the Tillamook Bay watershed in Tillamook County in northwestern Oregon (Figure 1, located at the end of this chapter). Five major rivers enter into Tillamook Bay and estuary. The lower valleys of three of these rivers (Wilson, Trask and Tillamook) merge to form a broad alluvial plain to the east and south of the bay on which the City of Tillamook is located. The lower portions of the rivers overflow frequently because channel capacity is inadequate to handle heavy flows during severe rainstorms when combined with high tides. Designated as a significant tidal estuary in the National Estuary Program (NEP) and a component of the *Oregon Coastal Salmon Restoration Initiative* (*Oregon Plan*), Tillamook Bay and its watershed are ecologically and economically valuable to the State of Oregon. Tillamook County is the local sponsor for the study.

The feasibility report describes the progression of the study and the activities that have been completed to date. It provides a status of the potential alternatives evaluated, including initial modeling results and preliminary cost estimates. The feasibility report is the final response to the study authority.

1.2. STUDY AUTHORITY

The Tillamook Bay and Estuary, Oregon, GI study was authorized by a U.S. Senate Committee Resolution on June 5, 1997:

> *RESOLVED BY THE COMMITTEE ON ENVIRONMENT AND PUBLIC WORKS OF THE UNITED STATES SENATE, that the Secretary of the Army is requested to review the report of the Chief of Engineers on Tillamook Bay and Bar, Oregon, published as House Document Numbered 349, Sixty-second Congress, and other pertinent reports, to determine the feasibility of modifications and improvements for the purposes of flood control, ecosystem restoration, erosion and other water resource needs in the Tillamook Bay estuary and watershed, Oregon.*

1.3. STUDY AREA

Tillamook Bay is located in Tillamook County in northwestern Oregon. Tillamook Bay is 50 miles south of the Columbia River and 60 miles west of Portland, Oregon. The watershed surrounding Tillamook Bay is dominated by broad valleys along the coastal plain that abruptly rise to steep mountains. Elevations vary from near sea level in the coastal lowlands to above 3,500 feet in the Coast Range Mountains. The majority of area of each watershed contributing to the bay is located within the Coast Range Mountains. Dense forest covers much of the terrain, which overlies impermeable strata in the mountainous watershed. The majority of human settlement has taken place in the broad river valleys. The valley forests were stripped, wetlands were filled, and dikes were placed in the valleys for agricultural purposes about 150 years ago.

The Wilson and Trask Rivers are the two largest rivers in the area and contribute to the majority of sedimentation and flooding in the region. The Miami and Kilchis Rivers have similar watersheds and characteristics as the Wilson and Trask, but they are smaller and are located in sparsely populated areas. The Tillamook River has a low gradient relative to the other rivers and a watershed located along the coastal foothills. The Tillamook River contributes the least to flooding and erosion problems in the region. Four of these rivers flow into the southern end of Tillamook Bay except for the Miami River, which flows into the bay at its northern end.

The majority of settlement in the area occurred in and around the City of Tillamook. The City was founded in 1891 along a low-ridge separating the Trask and Wilson Rivers. The surrounding floodplains of the Tillamook, Trask and Wilson Rivers were developed for agriculture. As the area is rich in rainfall, grasses are plentiful and the Tillamook area has long been an excellent location for dairy farming. Beyond the City lie numerous dairies throughout each of the five major river valleys.

For purposes of agriculture, the floodplains of the rivers have been diked, sloughs have been filled, and structures have restricted the historic movement of the river channels. In essence, the ties of floodplain to river channel have been separated in the river valleys. A few major sloughs remain connected to their rivers including Dougherty Slough to the Wilson River and Squeedunk Slough to the Kilchis River. Other sloughs in the area have generally lost their upstream tie to rivers and now are either stagnant or tidal sloughs.

1.4. Scope of Study

The existing conditions in the study area have been captured in numerous reports (see Section 1.5 of this chapter). An extensive analysis of the Tillamook Bay and watershed was conducted under the Tillamook Bay NEP, which resulted in the identification of four goals that were consistent with the study authority. These goals include: (1) restoration of critical habitat for salmonid species; (2) reduction of sedimentation for salmonid spawning and rearing habitat; (3) reduction of bacterial contamination; and (4) reduction of magnitude, frequency, and impact of flood events. In the Oregon Plan, the Tillamook Bay system has been identified as having poor habitat for native coastal salmon. Modeling shows that some salmon populations may experience a higher risk of extinction because of this condition. Anadromous salmonid species known to occur in the Tillamook Bay watershed include chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*O. kisutch*), chum salmon (*O. keta*), steelhead trout (*O. mykiss*), and coastal cutthroat trout (*O. clarki clarki*). In August 1998, coastal coho salmon were listed as a threatened species under the Endangered Species Act (ESA). Coastal cutthroat and steelhead are candidate species for listing.

Declared a Federal disaster area because of the February 1996 flood, Tillamook County suffered over $53 million in damage, which is the equivalent of 148% of the county's annual budget. The county suffered significant losses because of the disruption caused to U.S. Highway 101, the major north-south arterial along the Pacific Coast. The lower portions of the rivers overflow frequently because channel capacity is inadequate to handle heavy flows during severe rainstorms when combined with high tides. The resulting flooding cut off access to Highway 101 and inundated residential, commercial, and pasture areas. No vehicular access was possible between the north and south portions of the county; emergency and service vehicles could not go north and ambulances could not get to the hospital on the southwest side of the city. During the 1998-1999 flood season, damages due to flooding were $5 million in the study area.

The reconnaissance phase of the study was completed in August 1999. Key areas addressed in the reconnaissance report (*Section 905(b) Analysis, Tillamook Bay and Estuary, Oregon*, December 1998) included opportunities to modify existing floodplain features, stream channels, and the estuary in order to restore natural wetlands, high value estuarine habitats, and coastal salmonid habitats while reducing flood damages. Some of the measures included reconnecting wetland and floodplain areas with the rivers to absorb greater flood flows, channel modifications to restore flood capacity, restoring structural complexity in stream channels and the estuary, and riparian habitat development.

A Feasibility Cost Sharing Agreement was executed in July 1999 with Tillamook County Soil and Water Conservation District (TCSWCD). Tillamook County requested to become the formal sponsor, which the TCSWCD agreed to on February 17, 2000. A Feasibility Study Advisory Council was established to provide local public oversight for the study. Seven focus groups also were established at the request of the sponsor to develop a plan for ecosystem restoration and flood damage reduction. As the study progressed, the focus groups were combined into a larger Biological Focus Group and a Flood Damage Reduction Focus Group. Chapter 5 of this report discusses the public involvement undertaken for the study.

Fifty-nine potential alternative measures were initially considered. During the process to prioritize and narrow the measures, the sponsor decided to support only those alternatives providing both ecosystem restoration and flood damage reduction benefits, as well as having overall public support. This reduced the number of alternative measures to 33. Further evaluation with an area of focus in and around the City of Tillamook, and based on engineering and biological evaluation, further reduced this number to 14 potential alternatives.

A one-dimensional, hydrodynamic model (MIKE11) of the five rivers was developed as the primary evaluation tool for screening the 14 potential alternatives. Preliminary model runs were performed to increase the understanding of the system and to aid in the process of prioritization and narrowing of alternatives. A discussion of the potential alternative measures and modeling is found in Chapter 2 of this report. Chapter 3 provides a description of the MIKE11 model.

Initial model results were presented to the Feasibility Advisory Council and interested citizens on March 27, 2002. From these preliminary results, discussions ensued as to which alternatives were to remain for further evaluation and cost analysis. From the modeling results, it appeared that some alternative areas would not provide many benefits for flood damage reduction to the Tillamook area. Tillamook County decided that these alternatives would no longer be studied. Through a long process and much discussion, the Hall Slough and Wetland Acquisition/Swale alternatives were selected for further evaluation because they had the greatest potential to provide ecosystem restoration and flood reduction benefits.

The Hall Slough alternative consists of reconnection of tidal flows in the historic slough, high flow flushing from the Wilson River, and setback levees with riparian plantings. It is a high priority ecosystem restoration action and would eliminate flooding in the Highway 101 business district up to approximately the 2-year flood event. Because the sponsor indicated that they do not have adequate funds for implementation at this time, the alternative was not developed further.

The Wetland Acquisition/Swale alternative would restore tidal marsh/wetlands with actions to offset flood increases. It is a high priority ecosystem restoration action and would reduce flooding for lower flood events. However, the sponsor requested that remaining study funds focus on developing the Modified Wetland Acquisition alternative endorsed by the Tillamook Bay Habitat and Estuary Improvement District (TBHEID). This modified alternative meets ecosystem restoration requirements without causing an increase in flood elevations, meets the requirements of the sponsor, and is acceptable to the community. After initial evaluation and modeling, the sponsor requested that the Modified Wetland Acquisition alternative be transferred to either the Continuing Authorities Program (CAP) or to Section 536 of the Water Resources Development Act of 2000 (Public Law 106-541) for further evaluation and implementation.

With the decision to transition from the GI feasibility study process, a decision also was made to convert the existing MIKE11 model to the U.S. Army Corps of Engineers (Corps) HEC-RAS model. At the time the MIKE11 model was selected for use in the study, it had a solid reputation, whereas not enough information was available for the HEC-RAS model. Since then, a newer version of the HEC-RAS model has been developed, which is more sophisticated than MIKE11 and more capable of addressing the complex nature of flooding in the Tillamook area. The HEC-RAS is currently the most common river analysis model used. Chapter 3 provides a description of the HEC-RAS model.

1.4.1. Timeline of Study Events

Study Event	Date
Senate Resolution	June 5, 1997
Reconnaissance phase completed	August 1999
Feasibility Cost Sharing Agreement completed	July 1999
Initiated Feasibility Study	August 1999
Change of sponsor from TCSWCD to Tillamook County	February 17, 2000
Advisory Council established	May 2000
Notice of Intent in *Federal Register*	May 30, 2000
Public scoping meetings	July 25, 2000
MIKE 11 model completed	December 2001
Presentation of preliminary analysis using MIKE 11 model	March 2002
Updated plan for narrowing alternatives	April 2002
Public meeting presenting benefits of Hall Slough, Dougherty Slough and Wetland Acquisitions/Swale Alternatives	July 2002
Preliminary design and cost estimate for Hall Slough, Wetland Acquisition, and Modified Wetland Acquisition/Swale alternatives	August 2002
Decision to convert Modified Wetland Acquisition/Swale alternative to Continuing Authorities Program/Section 536	June 18, 2003
Model conversion to HEC-RAS completed	December 2003

1.4.2. Tillamook Area Flood Conditions

The flooding problems in the Tillamook region were evaluated by the Corps in order to develop alternatives that could alleviate flooding in the area. In order to understand flooding in and around the City of Tillamook, the topography of the lower Wilson, Trask and Tillamook Rivers was evaluated. The rivers of Tillamook are perched above their floodplains. The high sediment loads of the rivers spill out of each river during flood events and are deposited near their banks. The floodplains are lower and are reconnected to the river system through a network of sloughs. However, for agricultural use the floodplains were diked along their rivers and sloughs and do not allow tidal inundation. Therefore, floodwater from the Wilson, Trask, Kilchis and Tillamook Rivers is trapped in the floodplains behind the natural levees and constructed tidal dikes. ‘Flood cells’ were delineated for the study based on their independence of one another in flooding condition. Each flood cell acts independently because it is diked from its neighboring flood cell, slough, or river.

Both natural and constructed dikes have separated the rivers and sloughs in the Tillamook area from their floodplains. The complex nature of flooding in the Tillamook area had not been analyzed in a floodplain development context, including the placement of tidal dikes. The result is a system of channels that are disconnected and create increased flood problems including standing water when floods recede and increased flood stages within channels. Areas which did not flood historically may currently flood because of upstream or downstream actions of landowners in the Tillamook region.

Although the rivers have been forced to evacuate all floodwater, they will never have the capacity to do so. In analyzing the peak flows from gauges in the Tillamook area for the November 1999 flood event, it was apparent that the lower rivers do not have the capacity to carry their floodwater and depend largely on the floodplain to carry the floodwater to Tillamook Bay. Additional discussion on flooding in the Tillamook region is found in Chapter 3 of this report.

1.5. PRIOR STUDIES, REPORTS, AND EXISTING WATER PROJECTS

1.5.1. Prior Studies and Reports

Development of an Integrated River Management Strategy, September 21, 2002. Prepared by Philip Williams & Associates, Ltd., Clearwater BioStudies, Inc., Michael P. Williams Consulting, Urban Regional Research, and Green Point Consulting. Prepared for the U.S. Fish and Wildlife Service, U.S. Environmental Protection Agency, and U.S. Army Corps of Engineers.

This project put forward an integrated river management strategy that combined flood damage reduction with salmon recovery. The strategy was developed by an interdisciplinary team using Tillamook Bay Basin as a pilot study area. Analyses of the fluvial, biological, and institutional elements composing the Tillamook Bay river system were conducted at a number of spatial scales. The results were used to identify opportunities and constraints, and to develop a planning level Integrated River Management Strategy for Tillamook.

Tillamook Bay Wetlands: Management Plan for the Wilson, Fuhrman, and Farris Wetland Acquisition Properties, November 2001. Compiled and written by Derek Sowers and Mark Trenholm, staff of the Tillamook County Performance Partnership, for Wetlands Management Plan Development Team.

The purpose of this management plan is to describe how the properties proposed for acquisition and restoration by the Tillamook County Performance Partnership will be managed to meet the goals and objectives stated in the grant agreements with the Oregon Watershed Enhancement Board and the U.S. Fish and Wildlife Service (USFWS), and as agreed upon by the relevant local stakeholders. The management plan is designed to provide assurance to the grant funding agencies, all potentially affected parties, as well as the general public, that the acquisition and management of the land parcels will be implemented in a carefully planned manner and to address any existing or potential concerns. The management plan contains discussions of all of the major elements in need of consideration prior to making the substantial commitment of resources necessary to implement and maintain the project. The elements include goals and objectives, site descriptions and background information, restoration and enhancement activities, identification of responsible participants, public access plan, monitoring and evaluation, and costs and funding.

Wilson River Watershed Assessment, February 2001. Prepared by E&S Environmental Chemistry, Corvallis OR.

The assessment was prepared to inventory and characterize the current conditions of the Wilson River watershed, and to provide recommendations that address the issues of water quality, fisheries and fish habitat, and watershed hydrology. The assessment creates a framework for identifying restoration activities to improve water quality and aquatic habitat in the watershed.

Comprehensive Conservation and Management Plan for Tillamook Bay, Oregon, December 1999. Prepared by the Tillamook Bay National Estuary Project, Garibaldi OR.

The Tillamook Bay NEP was funded by the U.S. Environmental Protection Agency (USEPA) to evaluate the condition of the bay and estuary, especially concerning water quality issues. Coordination with and comments from representatives from public groups and local citizens supplemented extensive input from agencies at federal, state and local levels. The *Comprehensive Conservation Management Plan* presents the proposed actions and policies to achieve targets for solution of the problems identified since 1994. The four priority problems include: (1) critical habitat loss, (2) sedimentation, (3) bacterial contamination, and (4) flooding. The plan also includes characterization of the bay, an analysis of the current policies which impact the priority problems, a financing plan, and a monitoring plan. The technical analysis and extensive review process of the NEP provided a significant resource for the foundation of this GI study. Many of the agencies and groups that developed the policies, actions and targets in the comprehensive management plan were interested in participating in the GI study.

Tillamook Bay Environmental Characterization: A Scientific and Technical Summary, July 1998. Prepared by the Tillamook Bay National Estuary Project, Garibaldi OR.

This document summarizes the relevant facts and figures to describe the natural features of the Tillamook Bay watershed. The report provides an overview of the coastal landscape, discusses human uses, and focuses on the priority problems identified by the NEP: biological resources, water quality, sedimentation, and flooding.

Tillamook County Performance Partnership, June 1998.

This document is an action plan to achieve mutually agreed-upon, results-based outcomes, which addresses specific problems in Tillamook County. Agencies at various levels, along with public and private organizations, have agreed to partner with Tillamook County to attain the four goals of improved water quality, enhanced fish habitat, reduced flood damages, and improved economic conditions. Two of these goals specifically relate to ecosystem restoration and flood damage reduction, while the other two are closely associated. The Performance Partnership provides a framework for how the many active groups in Tillamook County work together and minimizes duplication of work in the pursuit of the common goals.

The Oregon Plan for Salmon and Watersheds (Oregon Plan), Executive Order EO99-01, January 8, 1999. State of Oregon.

The purpose of the *Oregon Plan* is to restore Oregon’s wild salmon and trout populations and fisheries to sustainable and productive levels that will provide substantial environmental, cultural, and economic benefits and to improve water quality. The *Oregon Plan* is a long-term, ongoing effort that began as a focused set of actions by state, local, tribal and private organizations and individuals in October of 1995. The *Oregon Plan* first addressed coho salmon on the Oregon Coast, was then broadened to include steelhead trout on the coast and in the Lower Columbia River, and then expanded to all at-risk wild salmonids throughout the state. The *Oregon Plan* is described in two principal documents, the *Oregon Plan* dated March 1997, and the *Oregon Plan for Salmon and Watersheds, Supplement I - Steelhead*, dated January 1998.

Tillamook County Flood Hazard Mitigation Plan, November 1996. Prepared by Tillamook County.

This plan addresses the events and impacts associated with the February 1996 flooding in Tillamook County. While flooding was common throughout Oregon and the Northwest, Tillamook County sustained damages well beyond other watersheds, when compared to the local economy. Damages totaled $53 million. In addition to descriptions of historic flood damage reduction solutions within the county, the plan includes proposed policies and general actions to deal with flooding in the future. Non-structural flood reduction measures are a major component of the program. This document serves as Tillamook County's strategy for reducing future flood damages.

Tillamook Bay NEP Studies

Numerous studies have been undertaken for the Tillamook Bay NEP, as listed below.

- July 2000 - Ecological interactions among eelgrass, oysters, and burrowing shrimp in Tillamook Bay, Oregon, year 2 (1999) report. Prepared by K. Griffin.
- July 2000 - Identifying sources of fecal coliforms delivered to Tillamook Bay. Prepared by J. Moore and R. Bower.
- October 1999 - Tillamook Bay fish use of the estuary. Prepared by R.H. Ellis.
- October 1998 - Three Graces Intertidal program: A report on visitor use patterns at Three Graces Intertidal. Prepared by B. White, Camp Magruder.
- August 1998 - Sediment sources and accumulation rates in Tillamook Bay, Oregon. Prepared by J. Mcmanus, P.D. Komar, G. Bostrom, D. Colbert, and J.J. Marra.
- August 1998 - Reconnaissance survey of tide gates in Tillamook Bay vicinity. Prepared by J. Charland.
- March 1998 - A biological inventory of benthic invertebrates in Tillamook Bay. Prepared by J.T. Golden, D.M. Gillingham, V.H. Krutzikowsky, D. Fox, J.A. Johnson, R. Sardiña, and S. Hammond, Oregon Department of Fish and Wildlife.
- March 1998 - Forest roads, drainage, and sediment delivery in the Kilchis River watershed. Prepared by K. Mills, Oregon Department of Forestry.
- March 1998 - Bathymetric analysis of Tillamook Bay, comparison among bathymetric databases collected in 1867, 1957 and 1995. Prepared by J.A. Bernert and T.J. Sullivan.
- September 1997 - Invertebrate fauna of Tillamook Bay. Prepared by B. Houck, S. Kolmes, L. Fergusson-Kolmes, and T. Lang, University of Portland.
- July 1997 - Eelgrass ecology and commercial oyster cultivation in Tillamook Bay, Oregon. Prepared by K. Griffin.
- September 1996 - Determining abundance and distribution of eelgrass (*Zostera* spp.) in the Tillamook Bay estuary, Oregon using multispectral airborne imagery. Prepared by J.R. Strittholt and P.A. Frost, Earth Design Consultants.
- June 1996 - An environmental history of the Tillamook Bay estuary and watershed. Prepared by K. Coulton and P.B. Williams, Philip Williams and Associates, Ltd., with P.A. Benner, Oregon State University and assistance from the Tillamook Pioneer Museum.
- 1996 - Spatial analysis of the bridges of Tillamook County. Prepared by S. Kujack as a cooperative effort with Tillamook Bay Community College and Tillamook Bay NEP.
- November 1995 - Landscape change in the Tillamook Bay watershed. Prepared by J.R. Strittholt and P.A. Frost, Earth Design Consultants.
- July 1995 - Tillamook Bay watershed analysis framework. Prepared by W. Nehlsen, and T.C. Dewberry, The Pacific Rivers Council.
- July 1995 - Identification and distribution of subtidal and intertidal shellfish populations in Tillamook Bay, Oregon. Prepared by K.F. Griffin.
- June 1995 - Inventory of the management framework for Tillamook Bay National Estuary Project priority problems: Phase I of the base programs analysis. Prepared by G. Plummer.
- February 1995 - Fish and wildlife issues in Tillamook Bay and watershed: Summary of a Tillamook Bay NEP Scientific/Technical Advisory Committee forum. Prepared by J. Miller and R.J. Garono.

- January 1995 - Impacts of erosion and sedimentation in Tillamook Bay and watershed: Summary of a Tillamook Bay NEP Scientific/Technical Advisory Committee forum. Prepared by J. Miller and R.J. Garono.
- December 1994 - Biochemical water quality issues in Tillamook Bay and watershed: Summary of a Tillamook Bay NEP Scientific/Technical Advisory Committee forum. Prepared by J. Miller and R.J. Garono.

1.5.2. Existing Federal Water Projects

Previous federal water projects in the Tillamook region were primarily built for navigational purposes. Although the entrance channel and navigation structures are still maintained to serve the small boat harbors at the north end of Tillamook Bay, the amount of dredging for navigation purposes within the bay has been greatly reduced over the years. All five of the major rivers in the Tillamook watershed are unregulated rivers. No major impoundments exist on any of the rivers except for a small dam on the upper Trask River, which influences less than 5% of the Trask River watershed. Existing flood control facilities consist of private dikes, which protect lands near the City of Tillamook. Beyond the one federally constructed levee (the Stillwell Levee), the majority of dikes in the area are tidal dikes locally constructed to control tide waters from inundating agricultural lands. Dikes in the area provide little flood protection and in some instances likely may make flood problems worse by storing floodwaters when rivers recede.

Tillamook Bay and Bar. This project provides for a north and south jetty along with an entrance channel and inner channel in the estuary. This project was initially authorized in 1912 and has since been modified several times, with the last increment being the south jetty extension in 1974. The north and south jetties are 5,700 and 8,000 feet in length, respectively. The entrance and inner channels are maintained to a depth of 18 feet. The entrance channel has no specified width, while the inner channel is 200 feet wide up to Miami Cove. Local interests maintain a small boat basin at Garibaldi. The project also provides for construction of a dike to stabilize the peninsula, where the south jetty is connected.

Stillwell Levee, Section 205 Flood Damage Reduction Project. This project upgraded a levee system initially constructed by local interests circa 1919. The Stillwell Drainage District operates and maintains this project, which is the only levee in the study area that offers major flood damage reduction. The levee was originally built to a sufficient height to protect against combinations of flood and tide such as could be expected to occur on an annual basis. The levee was upgraded in 1957 to provide protection for the 50-year recurrence frequency flood with 2 feet of freeboard. The levee is over 22,000 feet in length and circles approximately 450 acres of agricultural land. The drainage district is bounded on the north and east by the north branch of Trask River, on the south side by the south branch of Trask River and on the west by Tillamook River.

Section 14, Emergency Bank Protection. Emergency bank protection projects were undertaken at four locations in the study area using riprap to protect segments of county roads along the Miami, Wilson, and Trask Rivers. The work protected riverbanks from damage by erosion but provided no flood protection. Tillamook County, the Natural Resources Conservation Service (NRCS), and local diking districts have constructed riprap erosion protection at various locations in the study area in order to protect roads, dikes, and private property.

Figure 1. Location Map, Tillamook Bay and Estuary

Figure 2. Tillamook Bay River System

2. ALTERNATIVE ANALYSIS

2.1. INTRODUCTION

Fifty-nine potential alternative measures were identified for the feasibility study though a number of forums. Formulation of alternatives was based on the four main study objectives: reduced flooding, improved salmonid and wildlife habitat, reduced sedimentation, and improved water quality. One list was generated from local interests through a number of local groups including public meetings. The NOAA Fisheries, Oregon Department of Fish and Wildlife (ODFW), USFWS, NRCS, and the Corps, in conjunction with biologists from Tillamook County and the Performance Partnership, developed another list of potential ecosystem restoration projects for the study area. The Biological Focus Group played a significant role in this process. The Corps study team generated a list of potential ecosystem restoration and flood damage reduction measures. Provided below is a listing of the 59 potential alternative measures (Figure 3, located at the end of this chapter).

Tillamook River
- Tomlinson Slough connection.
- Peterson setback levee.
- Norwood setback levee.
- Fagan Creek setback levee, tide gate modification.
- Lendl-Shriver setback levee, slough and riparian restoration.
- Halthaway Marina restoration, enhancement, fencing.
- Horse property purchase, restoration.
- Setback levee.
- Hoffman land purchase, restoration.
- Anderson Creek restoration.
- Beaver Creek restoration, tide gate evaluation/modification.
- Setback levee along entire river, where possible.

Wilson River
- Wetland Acquisition area (includes Nolan Slough).
- Hall Slough restoration.
- Restoration of approximately 0.5-0.75 miles of channel off Hall Slough northeast of the main channel, below Highway 101.
- Bud Gienger riparian restoration/tide gate modification.
- Makenster setback levee.
- Reconnect old slough to Dougherty Slough.
- Lower Dougherty Slough riparian restoration.
- Yankee Branch Creek fish passage evaluation/enhancement.
- Beaver Creek restoration/passage evaluation.
- Hoquarten Slough/wetland restoration.

Trask River
- Rudee’s Slough restoration/tide gate evaluation/restoration.
- Setback/breach dike, restoration.
- Holden Creek tide gate modification.
- Unknown creek enhancement, restoration, fencing.

Trask River (continued)

- Mill Creek restoration.
- Riparian restoration across from fish hatchery.

Miami River

- Riparian restoration along entire corridor including tributaries.
- Estuarine/wetland restoration to Ellingsworth Creek.
- Breach dike and restore.
- Punch hole in old channel of Miami River upstream of Highway 101.
- Remove tile system upstream of Highway 101.
- Identify and replace all priority culverts, especially in tributaries.
- Reestablish meanders in Minich Creek.
- Reestablish meanders in tributary to Moss Creek.
- Reconnect forest and wetland.
- Placement of large woody debris.
- Enhance, restore, and reconnect channels and backwater areas in historic channel.
- Riparian planting and fencing.

Kilchis River

- Squeedunk Slough reconnection, restoration, passage modification; lower river, large area between Squeedunk Slough and Kilchis; potential levee modifications on east side of Squeedunk and northeast to Kilchis.
- Gienger dike restoration; approximately 0.2-mile section on lower river in wooded section.
- Vaughn Creek restoration, enhancement, passage modification; fish passage improvement, potential dike breach or setback levee.
- Stasek/Neilson Slough restoration, passage modification.
- Dooher setback levee, riparian enhancement; approximately 0.5-mile area west of Stasek Slough on the east side of Kilchis River.
- Coal Creek and Clear Creek channel restoration, enhancement; habitat improvements just above confluence of creeks and Kilchis River.
- Murphy Creek restoration, channel relocation.
- Oxbow reconnection, enhancement.
- Mapes Creek restoration, passage evaluation.
- Kilchis River off-channel rearing.
- Mrytle Creek fish riparian and passage enhancement.

During the process to narrow alternatives, the sponsor, Tillamook County, decided to only support ecosystem restoration alternatives that also provided flood damage reduction benefits, and that were of sufficient size to justify the steps required to receive Congressional authorization for project implementation. Another goal of the sponsor was to achieve general public commitment to the process and the alternatives developed. In addition, the sponsor made written contact with all landowners in the area of the initial 59 measures, and 9 landowners stated that they were not willing to participate in the study. Based on these sponsor requirements, the initial list of 59 measures was reduced to 33 measures that had the potential to provide dual benefits (flood damage reduction and ecosystem restoration).

The remaining 33 alternatives were evaluated based on engineering and biological evaluation as to their ability to provide dual benefits. Because Tillamook County determined that the area of focus should be in and around the City of Tillamook, the alternatives on the Miami and Kilchis Rivers were dropped from further consideration, with the exception of evaluating the lower Kilchis River. This left 14 alternatives for modeling with the MIKE11 model. Additional information about the development of the MIKE11 model can be found in Chapter 3 of this report.

The alternatives were modeled under several configurations and combined with other alternative measures to evaluate the response to flooding. Of these alternatives, it was determined that only nine areas provided flood reduction on a scale satisfactory to the sponsor. These alternatives were further evaluated (see Section 2.2). Each alternative was discussed with the sponsor, local citizens, and resource agencies. From these discussions, three alternatives remained to develop preliminary design and to determine preliminary costs and benefits (see Section 2.3). The other alternatives were dropped from consideration based on environmental concerns, low flood reduction benefits, high costs, or lack of local support.

2.2. Initial MIKE11 Modeling of Alternatives

Preliminary modeling of alternatives took place to evaluate each area's effectiveness on reducing flood impacts on Tillamook County. Preliminary alternatives were minimally designed to show greatest possible benefits for evaluation. The alternatives were modeled with MIKE11 for the November 1999 flood. Model results were compared to base condition results for the November 1999 flood. After running several scenarios in each alternative area, results were summarized and discussed with the Feasibility Advisory Council.

The following alternatives were evaluated with the MIKE11 model for their effectiveness in reducing flood stages in the Tillamook area. Alternatives were initially modeled with trapezoidal channel cuts and large channel changes. This was done to analyze the alternative's effectiveness in providing flood benefits. If it appeared that flood benefits did exist, then the alternative was kept in the process and further refined. If flood benefits were minimal or did not exist, then the alternative was dropped from further study. The following summary describes each of the alternatives initially modeled and its flood reduction potential (additional information is found in Appendix A).

2.2.1. Wetland Acquisition Area/Nolan Slough

The Wetland Acquisition area was purchased by the Tillamook County Performance Partnership in conjunction with Tillamook County and is slated for ecosystem restoration. The area is located between the mouths of the Wilson and Trask Rivers and Tillamook Bay. This area is critical in terms of flooding in the Tillamook area. This area was modeled with MIKE11 by Philip Williams and Associates, Ltd. (PWA) for Tillamook County. The area is currently cut-off from the rivers and bay by dikes that surround the property. The measures modeled with MIKE11 included dike removal or setback. Environmental restoration benefits include fish and wildlife habitat, fish passage, tidal wetland, ecosystem function, floodplain function, and water quality.

Initial modeling results showed that dike removal or setback in this area resulted in slightly increased peak flood stages at the Highway 101 business district. As this area recently had 10 tidegate culverts installed in the dike bordering Tillamook Bay, it was determined that the area currently helps alleviate flooding by storing floodwaters during flood tide and releasing floodwaters during ebb tide. It was determined that this area could be included in other alternatives and possibly more favorable results would occur with some modifications (see discussion of Wetland Acquisition/Swale in Section 2.3.3)

2.2.2. Hall Slough

Hall Slough is a side channel of the Wilson River. The slough's origins are upstream of Highway 101 near the Wilson River Loop Road, and its downstream end comes back into the Wilson River about 2 miles downstream (near the mouth of the Wilson River). Hall Slough was connected to the Wilson River at its upstream end before 1950. At that time, a bridge was in place that crossed Hall Slough on the Wilson River Loop Road. Since then the slough has been filled at its upstream end, the bridge removed, and a small culvert placed through the Wilson River Loop Road to drain the area behind it. This area currently represents the area of the Wilson River that overtops first during a flood event. Floodwaters flow over along the left bank of the river near the historic Hall Slough entrance and flow down the Wilson River Loop Road to Highway 101, where they flow south along the highway and eventually cross and flood the highway. These nuisance floods occur frequently and may be controlled by reestablishing the historic slough connection to the Wilson River. The measures modeled with MIKE11 included connecting the slough to the Wilson River at the upstream end, setting back dikes, establishing new levees along the slough, and deepening the slough. Environmental restoration benefits include fish and wildlife habitat, fish passage, tidal wetland, ecosystem function, floodplain function, and water quality.

Initial modeling results using the November 1999 flood event showed that the slough would carry approximately 1,000 cubic feet per second (cfs) of floodwater that would have previously flooded Highway 101. This alternative also lowered the duration of flooding on Highway 101 by approximately 4 hours. Although this alternative would not control flooding for all floods in excess of the nuisance floods, it would help to control the common flooding in the Highway 101 area.

2.2.3. Lower Trask River

This alternative is located along the Trask River between river mile (RM) 2 and the downstream confluence with the Tillamook River. This area represents a constriction in the Trask River because the lower river was rerouted and channelized. The current river channel has a much lower capacity in this reach than both reaches upstream and downstream from it. Furthermore, this reach of the river lacks riparian habitat and channel complexity. This reach is essentially a tidal flume devoid of riparian vegetation other than grazed, trapezoidal banks. The measures modeled with MIKE11 for this reach included setting back dikes and widening and deepening the channel. Environmental restoration benefits include ecosystem function, floodplain function, and water quality.

Initial modeling results showed that modifying the channel had the most profound effects on flood stages, whereas dike modification provided minimal flood reduction. Channel modifications were initially modeled as large cuts on the extreme side of what would be realistic to perform. However, this was done to determine the largest flood reduction benefit and to determine if further development of the alternative was warranted. For the November 1999 flood, water surface elevations were significantly reduced in the reach, as well as upstream of the reach. Stages in the Tillamook-Trask Drainage District, an upstream area frequently flooded, were reduced by about 1.3 feet. At the same time, the Trask River was carrying approximately 6,000 cfs more flow through this reach of river. From a flooding standpoint, this alternative increased flow through the reach and decreased flood stages. Although the channel modification was modeled on the extreme side in terms of channel geometry, the possibilities for minor flood reduction benefits in this area were shown.

2.2.4. Old Trask River

The Old Trask River is a branch of the Trask River, possibly representing the former mouth of the Trask River. This reach flows between the Trask River and the Tillamook River near Trask RM 1.8, and helps alleviate flooding on the Trask River. The reach currently has levees/dikes along both sides. The Stillwell Drainage District is on the north side of the channel and the Tillamook-Trask Drainage District is on the south side. The Stillwell levee provides approximately 50-year protection while the Tillamook-Trask dike only protects for tidal flows. Therefore, the area to the south is often flooded. The measures modeled with MIKE11 included modifying the channel by widening and deepening, as well as setting back the levees/dikes along the channel. Environmental restoration benefits include ecosystem function, floodplain function, and water quality.

Initial modeling results showed that this alternative had similar results as the Lower Trask River alternative, but on a smaller scale. Setting back only the levees/dikes showed minimal benefits, whereas setting back both the levees/dikes and modifying the channel provided the greatest flood reduction benefits. Channel stages were only slightly reduced; however, an increase in channel capacity of about 2,400 cfs was obtained from the combined measures when modeled using the November 1999 flood event.

2.2.5. Dougherty and Hoquarten Sloughs

Dougherty and Hoquarten Sloughs below Highway 101 represent a critical area in terms of both flood problems in the Highway 101 business district and environmental concerns. Several alternatives were evaluated with the MIKE11 model to assess possible solutions to flood problems in this area. The measures modeled included removal and/or setback of dikes, channel modifications, and a combination of alternatives in downstream reaches. Channel modifications included benching one side of Dougherty and Hoquarten Sloughs from the bridge at Highway 101 to the Trask River, lowering cross dikes along Hoquarten Slough, and setting back the Trask River dike in the Wetland Acquisition area. Also, an alternative was modeled with the channel modifications in the Trask River alternative. Environmental restoration benefits include spawning habitat, tidal wetland, ecosystem function, floodplain function, and water quality.

Initial modeling results showed that if modifications were only performed within Dougherty and Hoquarten Sloughs, very little effect would occur to flood levels at Highway 101. However, if the alternative incorporated dike setbacks and channel modifications, then significant flood reductions could be achieved at Highway 101.

2.2.6. Lower Wilson River Channel Modification

The objective for this alternative was to increase flood conveyance to Tillamook Bay in the lower reach of the Wilson River. The lower reach is between the railroad bridge over the lower Wilson River and Tillamook Bay on the Wilson River mainstem. The channel was modified throughout this reach to increase channel conveyance by a combination of deepening and widening. Environmental restoration benefits include ecosystem function, floodplain function, and water quality.

The channel was initially modified as a trapezoidal channel with a bottom width of 80 feet and 2:1 side slopes. This modification was only performed for narrow areas as some areas of the reach were already this large. The bottom was deepened such that a positive slope occurred throughout the reach. Most of the deepening was located where sedimentation has occurred below the ‘Big Cut’ branch between the Wilson and Kilchis Rivers to Tillamook Bay. Model results showed that flows could be increased by approximately 2,000 cfs in this reach and channel stages could be reduced by 0.3 foot at the railroad bridge to 1.3 feet near the bay. Flood cells adjacent to this reach also had reduced water surface stages and flood durations. This channel modification showed some flood benefits to the lower Tillamook region.

2.2.7. Lower Wilson River Dredging

The Wilson River branches into three reaches before its terminus into Tillamook Bay. Bathymetric data and historic accounts show that this area has been aggrading for some time. Sediment and woody debris deposits have been left in the area. This reach represents a very dynamic area in terms of sedimentation and planform morphology. At the tidal interface, sediments are deposited as the Wilson River slows. Historically, the river would have aggraded and changed course as a delta was formed. However, development created a condition where the river was not allowed to change course. To determine the extent of impact on flood conditions from sedimentation, the area was dredged and the three channels deepened in the MIKE11 model to determine if sedimentation was causing flooding problems upstream, and if dredging would alleviate the problems.

Using a trapezoidal channel, the ‘Little Cut’ and the ‘Big Cut’ branches between the Wilson and Kilchis Rivers were dredged with an 80-foot bottom width and the mainstem of the Wilson was dredged with a 100-foot bottom width. Side slopes were 2:1. Dredging depths ranged from zero to 5.5 feet to achieve a positive slope to the bay. Dredging was performed from RM 0.25 to the mouths of the three branches. Initial modeling results showed that there was stage reduction in the Wilson River at the dredge location and in nearby flood cells of up to 1 foot. Upstream, however, the stage reduction was reduced until it was null at Highway 101 across the Wilson River. This appears to be caused by the existing channel constraints between Highway 101 and the mouth of the Wilson River. These constrictions in the channel control the water surface slope during flood conditions.

2.2.8. Lower Wilson River Channel Modification/Dredging

This alternative combined the channel modification from the railroad bridge at RM 2 to the mouth and included full dredging of the Wilson and the ‘Big Cut’ and the ‘Little Cut’ branches as described for the dredging alternative. Modeling results using the November 1999 flood event showed that no further stage reduction was realized at Highway 101 during flood conditions. Some minor stage reduction did occur near the dredged area. These results show that water surface stages at or above Highway 101 during high water conditions are controlled by the capacity of the Wilson River channel, not by tidal conditions or sedimentation at the mouth of the river.

2.2.9. Lower Trask and Tillamook Rivers Dredging

Similar to the Wilson River, the Lower Trask and Tillamook Rivers have been aggrading at their tidal interface with Tillamook Bay. This alternative analyzed dredging the sediments in the Lower Trask and Tillamook Rivers to view the effects on flooding at upstream locations in the Tillamook region. The Tillamook River was dredged from RM 0.86 to the bay and the Trask River was dredged from RM 1.14 to the bay. The Tillamook River was dredged with a bottom width of 215 feet and depths varying from 0.6 to 5.2 feet. The Trask River was dredged with a bottom width of 80 feet and depths varying from zero to 3.0 feet.

Initial modeling showed results that were similar to those of the Lower Wilson River Channel Modification/Dredging alternative. Water surface stages during flooding were reduced in and near the dredged area. This included stage reductions of up to 1.6 feet on the Tillamook River near the Netarts Highway bridge and up to 0.8 feet on the Trask River near its mouth. Adjacent flood cells had a reduction in flood stage from 0.3-0.5 feet. Also, the Trask River had an approximate 1,200 cfs increase in flow at it peak. However, at locations upstream including Highway 101 at Hoquarten Slough, impacts from dredging were minimal. From these results, it appeared that a project on the Trask River may be beneficial to flood stages if it included either the Lower Trask River or Dougherty/Hoquarten Sloughs alternatives, or some combination of the alternatives.

2.3. Refined Alternative Analysis

The initial MIKE11 model results described above showed that the greatest flood damage reduction benefits could be achieved by increasing the capacity of the existing channels or by providing additional channels. The most effective way to increase the capacity of the channels would be to increase the width of the channel. Increasing the depth of the channel did have an effect and may be effective in conjunction with increased channel width based on the specific river under consideration. However, increasing channel depth had a much less significant impact on flood levels and is more localized in nature. The key for both ecosystem restoration and flood damage reduction benefits appeared to be associated with increasing channel width or providing additional channels.

Initial modeling results were presented to the Feasibility Advisory Council and interested citizens on March 27, 2002. From these preliminary results, discussions ensued as to which alternatives were to remain for further evaluation and cost analysis. From the modeling results, it appeared that some alternatives likely would not provide many flood damage reduction benefits to the Tillamook area. Therefore, Tillamook County decided that these alternatives would no longer be studied. Through a long process and much discussion, three alternatives remained for detailed evaluation because they had the greatest potential to provide dual ecosystem restoration and flood reduction benefits. The alternatives considered for further study included Dougherty Slough, Hall Slough, and the Wetland Acquisition/Swale area.

2.3.1. Dougherty Slough

The Dougherty Slough alternative would reconnect the slough to its floodplain from Highway 101 downstream to the Trask River. Dikes would be removed and the top 2 feet of soil would be scraped from the banks to reconnect the slough to the floodplain. Riparian vegetation and fencing would be placed adjacent to the slough channel, and some large wood would be placed in the slough for habitat complexity. To achieve more than incidental flood reduction, it would be necessary to increase channel capacity, a measure which would be unlikely to be economically justified. Because this alternative was the sponsor's lowest priority of the three alternatives being considered for further study, this alternative was not developed further, although it remains a viable ecosystem restoration alternative.

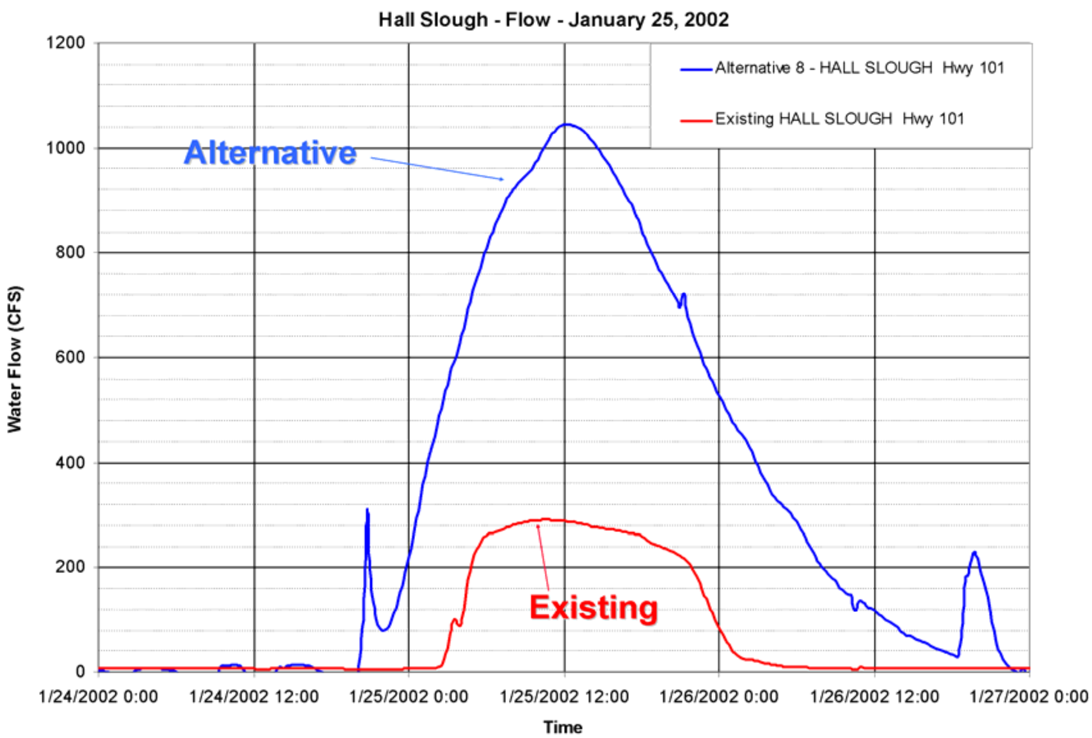
2.3.2. Hall Slough

The goals for the Hall Slough alternative were to restore upper Hall Slough to conditions that would be ecologically beneficial, especially to salmonids, as well as collecting overflow from the Wilson River into a channel for passage to Tillamook Bay. Hall Slough was disconnected from the Wilson River at its upper end and floodwater has since filled much of the historic upper channel with sediment. As floodwater overflows the Wilson River, it flows out towards the historic upper slough connection, but ends up flowing down roads and fields including down and across Highway 101. Hall Slough is not large enough to contain all the floodwater, but it could contain flows of up to about 1,000 cfs, which is approximately the amount of overflow that occurs with an annual flood. These nuisance floods disrupt Highway 101 could be completely controlled. Also, another goal was to take excess floodwater (above 1,000 cfs) from this area and direct it around Highway 101 to the greatest extent possible.

In the MIKE11 model, the slough was deepened throughout to maintain a positive slope to the bay and to be tidally active throughout its length (Figure 4, located at the end of this chapter). A conceptual overflow structure also was placed at the slough's upper end to allow flows from the Wilson River to enter Hall Slough when the river reached an elevation of 15.4 feet NAVD88 (North

American Vertical Datum of 1988). Wilson River flows would then be allowed in Hall Slough via a weir structure. In order for increased flows in Hall Slough to remain within the slough, the slough was widened and deepened from its upstream end down to the Goodspeed Road bridge. Also, small levees were needed in a few low spots along the slough. The Hall Slough bridge at Highway 101 was lined with vertical concrete walls and deepened to pass flows of 1,000 cfs. Hall Slough downstream of Goodspeed Road was unchanged other than the dike on the right bank was setback for riparian plantings.

Modeling was performed using the January 25, 2002 flood which represents an annual event on the Wilson River. Modeling results showed that overflows from the January 2002 flood that had flowed across Highway 101 and into the fields behind Fred Meyer were contained in Hall Slough. The following graph shows the change in flow in Hall Slough with and without the modeled changes.



In summary, the Hall Slough alternative consists of reconnection of tidal flows in the historic slough, high flow flushing from the Wilson River, and setback levees with riparian plantings. It is a high priority ecosystem restoration action and would eliminate flooding in the Highway 101 business district up to approximately the 2-year flood event. A preliminary cost estimate for this alternative is approximately $7.5 million. To meet the 35% cost-share requirement, the sponsor would need approximately $1.5 million in cash plus donated land (approximately $1 million) for implementing the alternative. Because the sponsor indicated that they do not have adequate funds for implementation at this time, the alternative was not developed further.

2.3.3. Wetland Acquisition/Swale

The wetland acquisition/swale alternative represents a unique area in the Tillamook Bay watershed. Not only is it at the tidal interface of the two largest rivers in the area (Wilson and Trask Rivers), it sits at the downstream end of the area's greatest flood prone properties, the Highway 101 business district. It appeared to be an area with a good likelihood of providing both flood reduction and ecosystem restoration benefits.

During initial MIKE11 modeling, it was shown that opening up the diked area to tidal conditions would increase flooding conditions at Highway 101. Since this would not be acceptable, other alternatives were considered. One of these alternatives showed some positive results for allowing the wetland acquisition area to be reconnected to tidal conditions of Tillamook Bay by setting back the existing dikes, while also reducing flooding at Highway 101 (Figure 5, located at the end of this chapter). This alternative included a large swale that would begin upstream of Highway 101 and continue downstream to the edge of the wetland acquisition area. The swale concept was simple in that it would be a large depression that would remain dry for most of the year. However, during flood conditions, overflows from Dougherty and Hall Sloughs would end up in the swale and be swiftly evacuated to Tillamook Bay during ebb tide. The current situation allows for these overflows to find their way to the bay through businesses, farm fields, and dikes. The swale was located in fields used for grazing of dairy cattle, and it was assumed this use could continue with the swale.

The initial swale design consisted of a long, shallow depression that would have a minimal slope and invert elevation of 5 feet NAVD88. The depression has a bottom width of 50 feet and a top width of 150 feet with varying side slopes of 10- to 25-feet horizontal to 1-foot vertical. The intention of the swale would be to collect overflows from Hall and Dougherty Sloughs in a central location and to evacuate those overflows in the most expedient manner possible. The swale included a bank of ten 6-feet in diameter tide-gated culverts at its downstream end in the levee for the wetland acquisition area. It also included culverts under Highway 101. Initial modeling results for this concept showed that during the November 1999 flood, maximum flood elevations at the swale just upstream of Highway 101 would have been 0.3 feet lower and the duration of flooding would have been 5 hours less with the swale in place.

A geotechnical investigation was undertaken by the Corps along the proposed alignment of the swale. Hand auger borings were made at each end of the swale and at six intermediate points. The borings were taken to a depth of 4 feet. Materials recovered in all borings were generally plastic silts and clays, except for peat that was found at approximately elevation 3.4 feet NAVD88 at the western end of the swale alignment. The soils were brown, with no signs of mottling which indicates that they were generally above the water table. In general, the soil in all borings had a medium consistency between the surface and a depth of 2 feet, but below about 2 feet the strength of the soil declined dramatically and the consistency dropped to very soft. This rapid change in soil strength is probably the result of cyclic saturation and drying which tends to cause plastic soils to develop high negative pore pressures that consolidate the soil. Compaction of the upper surface of the soil also is a function of it use by farm equipment and grazing animals.

The lack of soil strength below a depth of 2 feet will impact construction. It also will take some time for the soil to gain sufficient strength to support livestock once construction is complete. As would be expected, the soil moisture content increased with depth. Water was encountered in the last four borings at the western end of the swale, and depth to water was estimated in the remaining borings. Groundwater was estimated to be at about elevation 6.5 feet NAVD88 on the east side of Highway 101, and varied between about elevation 6 feet NAVD88 just west of the highway and elevation 4.5 feet NAVD88 at the west end of the swale. Groundwater in the western half of the swale alignment appears to be controlled by drainage ditches. It could not be determined if any agricultural drainage tile had been installed in any of the areas. If so, it is probable that it is helping control the groundwater elevation.

Therefore, with the swale at elevation +5 feet NAVD88, it is possible to keep the groundwater sufficiently low enough to allow beneficial use of the swale if a drainage ditch is incorporated into the swale design. The ditch would need to be tied to a local drainage system, which has a tide gate to control water levels to about elevation 3.5 to 4 feet NAVD88. Also, the soil below a depth of 2 feet has insufficient strength to support conventional construction equipment. Special considerations will be needed when planning the construction period and sequence. It is recommended that construction be scheduled for late summer, and that low soil pressure construction equipment will be necessary.

In summary, the Wetland Acquisition/Swale alternative restores tidal marsh/wetlands with actions to offset flood increases. It is a high priority ecosystem restoration action and would reduce flooding for lower flood events. However, the sponsor requested that remaining study funds focus on developing the Modified Wetland Acquisition alternative endorsed by the TBHEID. This modified alternative meets ecosystem restoration requirements without causing an increase in flood elevations, meets the requirements of the sponsor, and is acceptable to the community. After initial evaluation and modeling, the sponsor requested that the Modified Wetland Acquisition alternative be transferred to either the Continuing Authorities Program (CAP) or to Section 536 of the Water Resources Development Act of 2000 (Public Law 106-541) for further evaluation and implementation. The Modified Wetland Acquisition alternative is discussed in the next section.

2.3.4. Modified Wetland Acquisition Alternative

The TBHEID provided Tillamook County with four documents suggesting numerous concepts to modify the Wetland Acquisition/Swale alternative. The goals for the alternative are to form a large area of fully tidal saltwater marsh including two major slough systems, a large area of enhanced regulated tidal wetland for juvenile salmon habitat, and enhancement of an area for Aleutian Canada Goose habitat, as well as providing flood damage reduction benefits. The concepts were incorporated into the Wetland Acquisition/Swale alternative by the study team to develop the Modified Wetland Acquisition alternative. A preliminary cost estimate for the Modified Wetland Acquisition alternative is approximately $4.5 million. The Modified Wetland Acquisition alternative was modeled and analyzed with the HEC-RAS model (see Appendix C).

The dominant new feature includes a new levee dividing the area in half, east to west, separating a fully tidal area to the north with a flood storage area to the south (Figure 6, located at the end of this chapter). Agreement was reached that while flood storage area could be used for ecosystem restoration, it could not be fully tidal and it must be reserved for flood storage and conveyance during flood events. A muted tide concept was discussed. The muted tide gate would allow the flood tide to rise to a specified elevation, for example 5 feet NAVD88, but the tide gate would shut at the specified elevation. The muted tide would allow partial saltwater intrusion on the wetland acquisition property and prevent seawater from reaching the landowners beyond the project boundaries.

The full-time saltwater marsh to the north would be reconnected to the Wilson River by removing the plug in Blind Slough, removing the levee at several historic sloughs, and creating an overflow from the left bank of Hall Slough. Beyond the wetland acquisition property a swale would be required from the project boundary to Averil's property boundary but would not be required to extent upstream of Highway 101. Without the swale, the project caused a rise in 100-year flood elevations at several locations. The swale was included to ensure that the project did not increase flood elevations. An additional ecosystem restoration feature of the flood storage area could be an excavation of the existing drainage ditch and additional excavation to create saltwater marsh that would be inundated with the muted tide.

Figure 3. Ecological Restoration Areas

Figure 4. Hall Slough Alternative

Figure 5. Wetland Acquisition/Swale Alternative

Figure 6. Modified Wetland Acquisition Alternative

3. ENGINEERING ANALYSIS

3.1. TILLAMOOK AREA HYDROLOGY

The Tillamook area is hydrologically active. Located on the northwest coast of the United States, Tillamook lies in the direct path of the north pacific jet stream. Storms come off the Pacific Ocean and encounter the Coast Range Mountains immediately east of the coast. As they rise over the coastal mountains, these storms release significant amounts of precipitation. In fact, with locations at the top of the Coast Range receiving over 200 inches of precipitation per year, this is one of the wettest locations in North America. Most of the precipitation falls as rain and most falls between the months of October and March. Locations in the lowland valleys receive significant rainfall as well, averaging approximately 100 inches per year. With all the rainfall comes a large amount of runoff. It is common for the Wilson River to rise 10,000 cfs in a matter of hours during winter storm events.

The Tillamook region has very few long-term precipitation gauges. One gauge is located at the local radio station, and another gauge is located in the upland area at the South Fork of the Wilson River. Other precipitation gauges have been in operation throughout the coastal areas on a sporadic basis. Stream gauges have been operated on a sporadic basis as well.

3.1.1. Discharge-Frequency Relationships

3.1.1.1. Wilson River

The Wilson River has a drainage area of 161 square miles at its gauged location with an additional 30 square miles of area that joins the Wilson River on its way to Tillamook Bay. Therefore, approximately 84% of the drainage area is gauged. The North Fork of the Wilson River enters the Wilson at RM 8.61 and represents approximately 66% of the remaining 30 square miles of ungauged tributary area. Using the Corps' HEC-FFA program (flood flow frequency model), a discharge-frequency relationship was computed for the Wilson River (see Appendix A). The frequency curve contains 71 years of peak flood values ranging from a peak value of 36,000 cfs in 1972 to 3,665 cfs in 2001. Utilizing current Corps regulations, values used for this study rely on the expected probability of occurrence.

Historic computations of discharge-frequency on the Wilson River include a 1993 U.S. Geological Survey (USGS) report documenting statistical summaries of gauges in Oregon. Other historic computations include the 1978 Federal Emergency Management Agency (FEMA) Flood Insurance Study for Tillamook County that was updated in 1999 for the lower Wilson River. Table 1 summarizes peak discharge values from the two historic studies in comparison with this study.

Table 1. Wilson River near Tillamook, Annual Peak Discharge-frequency Values

Study/Date	Discharge for Indicated Annual Percent Chance of Exceedance (cfs)				
	50%	10%	2%	1%	0.2%
Corps 2002 Record 1932-2002	17,700	27,800	36,100	39,400	47,200
USGS 1993 Record 1915-1987	17,200	26,300	33,100	35,800	NA
FEMA 1978 Record 1932-1976	NA	25,000	33,000	36,300	43,500

3.1.1.2. Trask River

The Trask River has a drainage area of 145 square miles at its gauged location, with an additional 14 square miles of area that joins the Trask River on its way to Tillamook Bay. Therefore, approximately 91% of the drainage area is gauged. Only minor tributaries enter the Trask River below the gauge. Using HEC-FFA, a discharge-frequency relationship was computed for the Trask River (see Appendix A). The frequency curve contains 48 years of peak flood values ranging from a peak value of 25,800 cfs in 1996 (estimated) to 2,520 cfs in 2001.

Historic computations of discharge-frequency on the Trask River include the 1993 USGS report documenting statistical summaries of gauges in Oregon. Other historic computations include the 1978 FEMA Flood Insurance Study. Table 2 summarizes peak discharge values from the two historic studies in comparison with this study.

Table 2. Trask River near Tillamook, Annual Peak Discharge-frequency Values

Study/Date	Discharge for Indicated Annual Percent Chance of Exceedance (cfs)				
	50%	10%	2%	1%	0.2%
Corps 2002 Record 1932-1972, 1996-2002	12,600	19,400	26,000	29,100	37,200
USGS 1993 Record 1922-1972	12,600	19,300	25,800	28,800	NA
FEMA 1978 Record 1932-1972	NA	19,000	24,700	27,400	33,100

3.1.1.3. Tillamook River

The Tillamook River has a drainage area of approximately 60 square miles at its downstream terminus into Tillamook Bay. The watershed of the Tillamook River differs from the other four major rivers because its origins arise in the lowland coastal foothills and valleys paralleling the coast rather than from the Coast Range Mountains. Therefore, orographic effects on the watershed are less pronounced as compared to the other four rivers, which results in a lower flood peak-to-drainage area ratio. Also, there is less historic hydrologic data for this watershed than for the other watersheds in the region. The river has had a few periods of gauging including 1973-1977, 1995-1998, and February 2001 to present. All gauging has been performed by the Oregon Water Resources Department (OWRD). With only 8 years of broken record, it was difficult to produce a discharge-frequency curve for this river. Table 3 shows the Tillamook River discharge-frequency values from the 1978 FEMA Flood Insurance Study. These values are based on the USGS regional flood frequency method. Further analysis was not performed for this river during this feasibility study.

Table 3. Tillamook River at Old Trask Confluence, Annual Peak Discharge-frequency Values

Study/Date	Discharge for Indicated Annual Percent Chance of Exceedance (cfs)				
	50%	10%	2%	1%	0.2%
FEMA 1978	NA	7,170	9,730	10,800	13,400

Note: Values based on USGS regional methods.

3.1.1.4. Kilchis River

The Kilchis River has a drainage area of approximately 67.3 square miles at its terminus in Tillamook Bay. The watershed of the Kilchis River is similar to that of the Wilson River in that it is dominated by the Coast Range, which is steep, forested terrain with shallow soils over impermeable strata. Orographic characteristics of the watershed lead to steep hydrographs with relatively large peak flows during winter rain events. Little gauging has been performed on this river. The OWRD began gauging the river in 1995 and continued this gauge until 1998. This study funded the OWRD to continue gauging the river from spring 2001 to spring 2003. The intention of additional gauging was to capture large storm events, to analyze the watershed’s response to those events, and to use the information as a boundary condition in the hydrodynamic model.

With only 4 years of gauging data, it was difficult to develop statistical relationships for the Kilchis River beyond the 10% to 50% chance of exceedance. The flood of 1996 approximately represented a 2% chance of exceedance event on the Wilson River, and the peak flow on the Kilchis River for this event was approximately 15,971 cfs. From the inherent locations and geology of the two watersheds, they appear to behave similarly. Also, the discharge-frequency from the 1978 FEMA Flood Insurance Study shows that the estimate of 13,895 cfs for the 50-year event on the Kilchis River is approximately 14% less than the peak in 1996, while from their estimate the Wilson peak (35,000 cfs versus 33,000 cfs) also was underestimated. It is assumed that 16,000 cfs approximately represents the 2% chance of exceedance for the Kilchis River. From this preliminary analysis, it was assumed that the expected probabilities for the Wilson and Kilchis Rivers are linearly related. Table 4 shows the peak discharge-frequency values from the 1978 FEMA Flood Insurance Study as compared to this feasibility study.

Table 4. Kilchis River near Tillamook, Annual Peak Discharge-frequency Values

Study/Date	**Discharge for Indicated Annual Percent Chance of Exceedance (cfs)**				
	50%	**10%**	**2%**	**1%**	**0.2%**
Corps 2002 (based on 0.457*Wilson peak)	8,100	12,700	16,500	18,000	21,600
FEMA 1978 1978-estimated	NA	10,240	13,895	15,360	18,965

3.1.1.5. Miami River

The Miami River has a drainage area of 36.4 square miles at its terminus with Tillamook Bay. Like the Kilchis, Wilson and Trask Rivers to the south, the Miami has its origins in the Coast Range. Therefore, the Miami River responds quickly to intense precipitation, often producing steep hydrographs with significant peak flows relative to the size of its watershed. The Miami River has been gauged near Moss Creek by the OWRD intermittently since 1975. Although a significant amount of gauge data exists, the Corps was able to obtain gauge data only for the years 1995-1998 and 1999-2002, and a continuous record for the past 7 years was compiled. However, with only 7 years of data, it was difficult to develop sufficient discharge-frequency relationships beyond the 10-year event. In the period 1995-2002, the largest event occurred on February 7, 1996 with a recorded flow of approximately 9,900 cfs. However, this reading is suspect because the gauge was washed out during the flood. Other large floods during the period included the November 1999 flood where the gauge recorded a peak flow of approximately 5,600 cfs. Another large flow of 6,200 cfs occurred in

November 1995. Discharge-frequency curves were not developed for this gauge. Table 5 shows the peak discharge-frequency values from the 1978 FEMA Flood Insurance Study.

Table 5. Miami River at Mouth of Miami Cove, Annual Peak Discharge-frequency Values

Study/Date	**Discharge for Indicated Annual Percent Chance of Exceedance (cfs)**				
	50%	**10%**	**2%**	**1%**	**0.2%**
FEMA 1978	NA	5,650	7,220	7,900	9,400

Note: Values based on USGS regional methods.

3.2. FLOODING ANALYSIS FOR THE TILLAMOOK REGION

The flooding problems in the Tillamook area were evaluated by the Corps in order to define alternatives that would possibly alleviate flooding in the area (see Appendix A). In order to understand flooding in and around the City of Tillamook, the topography of the lower Wilson, Trask and Tillamook Rivers was evaluated. The rivers of Tillamook are perched above their floodplains. The high sediment loads of the rivers spill out of each river during flood events and are deposited near their banks. The floodplains are lower and are reconnected to the river system through a network of sloughs. For agricultural use, the floodplains were diked along their rivers and sloughs to not allow tidal inundation. Therefore, when floodwater exits the Wilson, Trask, Kilchis and Tillamook Rivers, it is trapped in the floodplains behind the natural and constructed dikes. ‘Flood cells’ were delineated for the study based on their independence of one another in flooding condition. Each flood cell acts independently because it is diked from its neighboring flood cell, slough, or river.

Both natural and constructed dikes have separated the rivers and sloughs in the Tillamook area from their floodplains. The complex nature of flooding in the Tillamook area had not been analyzed in a floodplain development context, including the placement of tidal dikes. The result is a system of channels that are disconnected and create increased flood problems including standing water when floods recede and increased flood stages within channels. Man-made features such as levees, dikes and roads, along with land use practices have caused flooding in areas that did not historically flood. Although the rivers have been forced to evacuate all floodwater, they will never have the capacity to do so. In analyzing the peak flows from gauges in the Tillamook area for the November 1999 flood event, it was apparent that the lower rivers do not have the capacity to carry their floodwater and depend largely on the floodplain to carry the floodwater to Tillamook Bay.

The lower Wilson and Trask Rivers do not have the capacity to move their floodwaters to Tillamook Bay. The Wilson River has approximately 12,000 cfs of capacity and the Trask combined with the ‘Old Trask’ has approximately 11,900 cfs capacity. It is natural for rivers to not have the capacity to take flood flows within their banks. Their bankfull discharge (or channel forming discharge) is that discharge that the river can move before it overflows its banks. The bankfull discharge of a river is typically on the order of an annual or bi-annual event. For the Wilson River, 12,000 cfs capacity represents approximately the 90% chance of exceedance flow; for the Trask River, 11,900 cfs capacity represents approximately the 60% chance of exceedance flow for any given year. However, the Tillamook River is an anomaly among the three rivers; its lower reach is broad in comparison to its flow and it has more capacity than the river typically flows. The reason for this is that the Trask River flows towards and into the Tillamook River through floodplains and the Old Trask River adding large amounts of floodwater to the Tillamook River near its mouth.

Much of the impetus for this feasibility study lies in the regular flooding that occurs in the valleys of the Tillamook region, with the most severe flooding occurring in and around the City of Tillamook. The flood of February 1996 was region-wide and was especially devastating in the Tillamook area. The City of Tillamook lies along a ridge that separates the Wilson and the Trask Rivers. Just downstream of the City is Tillamook Bay. The Wilson and Trask Rivers are the two largest Rivers that flow into Tillamook Bay and produce the largest floods. The Wilson River has reached flood stage (approximately 14,100 cfs) numerous times over the past 32 years; it has exceeded flood stage approximately 60 times, averaging almost two floods per year in the recent past.

The City itself largely remains flood free; however, newly developed areas to the north and south of the City experience catastrophic flooding on a regular basis. The worst flooding occurs north of the City along the Highway 101 business area. This recently developed area lies in the direct path of floodwaters from the Wilson River. Floodwaters come from all sides in this area, from the Wilson, Trask, and the Tillamook Rivers and from high tides and storm surges in Tillamook Bay. Other areas in Tillamook along the Trask, Tillamook and Kilchis Rivers also have historically flooded. The majority of lands in the area are operated as dairy farms and many of the historic dairies are located on high points throughout the area. Although many dikes have been built around the area, only the Stillwell levee actually protects a large tract of land from flooding. The levee protects a large farmed area that lies at the mouth of the Trask and Tillamook Rivers. The levee forces waters to flow around it through two narrow channels, the Trask and Tillamook Rivers. As a result, floodwater regularly overtops their banks upstream of the Stillwell levee and floods the area between the Trask and Tillamook Rivers.

3.3. MIKE11 MODEL

The MIKE11 model is a one-dimensional, unsteady flow model developed by the Danish Hydraulic Institute. The hydrodynamic model solves the Saint Venant equations for fluid momentum and continuity by a finite difference scheme utilizing an alternating grid. At each point in the model grid, the model solves for either stage (H) or flow (Q) on an alternating basis. The model also is able to solve general hydraulic equations for hydraulic structures as internal boundary conditions such as weirs and culverts. Basic input to the model includes river cross-sections, structural geometries and geographical networks. The model utilizes branches for rivers and floodplains that consist of nodes (points along the branch) with corresponding cross-sectional dimensions. Like all unsteady flow models, the MIKE11 model requires a boundary condition at all upstream branches and downstream branches of a model network. In the case of Tillamook, flow gauges were utilized at all upstream ends of the five rivers and the downstream boundary consisted of tidal conditions in Tillamook Bay.

Geometric data collection done by the Corps included river cross sections; floodplain mapping; river structures (cross sections of bridges, culverts, dikes, levees, and tidegates); boundary condition data (hydrologic data for each point within the model that is either an end to a reach, a beginning of a reach or a source or sink of water within a reach); crest stage gauge data; highwater mark surveys; and tributary inflows.

Interior drainage in the Tillamook region is provided by hundreds of tide-gated culverts throughout the lower river system. As there are so many private culverts, it was impossible for this study to survey them all. However, the Tillamook County Watershed Council in cooperation with the Tillamook Bay NEP completed a cursory inventory of all culverts in the area. This data was used to develop the initial models. Some culvert lengths and most elevations of culverts were estimated from floodplain mapping. For 20 culverts, a local contractor, Nehalem Marine, was hired to survey culvert properties. Other data was gathered from Nehalem Marine’s records of recent culvert replacement and installations.

Prior to the MIKE11 model study, the most recent hydraulic modeling study of the Tillamook area was performed in late 1960s and early 1970s by the Corps and CH2M Hill in development of the 1978 FEMA Flood Insurance Report for Tillamook County. This modeling utilized 2-foot topographic data and cross-sectional data gathered in 1965. The study evaluated the rivers with the one-dimensional, steady-state model HEC-2. As all the rivers of Tillamook Bay are tidally influenced, it was readily apparent that the only way to develop a good understanding of flood behavior in the Tillamook area was to develop an unsteady flow model of the rivers.

Initial scoping efforts for the MIKE11 model study included the development of the Corps' one-dimensional, unsteady-flow model, UNET. However, during the scoping phase for the study, the Danish Hydraulic Institute was in the region promoting their unsteady flow model MIKE11. At the time, their model boasted the ability to create flood area maps and slide shows. Also, their model was integrated in a system that allowed the user to incorporate multiple modeling modules such as sedimentation, water quality, and hydrologic models. The sponsor, Tillamook County, supported the use of the MIKE11 model for the feasibility study.

3.3.1. MIKE11 Model Development

WEST Consultants Inc., under contract by the Corps, developed the MIKE11 one-dimensional, unsteady-flow model of the combined Tillamook, Trask, and Wilson River systems for the study (see Appendix B). Surveyed cross-section information was provided for the Tillamook, Trask, Wilson and Old Trask Rivers; Hall, Dougherty, and Hoquarten Sloughs; and the 'Little Cut' and 'Big Cut' branches between the Wilson and Kilchis Rivers.

A geographic information system (GIS) triangular irregular network (TIN) was used to define overbank features including floodplain geometry and dike/levee heights for the model, and to delineate flooding extents and depths. Aerial mapping for two-foot contour accuracy of the TIN was conducted by the Corps in September 1999 and May 2000. Bathymetric data for Tillamook Bay was collected by the Corps in 1995 and 2000.

Wilson and Trask River hourly stage and flow data, gauges #14301500 and #14302480, respectively, were obtained from the USGS. Tillamook River flows, gauge #14302700, were collected by the OWRD. Fifteen-minute tidal information at Garibaldi (located near the north end of Tillamook Bay), as well as 15-minute hourly stage data at Kilchis Cove and Dick Point (both in Tillamook Bay), Gienger Farm (on the Wilson River), and Carnahan Park (on the Trask River) were recorded at Corps gauges.

Bridge information was supplied from Corps surveys, Oregon Department of Transportation bridge scour reports and bridge plans, and the 1999 FEMA Flood Insurance Restudy. Culverts included in the model typically connect the overbank areas to the rivers or sloughs. Culvert data were collected and supplied by Tillamook County. Upstream and downstream invert elevations were estimated from the TIN when survey data were not available.

Orthophotos (color photos dated 2000, black and white photos dated 1995) were supplied by the Corps. A photo album by the Best Impressions Picture Company in Rockaway, Oregon and an aerial video of the November 1999 flood event also were provided. Highwater marks for the November 1999, May 2001, and November 2001 flood events were provided by the Corps and Tillamook County. The stage data at Dick Point, Gienger Farm, and Carnahan Park, as well as the imagery of the November 1999 event, also were used in calibrating the hydraulic model.

The MIKE11 model was calibrated to an in-bank event (May 2001) and out-of-bank event (November 1999). In both cases, the simulated versus observed peak values compared relatively well, differing by ±0.4 and ±0.8 feet, respectively, for the two events. The verification run (November 2001) using the November 1999 Manning's 'n' values and geometry varied by ±2.1 feet. However, the November 2001 discharge values were between those in the November 1999 and May 2001 simulations, and different Manning's 'n' values were used when calibrating these two latter events. Therefore, the Manning's 'n' values should likely be modified as well to better calibrate this 'in-between' flow. A verification run of magnitudes similar to those of the November 1999 and May 2001 events would better verify the MIKE11 model parameters.

Areas of potential improvements to the model include making modifications and additions to the culverts and dikes/levees. Only the significant culverts were added to the model, and many of the invert elevations of these were estimated from the TIN. Additional culverts and surveyed invert elevations may be necessary to perform more detailed modeling in any specific location. Dike/levee ('link channel') elevations were also estimated from the TIN. Surveying the dike/levee elevations and modifying the MIKE11 model accordingly may yield more accurate results.

3.4. CONVERSION TO HEC-RAS MODEL

With the decision to transition from the GI feasibility study process, a decision also was made to convert the existing MIKE11 model to the Corps' HEC-RAS model. At the time the MIKE11 model was selected for use in the study, it had a solid reputation, whereas not enough information was available for the HEC-RAS model. Since then, a newer version of the HEC-RAS model has been developed, which is more sophisticated than MIKE11 and more capable of addressing the complex nature of flooding in the Tillamook area. The HEC-RAS is currently the most common river analysis model used. The HEC-RAS model will be able to serve the Tillamook project in an easier and less expensive manner. WEST Consultants Inc., under contract by the Corps, performed the conversion of the MIKE11 model to HEC-RAS (see Appendix C).

3.5. FLUVIAL GEOMORPHIC ANALYSIS

A fluvial geomorphic analysis of the five major rivers in the Tillamook area was performed by Monte Pearson under contract to the Corps and Tillamook County (see Appendix D). The purpose of the analysis was to inventory and characterize the Miami, Kilchis, Wilson, Trask and Tillamook River watersheds in the study area, and to provide a foundation for undertaking a geomorphic analysis. The resulting report provides a discussion of the sediment problem, regional geologic setting, geographic and physiographic setting, geomorphic sedimentation and transport, landforms and geomorphic processes, fluvial and geomorphic analysis, and future geomorphic landscapes. Provided below is a summary of the erosion-sediment problem found in the Tillamook region.

- Channels in the bay are impassable to most shipping because of sediment.
- Sediment carried down the rivers and into the bay has built up at rapid rates, filling former channels south of Garibaldi.
- The drastic erosion-sediment problem has been traced in part to the devastating forest fires in the region from 1933 and 1945. These fires have exposed over 228,000 acres of highly erodible material to severe winter storms.
- As the channels became larger, more soil particles and debris were carried down the slope and accelerated erosion problems.
- The lower river channels were choked with sediment; as a result of reduced channel capacity, flooding was often aggravated during storms.

- Commercial activities such as farming, logging, road construction, and uncontrolled cattle movement across stream banks increased the erosion-sediment problem.
- The general problem is obvious: too much sediment.
- The problems are complicated and oversimplification is a hazard.

The analysis concluded that positional landscapes prevail in the Tillamook region. Erosion is the dominant geomorphic process occurring in the upland/mountain regions. Historical fires in the Tillamook Basin have caused erosion and sediment yield which, when combined with the region's hydrology, supports and aids the mass movement process.

Given the scale of the rivers in the study area, with the floodplain and the long relaxation time involved in fluvial processes, it appears unlikely that the river-floodplain and river-bay transition zones are in equilibrium. Erosion and sedimentation events and location adjust on different time-scales and to a different frequency distribution. It appears that the major forest fire events were the most significant sediment producers from the upland/mountainous regions. The fire events and burn patterns appear to have produced pseudo-cycles in which periods of high quantities of sediment were generated and then delivered to the channel networks. During initial sediment generation from the uplands, areas the floodplain and river/bay zones could have been in a stable geomorphic state or equilibrium.

Due to changing sediment supply and transport location, the geometry of the channel system and related floodplain has quite different effects on the bay or river-bay transition zone. The partial uncoupling of the river-floodplain and river-bay zones has been greatly increased by human actions. These include deliberately increasing flood deposits on some floodplain locations, reducing flood deposits by construction of dikes and some dredging, the prevention of avulsion and migration by dikes and revetments, and filling or blocking secondary channels and sloughs.

The recommendations for controlling or reducing the flooding impact can be presented with two perspectives: the geologic and the geomorphic. The geologic perspective is strictly based on geologic processes and events of geologic time. The channel system in the Tillamook Bay area is attempting to return to an equilibrium state by way of tectonics, climatic conditions, and basin geology. Left alone, the alluvial plain will reestablish connectivity with the sloughs in order to regain the fluvial geomorphic pyramid. Bank and bed erosion is direct evidence that this process is evolving. Sediment wedge development at the rivers' mouths is the first phase to increasing sinuosity and channel freedom. The lower half of the alluvial plain could become a more complex alluvial fan and delta environment resulting from sedimentation processes. Failure to remove or modify a large percentage of structures that reduce channel freedom would preclude the natural process from occurring. Nevertheless, the channel system will evolve to one of equilibrium and continuing human intervention will attempt to manage this evolution. Flooding is a process nature uses to maintain balance and advance the return to an equilibrium state.

The geomorphic perspective is a mix of geologic, geomorphic, and human intervention. Human actions, including engineering elements, will attempt to manage the Tillamook river systems to enhance geomorphic and geologic processes. The reestablishment of hydrologic conductivity between the upper alluvial plain to Tillamook Bay is needed. This could be completed by the reconnection of the sloughs and the mainstem channel systems. This would allow some fluvial pyramid development to proceed, as well as increase the degree of channel freedom in the deltaic area. However, the total removal of dikes and other structural elements retarding channel freedom would not be an acceptable solution. Allowing some set back of these structures would allow natural channel processes to develop. The increase in channel cross-sectional area would reduce high flow or flood events. There must be a combination of restoring natural channel processes, while at the same time controlling the degree of freedom of the channels with some engineering elements. The mix and location becomes a political situation; however, without some combination, there would be no reduction of flood events in the Tillamook area.

3.6. NUMERICAL SIMULATION OF FLOW FIELDS IN TILLAMOOK BAY

A two-dimensional, finite element model ADvanced CIRCulation (ADCIRC) was used to evaluate several alternatives for decreasing the stage of multiple rivers that discharge into the Tillamook Bay estuary (see Appendix E). Tillamook Bay is a shallow estuary with complex system of tidal channels and broad inter-tidal mudflats. The estuary receives riverine input from five rivers, all with headwaters in the Coast Range. A number of narrow channels provide confined pathways for riverine flows entering the estuary from upland sources and the tidal flows entering and leaving the estuary from the ocean. During times of significant upland precipitation and runoff, the hydraulic conditions within the backbay area of the estuary become dominated by riverine flow. The situation becomes a battle of two flow regimes: riverine versus estuarine.

The objective of the ADCIRC modeling was to determine if an estuarine-based channel modification could reduce the water elevation in the backbay area of the estuary during high riverine flow events. Conventional wisdom could lead to the conclusion that increasing the conveyance of estuary would reduce stage at the river mouths during a high riverine flow event. However, based on the modeling results, estuary-based alternatives were not effective for reducing the stage at the river mouths during high riverine flow events. The best method for reducing river stage and alleviate coastal flooding around Tillamook is to (partially) restore the floodway for each of the major coastal rivers discharging into the bay.

Based on the model results, inland flooding near the City of Tillamook was found not to be related to conveyance issues within Tillamook Bay. The only feasible way to reduce inland riverine flooding from the bay would be to change to hydraulic characteristics of the rivers and associated floodways.

4. ENVIRONMENTAL ANALYSIS

A Biological Focus Group was formed for the feasibility study and consisted of representatives from county, state, federal agencies, non-profit organizations, and citizens including:

U.S. Fish and Wildlife Service
NOAA Fisheries
Natural Resources Conservation Service
Oregon Department of Fish and Wildlife
Oregon Department of Land Conservation and Development
Oregon State University Sea Grant Extension
Tillamook County Planning
Tillamook County Performance Partnership
Tillamook County Watershed Council
Tillamook County Soil and Water Conservation District

The Biological Focus Group developed an Ecosystem Matrix to evaluate environmental outputs based on several existing rating methods utilized by other Corps' GI studies (the Bellingham Bay Demonstration Project, the Green-Duwamish and Stillaguamish Ecosystem Restoration Project, and the Chehalis River Study, all in the Corps' Seattle District). These studies utilized a rating system for the ecosystem restoration projects in riverine and estuarine areas based on several criteria and/or limiting factors to fish and wildlife. These parameters included: hydrologic processes, habitat connectivity, critical and rare habitats, fish passage, channel diversity, floodplain function, water quality, sediment transport and recruitment, and habitat availability and complexity.

The Biological Focus Group devised a similar method for this feasibility study that rated existing conditions and potential alternatives based on both watershed-level processes and local habitat features, for both fish and wildlife species. Initially, several watershed processes and habitat parameters were listed and defined and the group went through several iterations to include all of the factors deemed important within the study area. The rating system and parameters were defined so that no additional data collection other than observation would be necessary. The Biological Focus Group then agreed on the methodology and definitions, and developed a tidal and non-tidal matrix (Tables 6 and 7) for scoring each alternative utilizing the expertise within the group to come to consensus. A matrix score sheet showing its use for the Hall Slough, Dougherty Slough, and Wetland Acquisition alternatives is shown in Table 8.

Table 6. Tidal Ecosystem Matrix

Parameter	Rating	Definitions
Spawning Habitat for Anadromous Salmonids (chum salmon)	5	Excellent cover, depth, velocity, and gravel composition.
	4	Very good cover, depth, velocity, and gravel composition.
	3	Good habitat is present but limited conditions.
	2	Fair to marginal conditions.
	1	Poor conditions, little or no habitat.
Fish Passage	5	Localized habitat fully accessible to fish species for all life histories at all times of the year, as appropriate to geomorphic setting.
	4	
	3	Localized habitat accessible to fish species for all life histories during most of the year, but may be inaccessible seasonally or periodically to fish species due to constraints.
	2	
	1	Localized habitat is not accessible to fish species.
Tidal Wetland/Salt Marsh	5	Wetlands/salt marsh present as expected for geomorphic setting. Community structure dominated by native species. Wetlands fully connected to hydrologic sources and unconstrained in providing expected functions (includes as appropriate, flood storage, sediment detention, groundwater recharge/discharge, nutrient detention, habitat for fish and wildlife species, native plant richness, primary production/organic export). 100% tidal connection - no structures (i.e., culverts with tide gates) to impede hydrology.
	4	
	3	Wetlands/salt marsh present as expected for geomorphic setting. Community structure dominated by native and non-native species. Wetlands losing hydrologic connections and often isolated from providing expected functions. Partial tidal connection/structures (i.e., culverts with tide gates) may impede hydrology.
	2	
	1	Wetlands not present due to filling, draining, etc. No tidal connection.
Ecosystem Function	5	Aquatic and terrestrial habitats highly diverse, complex, and support native species. Off-channel habitat areas, if present, are accessible during normal tidal cycles. Large woody debris (LWD) abundant. Riparian and floodplain habitats function properly and provide a diverse mix of habitat types. Local habitat is connected to upstream and downstream areas.
	4	
	3	Aquatic and terrestrial habitats of moderate to low diversity and support native and non-native species. Off-channel habitat areas, if present, have partial tidal connection. LWD present but infrequent. Riparian and floodplain habitats still function, but are disturbed and/or fragmented. Local habitat partially fragmented from upstream and downstream by land use practices or structures (i.e., pasture/hayland, dikes/levees, roads, bridges).
	2	
	1	Aquatic and terrestrial habitats not diverse and dominated by non-native species. Off-channel habitat areas not present. Tidal flow rarely occurs (except extreme high tides). LWD not present. Riparian and floodplain habitats not functioning, limited, and disturbed/fragmented. Local habitat disconnected from upstream and downstream areas.

Table 6. Tidal Ecosystem Matrix (continued)

Parameter	Rating	Definitions
Floodplain Function	5	Over bank flows occur during higher tides and occupy the floodplain. River freely migrates in its floodplain, channel armoring rare, off-channel habitats abundant as appropriate to geomorphic setting. Natural floodplain plant communities common. LWD present and captures/retain sediments.
	4	
	3	Over bank flows occur during extreme tides and occupy a fragmented floodplain due to land use practices. Natural floodplain plant communities present but competing with exotic species. LWD present but not abundant. Channel armoring occurs in some areas. Off-channel habitat approximately 50% disconnected.
	2	
	1	Over bank flows do not occur during extreme tides, channel not connected to floodplain. River is confined. Channel armoring occurs. Erosion common and channel is incised. Off-channel habitats rare or absent.
Water Quality/Hydrologic Connection	5	Functioning properly, no impairment, has hydrologic connection.
	4	
	3	Functioning with partial impairment, losing hydrologic connections and often isolated.
	2	
	1	Not functioning properly, impaired, current land use negatively influencing water quality, poor or no hydrologic connection.

Table 7. Non-tidal Ecosystem Matrix

Parameter	Rating	Definitions
Spawning Habitat for Anadromous Salmonids	5	Excellent cover, depth, velocity, and gravel composition.
	4	Very good cover, depth, velocity, and gravel composition.
	3	Good habitat is present but limited conditions.
	2	Fair to marginal conditions.
	1	Poor conditions, little or no habitat.
Fish Passage	5	Localized habitat fully accessible to fish species for all life histories at all times of the year, as appropriate to geomorphic setting.
	4	
	3	Localized habitat accessible to fish species for all life histories during most of the year, but may be inaccessible seasonally or periodically to fish species due to constraints.
	2	
	1	Localized habitat not accessible to fish species.
Wetlands	5	Wetlands present as expected for geomorphic setting. Community structure dominated by native species. Wetlands fully connected to hydrologic sources and unconstrained in providing expected functions (includes flood storage, sediment detention, groundwater recharge/discharge, nutrient detention, habitat for fish and wildlife species, native plant richness, primary production/organic export).
	4	
	3	Wetlands present as expected for geomorphic setting. Community structure dominated by native and non-native species. Wetlands losing or lost hydrologic connections and often isolated from providing expected functions.
	2	
	1	Wetlands not present due to past/current land use practices (i.e., filling, draining).
Ecosystem Function	5	Aquatic and terrestrial habitat highly diverse. Off-channel habitat areas, if present, are accessible at most or all flows. LWD abundant. Riparian and floodplain areas provide a diverse mix of habitat types and local habitat is well connected to upstream and downstream areas.
	4	
	3	Aquatic and terrestrial habitats of moderate to low diversity. LWD present, but infrequent. Off-channel habitat areas, if present at site, have low flow or other passage difficulties. Riparian and floodplain habitats still function, but are disturbed and/or fragmented. Local habitat partially fragmented from adjacent upstream and downstream habitats by roads/bridges or other land use practices
	2	
	1	Aquatic and terrestrial habitats not diverse. One aquatic habitat type dominant. LWD and off-channel habitats absent. Riparian vegetation limited and dominated by non-native species. Overbank flows rarely occur (flows~100 yr.). Local habitat does not provide a migratory link between upstream and downstream habitats.

Table 7. Non-tidal Ecosystem Matrix (continued)

Parameter	Rating	Definitions
Floodplain Function	5	Over bank flows occur at 2-yr. flow event and occupy the floodplain. River freely migrates in its floodplain, channel armoring rare, off-channel habitats abundant as appropriate to geomorphic setting. Natural floodplain plant communities common. LWD present and captures/retain sediments.
	4	
	3	Over bank flows occur at >5- to 10-yr. flow events. Channel armoring occurs in some areas. Natural floodplain plant communities present but competing with exotic species. LWD present but not abundant. River is disconnected from 50% of its former off-channel areas. Channel migration significantly reduced.
	2	
	1	Over bank flows restricted to ~100-yr. flow event. Channel not connected to floodplain. Off-channel habitats rare or absent. River is confined, does not meander. Channel armoring occurs. Erosion common and channel is incised.
Water Quality/Hydrologic Connection	5	Functioning properly, no impairment, has hydrologic connection.
	4	
	3	Functioning with partial impairment, losing hydrologic connections and often isolated.
	2	
	1	Not functioning properly, impaired, current land use negatively influencing water quality, poor or no hydrologic connection.

Table 8. Matrix Score Sheet

Parameter	Hall Slough		Dougherty Slough		Modified Wetland Acquisition	
	Existing Score	Post-project Score	Existing Score	Post-project Score	Existing Score	Post-project Score
Fish Passage	2	4	5	5	2	5
Tidal Wetland/ Salt Marsh	2	4	2	4	2	4
Ecosystem Function	2	3	2	4	2.5	5
Floodplain Function	1	3	1	4	1	4
Water Quality/ Hydrologic Connection	1	4	1	3	1	4
Total Score	8	18	11	20	8.5	22

5. ECONOMIC ANALYSIS

Only limited economic screening was done during the feasibility study. Several iterations of alternatives were considered with the sponsor and the Feasibility Study Advisory Council. In the spring of 2002, preliminary discussions focused on the need to screen potential alternatives. One of the considerations important to the sponsor was the potential for flood reduction benefits in each of the alternative areas.

Previous Corps' flood reduction studies in the Tillamook area did not result in economically justified federal projects. While the local area recognizes that there are serious flood problems in Tillamook, it is more difficult to realize that there are difficulties in implementing alternatives that significantly reduce flood damages from the types of flooding experienced. There has been continued development in flood prone areas, as well as a general policy of no net loss of agricultural land for cattle grazing. In some cases, a potential solution in one area causes flooding in another area. In other cases, an alternative may reduce flooding from nuisance flood events, but then larger flood events overcome its potential to make much difference and flooding problems continue. To some degree, land availability was a constraint on workable alternatives, as well as the potential operation and maintenance costs that the sponsor would be responsible for in the event that long-term sedimentation was an issue.

Given the difficulty in finding a flood reduction alternative that could be economically justified, it was determined in the project study plan to look at ecosystem restoration as the initial benefit, because it would likely be necessary to economically justify alternatives based on ecosystem restoration, with incidental flood reduction benefits. After this initial evaluation, the potential to add an additional increment for flood reduction could be evaluated to determine if it showed a positive benefit-to-cost ratio, based on Corps' National Economic Development criteria.

During the initial screening process, the study team looked at the alternative areas that appeared to have the highest potential for flood reduction benefits, as requested by the sponsor. Discussions focused on the lower Trask River, lower Trask and the Old Trask Rivers, Hall Slough, the lower Wilson River, and Dougherty Slough. A preliminary assessment of areas that may benefit from reduced flooding was made, so that an initial number of properties (residences, commercial properties, farms/barns/homes, and farm land acreage) could be estimated.

The initial MIKE11 modeling effort showed an approximate frequency up to which potential flood reduction measures could make a difference in damages. Based on the preliminary estimates of numbers of properties, average inundation depths, frequencies, average values, and associated types of damage functions, estimates of the potential for flood reduction benefits were made by the study team.

In conjunction with the preliminary assessment of flood reduction benefits, an initial assessment was made of the potential for realizing environmental outputs given the general magnitude of associated costs. The study team discussed the potential outputs and developed a spreadsheet for review with the sponsor, which showed the likelihood of alternatives that supported both ecosystem restoration and incidental flood reduction benefits. In April 2002, the following list of priority alternatives was provided to the sponsor. One list focused on the potential for flood damage reduction while the other list focused on ecosystem restoration.

Ecosystem Restoration	Flood Damage Reduction
Tomlinson Slough	Dougherty Slough (high)
Dougherty Slough	Hall Slough (high)
Boquist Creek	Trask River Alternatives (high)
Juno Creek	Wilson River (medium)
Hall Slough	
Nolan Slough	
Wilson River (depending on alternative specifics)	

In general, Hall Slough and Dougherty Slough were considered to have good opportunity to be justified based on ecosystem restoration, with incidental flood reduction benefits. Hall Slough was expected to reduce durations and reduce nuisance flooding north of Hall Slough to the Wilson River around Highway 101. Dougherty Slough was expected to reduce flooding near Highway 101 for nuisance floods. While both alternatives would have been evaluated based on ecosystem restoration, they also were expected to yield some incidental flood reduction benefit. To achieve more than incidental flood reduction for Dougherty Slough, it likely is necessary to increase channel capacity, which is unlikely to be economically justified.

6. REAL ESTATE ANALYSIS

The Real Estate Division provided general and technical input and support on real estate matters for the GI study. General study support included participation in site visits, study team and public meetings, coordination with local sponsor representatives, coordination with other team members to identify real property requirements for the alternatives, and evaluation of alternatives developed during the study.

Technical input and support included acquisition of real estate in-grants (rights-of-way) required for study purposes, and research and development of information related to real property ownership, zoning, and value for the study area. In coordination with the local sponsor, more than 30 'rights-of-entry for survey and exploration' were obtained from landowners in the study area to allow access to their property for field investigations, soil sampling and survey work. A permit was obtained from the U.S. Coast Guard to install, operate, and maintain a meteorological gauging station at the Coast Guard Station in Garibaldi. The gauging station permit allows for use of the site to gather tidal stage and wind data for study purposes. The temporary permit covered the period from July 1, 2000 through June 30, 2005. A lease agreement also was obtained from a private landowner (Gienger Farms, Inc.) to install, operate and maintain tide gauging equipment on the Wilson River to record river stage data for study purposes. The lease covered the period from January 1, 2001 through September 30, 2005.

As part of the study, real property ownership and valuation information was obtained from the Tillamook County Assessor's office for properties which would be affected by implementation of the alternatives identified for further study. Based on an assessment of the features and right-of-way requirements needed for implementation, a preliminary real estate cost/value estimate was prepared for each alternative.

7. PUBLIC INVOLVEMENT

In order to provide local public oversight for the feasibility study, a Feasibility Study Advisory Council was established and held its first meeting on May 17, 2000. Members of the public make up the Advisory Council, supported by public agency staff, all of whom were formally appointed by the Tillamook County Board of Commissioners. Formal meetings were held once a month for the purpose of analyzing and formulating policy recommendations and alternative proposals. Advisory Council members also functioned in focus groups dealing with the following aspects of the feasibility study.

- Public Involvement/Website
- Model Development/Oversight
- Historical Conditions
- Water Quality and Land Use Impacts
- Alternative Project Formulation
- Fish and Wildlife Habitat
- Budget/Fiscal Management

However, as the study progressed, these focus groups were combined into a larger Biological Focus Group, chaired by the Corps, and a Flood Damage Reduction Focus Group, chaired by the sponsor.

Numerous presentations were given by the Corps study team to the Advisory Council.

- November 20, 2001 – MIKE11 model presentation.
- March 27, 2002 – Geomorphologic analysis presentation.
- March 27, 2002 – Preliminary modeling results presentation.
- April 30, 2003 – Study status/modeling results presentation.
- September 24, 2003 – Continuing authorities program presentation.

A *Notice of Intent to prepare a Draft Environmental Impact Statement for the Tillamook Bay and Estuary Flood Damage Reduction and Ecosystem Restoration Project* appeared in the *Federal Register* on May 30, 2000 [65(104):34452-34453]. Two initial public scoping meetings were held on July 25, 2000 at the Tillamook County Courthouse. The Corps and Tillamook County discussed the work plan for the feasibility study, model development, and elements of the Environmental Impact Statement. The public was encouraged to provide comments on the scope of the Environmental Impact Statement.

Two public meetings also were held on July 25, 2002 at the Tillamook County Courthouse to discuss the status of the feasibility study, including development of the hydrodynamic model and potential alternatives being considered. At the public meetings held for the study, local citizens voiced concerns on several issues. The most significant issues are discussed below.

Issue: Dredging at the River Mouths

<u>Response</u>: The model analysis shows that dredging to increase the depth of the rivers has a less significant reduction on flood levels than increasing the width of the channels. It also is more localized in its effects. Also, dredging to increase channel depths is not expected to provide ecosystem benefits, unless it results in opening up an old slough or channel that has become disconnected from a river. Therefore, the project would have to be economically justified from a

flood damage reduction standpoint, which is not likely. In addition, even if it were economically justified, the sponsor would be required to provide funding for channel maintenance over the life of the project. Because of these reasons, dredging to deepen the channels was not considered a viable option in the feasibility study.

Issue: Increasing the Width of River Channels

Response: This would require willing landowners to provide some land that would cease to be available for current uses. There are local issues concerning the loss of grazing lands that could affect the amount of land available for a potential project. However, obtaining land for additional width is a key issue for providing both flood damage reduction and ecosystem restoration benefits.

Issue: Eliminating the Kilchis River from Further Consideration

Response: Modeling analysis showed that changes to the Kilchis River to reduce flows in Squeedunk Slough would not affect flood levels at the Highway 101 business district. In addition, the flood reduction benefits would be localized in the immediate area of the project. Because of these reasons, all potential measures on the Kilchis River were eliminated from further consideration in the feasibility study.

8. CONCLUSIONS AND RECOMMENDATION

8.1. SUMMARY AND CONCLUSIONS

- The Tillamook Bay and Estuary, Oregon, General Investigations study was authorized by a U.S. Senate Committee Resolution on June 5, 1997. The purpose of the study is to evaluate flood damage reduction and ecosystem restoration in the Tillamook Bay watershed in Tillamook County in northwestern Oregon.

- A Feasibility Cost Sharing Agreement was executed in July 1999 with Tillamook County Soil and Water Conservation District. Tillamook County requested to become the formal sponsor, which the District agreed to on February 17, 2000. A Feasibility Study Advisory Council was established to provide local public oversight for the study.

- Five major rivers enter into Tillamook Bay and the lower valleys of these rivers merge to form a broad alluvial plain to the east and south of the bay on which the City of Tillamook is located. Declared a federal disaster area because of the February 1996 flood, Tillamook County suffered over $53 million in damage, which is the equivalent of 148% of the county’s annual budget. The county suffered significant losses because of the disruption caused to U.S. Highway 101, the major north-south arterial along the Pacific Coast. The lower portions of the rivers overflow frequently because channel capacity is inadequate to handle heavy flows during severe rainstorms when combined with high tides.

- Designated as a significant tidal estuary in the National Estuary Program and a component of the Oregon Coastal Salmon Restoration Initiative (*Oregon Plan*), Tillamook Bay and its watershed are ecologically and economically valuable to the State of Oregon. An extensive analysis of the watershed was conducted under the National Estuary Program, which resulted in the identification of four goals that are consistent with the Corps’ study authority. These goals include: (1) restoration of critical habitat for salmonid species; (2) reduction of sedimentation for salmonid spawning and rearing habitat; (3) reduction of bacterial contamination; and (4) reduction of magnitude, frequency, and impact of flood events.

- Fifty-nine potential alternative measures were initially considered. During the process to prioritize and narrow the measures, the sponsor decided to support only those alternatives providing both ecosystem restoration and flood damage reduction benefits, as well as having overall public support. This reduced the number of alternative measures to 33. Further evaluation with an area of focus in and around the City of Tillamook, and based on engineering and biological evaluation, further reduced this number to 14 potential alternatives.

- A one-dimensional hydrodynamic model (MIKE11) of the five rivers in the study area was developed as the primary evaluation tool for screening the 14 potential alternatives. Preliminary model runs were performed to increase the understanding of the system and to aid in the process of prioritization and narrowing of alternatives.

- From the modeling results, it appeared that some of the potential alternatives would not provide many benefits for flood damage reduction. The sponsor decided that these alternatives would no longer be considered in the feasibility study. The Wetland Acquisition/Swale and Hall Slough alternatives remained for further evaluation because they had the greatest potential to provide both ecosystem restoration and flood reduction benefits.

- The Hall Slough alternative consists of reconnection of tidal flows in the historic slough, high flow flushing from the Wilson River, and setback levees with riparian plantings. It is a high priority ecosystem restoration action and would eliminate flooding in the Highway 101 business district up to approximately the 2-year flood event. Because the sponsor indicated that they do not have adequate funds for implementation at this time, the alternative was not developed further.

- The Wetland Acquisition/Swale alternative would restore tidal marsh/wetlands with actions to offset flood increases. It is a high priority ecosystem restoration action and would reduce flooding for lower flood events. However, the sponsor requested that remaining study funds focus on developing the Modified Wetland Acquisition alternative endorsed by the Tillamook Bay Habitat and Estuary Improvement District. The Modified Wetland Acquisition alternative meets ecosystem restoration requirements without causing an increase in flood elevations, meets the requirements of the sponsor, and is acceptable to the community. After initial evaluation and modeling, the sponsor requested that the Modified Wetland Acquisition alternative be transferred to either the Continuing Authorities Program or to Section 536 of the Water Resources Development Act of 2000 (Public Law 106-541) for further evaluation and implementation.

- This feasibility report describes the progression of the feasibility study and the activities completed to date. It provides a status of the potential alternatives evaluated, including initial modeling results and preliminary cost estimates. The feasibility report is the final response to the study authority.

8.2. RECOMMENDATION

I have given consideration to all significant aspects of this study in the overall public interest, including the environmental, social, and economic, and engineering aspects, and the requirements of the sponsor, Tillamook County.

I recommend that the Modified Wetland Acquisition alternative be transferred to either the Continuing Authorities Program or to Section 536 of the Water Resources Development Act of 2000 (Public Law 106-541) for further evaluation and implementation. This proposed alternative meets ecosystem restoration requirements without causing an increase in flood elevations, meets the requirements of the sponsor, and is supported by the community.

The recommendations contained herein reflect the information available at this time and current Departmental policies governing formulation of individual projects. They do not reflect program and budgeting priorities inherent in the formulation of national Civil Works construction program nor the perspective of higher review levels within the Executive Branch.

Date: ___________________

RICHARD W. HOBERNICHT
Colonel, EN
Commanding

US Army Corps
of Engineers ®
Portland District

Tillamook Bay and Estuary, Oregon
General Investigation Feasibility Report

APPENDIX A

Overview of Hydrologic Study and Model Development

Prepared by
U.S. Army Corps of Engineers
Portland District
CENWP-EC-HY

July 2004

APPENDIX A
Overview of Hydrologic Study and Model Development

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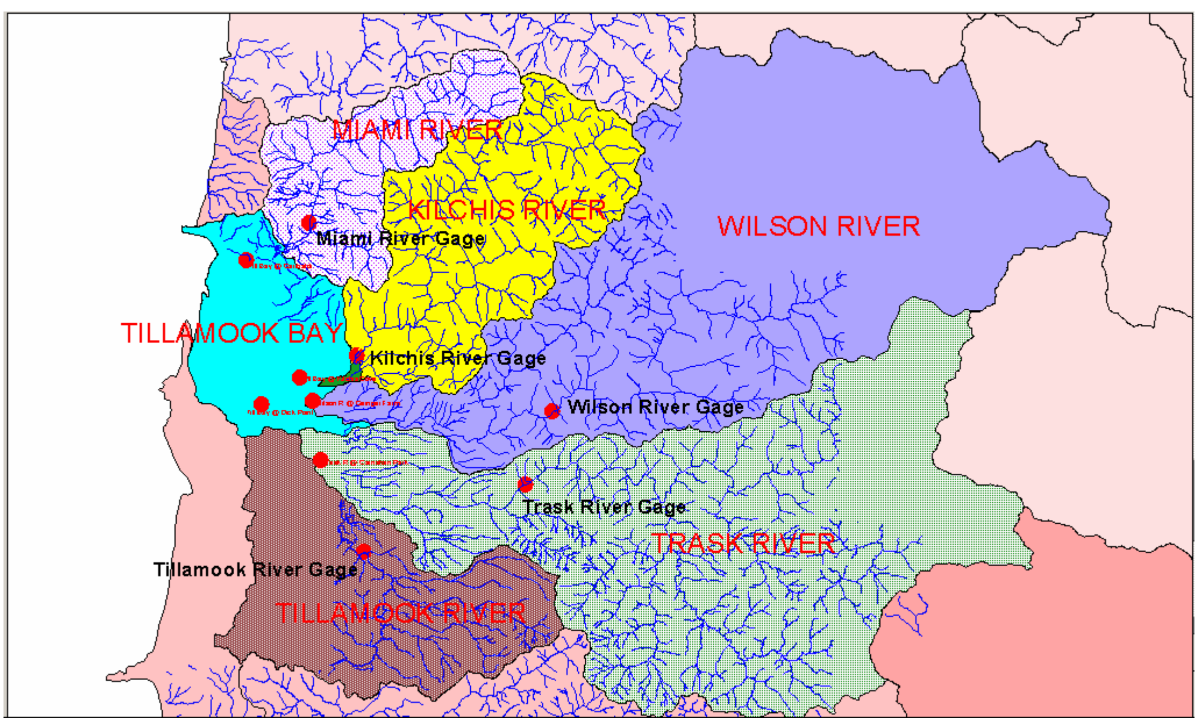
INTRODUCTION

Like many rivers along the northwest Oregon Coast, the rivers of Tillamook Bay represent a complex ecosystem of multiple channels exiting into a shallow bay. This General Investigation feasibility study involved studying the five rivers of Tillamook Bay as well as the bay itself to determine the nature of flooding and changes that have occurred over time that have altered the natural regime of ebb and flood in the area. Tillamook is a shallow bay with an average depth of 5.9 feet and an average tidal range of 5.6 feet. During ebb tide the bay becomes a virtual mudflat. The bay enters the Pacific Ocean through a single channel that has been modified by jetties and dredging at its northern end for navigation purposes.

The watershed surrounding Tillamook Bay is dominated by broad valleys along the coastal plain that abruptly rise to steep mountains of the Coast Range. Elevations vary from near sea level in the coastal lowlands to above 3,500 feet in the Coast Range. The majority of area of each watershed contributing to the bay is located within the coastal mountains. Dense forest covers much of the terrain, which overlies impermeable strata in the mountainous watershed. The majority of human settlement has taken place in the broad river valleys. The valley forests were stripped, wetlands were filled and levees were placed in the valleys for agricultural purposes around 150 years ago.

Tillamook Bay has five principle rivers – the Wilson, Trask, Tillamook, Kilchis, and Miami. The Wilson and Trask Rivers are the two largest rivers in the area and contribute to the majority of sedimentation and flooding in the bay. The Miami and Kilchis Rivers have similar watersheds and characteristics as the Wilson and Trask, but they are smaller and are located in sparsely populated areas. The Tillamook River is the odd river of the five with a low gradient relative to the other rivers and a watershed located along the coastal foothills. The Tillamook River contributes the least to flooding and erosion problems in the region. Four of the five rivers are concentrated at the southern end of the bay, while the Miami River flows into its northern end (Figure 1).

Figure 1. Five Watersheds of Tillamook Bay



The majority of settlement in the area occurred in and around the community of Tillamook. The City of Tillamook was founded in 1852 along a low-ridge separating the Trask and Wilson Rivers. The surrounding floodplains of the Tillamook, Trask and Wilson Rivers were developed for agriculture. As the area is rich in rainfall, grasses are plentiful and the Tillamook area has long been an excellent location for dairy products. Beyond the city lie numerous dairies throughout each of the five major river valleys.

For purposes of agriculture, the floodplains of the rivers have been diked, sloughs have been filled, and structures have restricted the historic movement of the river channels. In essence ties of floodplain to river channel have been separated in the river valleys of the area. A few major sloughs remain connected to their rivers including the Dougherty Slough to the Wilson River and Squeedunk Slough to the Kilchis River. Other sloughs in the area have generally lost their upstream tie to rivers and now are either stagnant or tidal sloughs.

The original boundary of this study included Tillamook Bay and its entire watershed. Upon evaluation of the area and discussions with the Oregon Department of Forestry (ODF), it became apparent that the upland forests could not be studied. First, it was too large of an area to perform any detailed analysis and secondly, ODF was not interested in participating as it was their contention that impetus for the study did not coincide with their interests. Furthermore, the original scope of work for this study included a hydrologic modeling effort of the watersheds of Tillamook Bay. However, ODF did not support the use of hydrologic models. It was determined that the majority of issues concerning flooding, salmon habitat, water quality, and sedimentation were focused on the developed floodplains on each of the five rivers. Therefore, the study was scoped based on evaluating the areas that include the lowland river valleys and coastal floodplains to Tillamook Bay.

Prior to this study, the most recent hydraulic modeling study of the Tillamook area was performed in late 1960s and early 1970s by the Corps and CH2M Hill in development of the Federal Emergency Management Agency's (FEMA) Flood Insurance Report for Tillamook County. This modeling utilized 2-foot topographic data and cross-sectional data gathered in 1965. The study evaluated the rivers with the one-dimensional, steady-state model HEC-2. As all the rivers of Tillamook Bay are tidally influenced, it was readily apparent that the only way to develop a good understanding of flood behavior in the area was to develop an unsteady flow model of the rivers of Tillamook Bay.

Initial scoping efforts for the study included the development of the Corps' one-dimensional, unsteady flow model UNET. However, during the scoping phase of the study, the Danish Hydraulic Institute was in the region promoting their unsteady flow model MIKE11. At the time, their model boasted the ability to create flood area maps and 'slideshows.' Also, their model was integrated in a system that allowed the user to incorporate multiple modeling modules such as sedimentation, water quality, and hydrologic models. The study sponsor, Tillamook County, was sold on the benefits of viewing flooded areas with the MIKE11 model. Therefore, it was initially decided to use the Danish Hydraulic Institute's MIKE11 model for this feasibility study.

However, later in the study a decision was made to convert the existing MIKE11 model to the Corps' HEC-RAS model. At the time the MIKE11 model was selected for use, it had a solid reputation, whereas not enough information was available for the HEC-RAS model. Since then, a newer version of the HEC-RAS model was developed, which is more sophisticated than MIKE11 and more capable of addressing the complex nature of flooding in the Tillamook area. The HEC-RAS is currently the most common river analysis model used. The HEC-RAS model will be able to serve the Tillamook study area in an easier and less expensive manner. WEST Consultants Inc., under contract by the Corps, performed the conversion of the MIKE11 model to HEC-RAS.

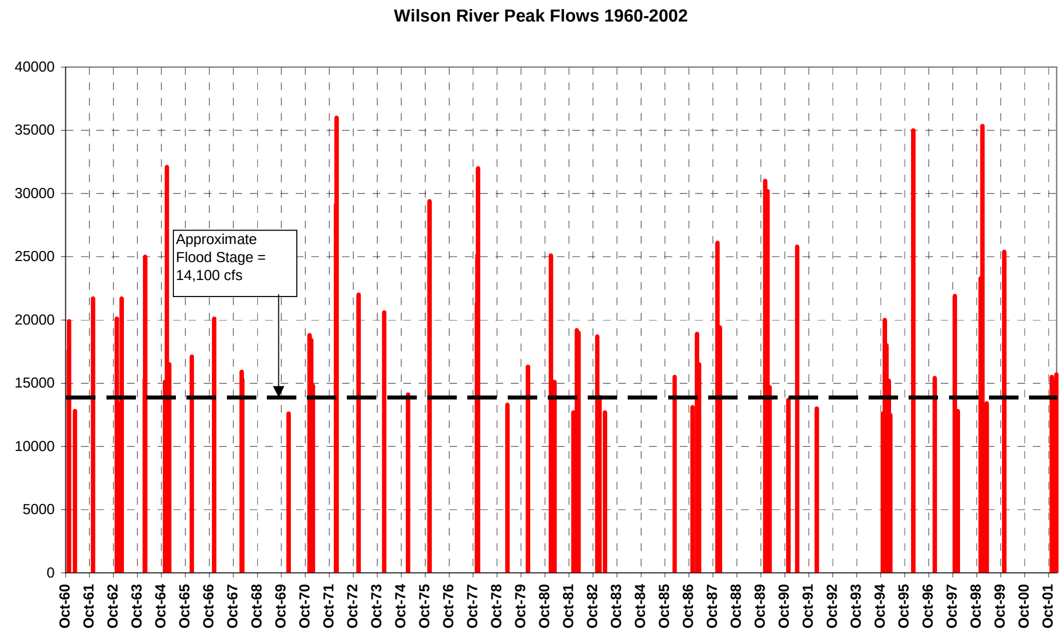
FLOODING IN THE TILLAMOOK REGION

Much of the impetus for this study lies in the flooding that has occurred in the valleys of the Tillamook Bay region, with the most severe flooding occurring in and around the City of Tillamook. The floods of February 1996 were region-wide and were especially devastating in the area. Flooding in the region occurs on a regular basis. The city lies along a ridge that separates the Wilson and the Trask Rivers. Just downstream of the City is Tillamook Bay. The Wilson and Trask Rivers are the two largest Rivers flowing into the bay; in turn, they produce the largest floods. The city itself largely remains flood free; however, newly developed areas to the north and south of the city experience flooding on a regular basis. The worst flooding occurs to the north of the city along Highway 101. This recently developed area lies in the direct path of floodwaters from the Wilson River. With elevations as low as 9 feet MLLW on Highway 101, it is apparent why flooding is so devastating to this area. Flood waters come from all sides, from the Wilson River, the Trask River, the Tillamook River, and from high tides and storm surges in Tillamook Bay. Other areas of Tillamook including along the Trask, Tillamook and Kilchis Rivers have been historically flooded as well.

The majority of lands in the area are operated as dairy farms and many of the historic dairies are located on high points throughout the area. Many dikes have been built around the area; however, only the Stillwell levee actually protects a large tract of land from being flooded. The Stillwell Levee was completed by the Corps in 1960 and protects a large farmed area that lies at the mouth of the Trask and Tillamook Rivers. The levee forces waters to flow around it through two narrow channels – the Trask and Tillamook Rivers. Floodwaters regularly overtop their banks upstream of the Stillwell levee and flood the area between the Trask and Tillamook Rivers as a result.

Lying between the Pacific Ocean and one of the wettest coastal mountain ranges in North America, the lowlands of Tillamook have always flooded and will continue to flood. As shown in Figure 2, the Wilson River has reached flood stage (approximately 14,100 cfs) numerous times over the past 32 years. In fact, the Wilson has exceeded flood stage approximately 60 times, averaging to almost two floods per year in the recent past.

Figure 2. Peaks for Recent Floods on the Wilson River (in cfs)



TILLAMOOK AREA HYDROLOGY

The Tillamook area is hydrologically active. Located on the Northwest Coast of the United States, Tillamook lies in the direct path of the north pacific jet stream. Storms come off the Pacific Ocean and encounter the Coast Range immediately east of the coast. As the storms rise over the coastal mountains, they release significant amounts of precipitation. With locations at the top of the Coast Range receiving over 200 inches of precipitation per year, this is one of the wettest locations in North America. Most of the precipitation falls as rain and most falls between the months of October and March. Locations in the lowland valleys receive significant rainfall as well, averaging approximately 100-inches per year. With all the rainfall come large amounts of runoff. It is fairly normal for the Wilson River to rise 10,000 cfs in a matter of hours during winter storm events.

The Tillamook region has very few long-term precipitation gauges. A precipitation gauge at the local radio station has been in operation since 1948, and another gauge near the Nehalem River has been operated since 1948. Other precipitation gauges have been in operation on a sporadic basis. Stream gauges also have been operated on a sporadic basis.

Discharge-frequency Relationships

Wilson River

The Wilson River has a drainage area of 161 square miles at its gauged location an additional 30 square miles of area joins the Wilson River on its way to Tillamook Bay. Therefore, approximately 84% of the drainage area is gauged. The North Fork of the Wilson River enters the Wilson River at river mile (RM) 8.61 and represents approximately 66% of the remaining 30 square miles of ungauged tributary area.

Using the Corps' HEC-FFA (flood flow frequency model), the following discharge-frequency relationship was computed for the Wilson River (Figure 3). The frequency curve contains 71 years of peak flood values ranging from a peak value of 36,000 cfs in 1972 to 3,665 cfs in 2001. Utilizing current Corps' regulations, values used for this study rely on expected probability of occurrence.

Historic computations of discharge-frequency on the Wilson River include the U.S. Geological Survey (USGS) report of 1993 documenting statistical summaries of gauges in Oregon. Other historic computations include the Tillamook County FEMA Flood Insurance Study of 1978 that was recently updated for the lower Wilson River in 2000. Table 1 summarizes peak discharge values from the two historic studies in comparison with this study.

Table 1. Wilson River near Tillamook, Oregon - Annual Peak Discharge-frequency Values from Historic Studies

Study/Date	**Discharge in cfs for Indicated Annual Percent Chance of Exceedance**				
	50%	**10%**	**2%**	**1%**	**0.2%**
Corps/2002 p.o.r. 1932-2002	17,700	27,800	36,100	39,400	47,200
USGS/1993 p.o.r. 1915-1987	17,200	26,300	33,100	35,800	NA
FEMA (CH2M Hill)/1978 p.o.r. 1932-1976	NA	25,000	33,000	36,300	43,500

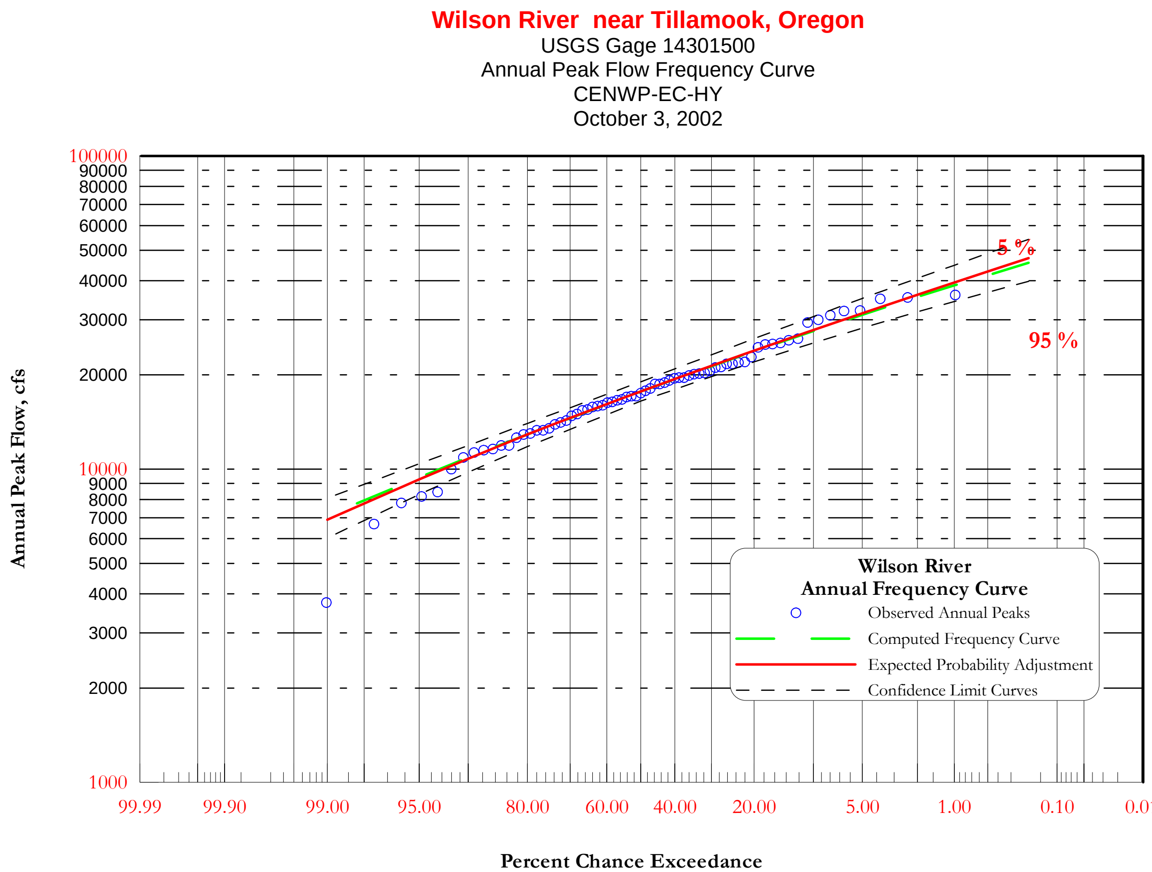


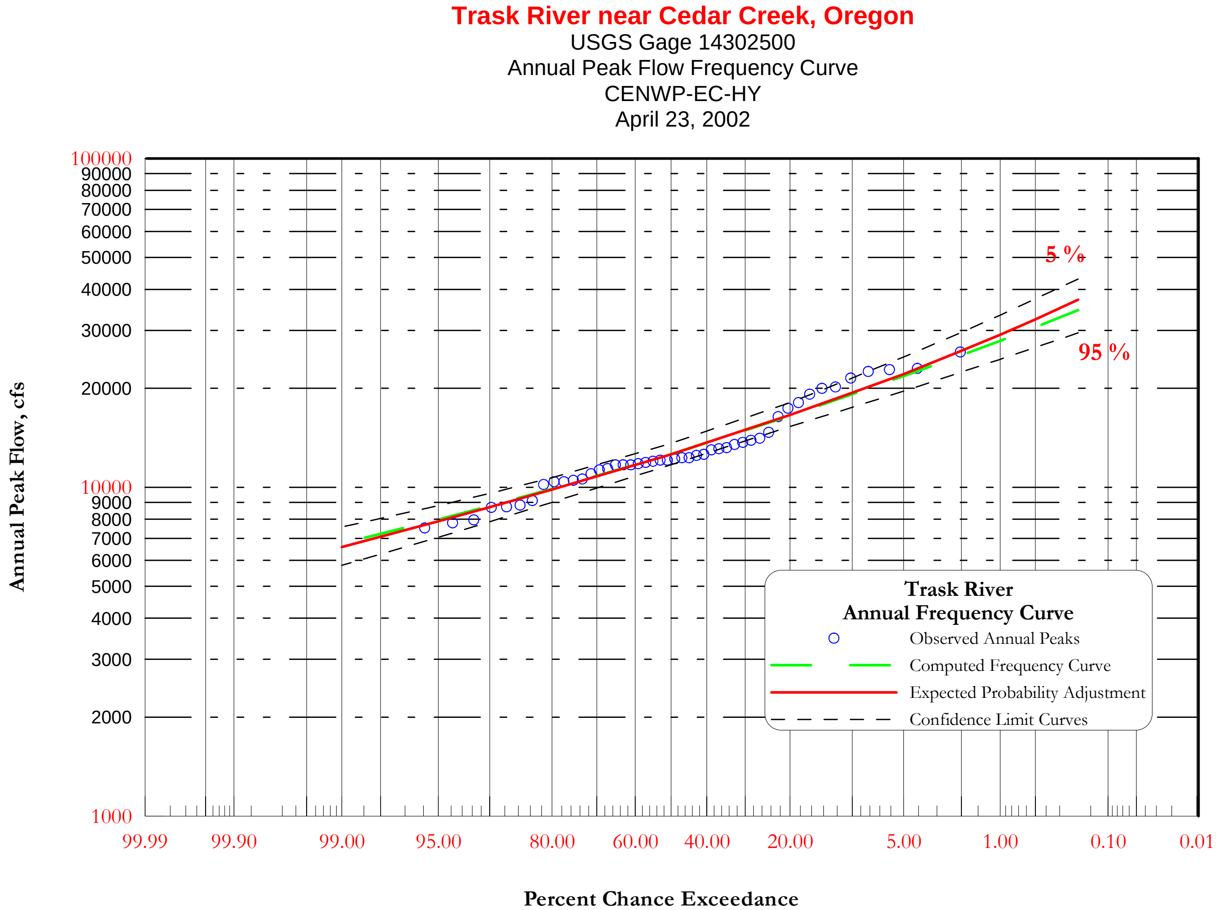
Figure 3. Wilson River near Tillamook, Oregon Peak Discharge-frequency Relationship

Trask River

The Trask River has a drainage area of 145 square miles at its gauged location with an additional 14 square miles of area that joins the Trask River on its way to Tillamook Bay. Therefore, approximately 91% of the drainage area is gauged. No major tributaries enter the Trask River below the gauge, only minor tributaries.

Using the Corps' program HEC-FFA, the following discharge-frequency relationship was computed for the Trask River (Figure 4). The frequency curve contains 48 years of peak flood values ranging from a peak value of 25,800 cfs in 1996 (est.) to 2,520 cfs in 2001.

Figure 4. Trask River near Cedar Creek, Oregon Peak Discharge-frequency Relationship



Historic computations of discharge-frequency on the Trask River include the USGS Report of 1993 documenting statistical summaries of gauges in Oregon. Other historic computations include the 1978 Tillamook County FEMA Flood Insurance Study. Table 2 summarizes peak discharge values from the two historic studies in comparison with this study.

Table 2. Trask River near Cedar Creek, Oregon - Annual Peak Discharge-frequency Values from Historic Studies

Study/Date	**Discharge in cfs for Indicated Annual Percent Chance of Exceedance**				
	50%	**10%**	**2%**	**1%**	**0.2%**
USACE/2002 p.o.r. 1932-1972, 1996-2002	12,600	19,400	26,000	29,100	37,200
USGS/1993 p.o.r. 1922-1972	12,600	19,300	25,800	28,800	NA
FEMA (CH2M Hill)/1978 p.o.r. 1932-1972	NA	19,000	24,700	27,400	33,100

Tillamook River

The Tillamook River has a drainage area of approximately 60 square miles at its downstream terminus into Tillamook Bay. The watershed of the Tillamook River differs from the other four major rivers of the bay in that its origins arise in the lowland coastal foothills and valleys paralleling the coast rather than from the steep Coast Range. Therefore, orographic effects on the watershed are less pronounced than the other four rivers resulting in a lower flood peak to drainage area ratio. Also, there is much less historic hydrologic data for the watershed than other watersheds in the region. The river has had a few periods of gauging including 1973-1977, 1995-1998, and February 2001 to the present. All gauging has been performed by the Oregon Water Resources Department (OWRD) and the latter period of gauging was funded for this feasibility study. With only 8 years of non-continuous record, it is difficult to produce a discharge-frequency curve for this river for any event larger than possibly a 10% chance of exceedance. Table 3 shows the Tillamook River discharge-frequency values from the 1978 FEMA Flood Insurance Study of Tillamook County. These values are based on the USGS Regional flood frequency method. Further analysis was not performed for this river during this feasibility study.

An estimate of the flow for the Tillamook November 1999 flood event was required since no data was recorded on the Tillamook River during this time. Comparisons were made between the peak flows on the Wilson, Trask, and Tillamook Rivers when they occurred for the same event between November 1995 and November 1998 (see Appendix B, *Hydraulic Modeling for the Tillamook Bay and Estuary Study*, prepared by WEST Consultants, Inc.). The Tillamook River was approximated as 18% of the Wilson River flow for the November 1999 event based on this analysis.

Table 3. Tillamook River at Old Trask Confluence - Annual Peak Discharge-frequency values from 1978 FEMA Study

Study/Date	**Discharge in cfs for Indicated Annual Percent Chance of Exceedance**				
	50%	**10%**	**2%**	**1%**	**0.2%**
FEMA (CH2M Hill)/1978	NA	7,170	9,730	10,800	13,400

Kilchis River

The Kilchis River has a drainage area of approximately 67.3 square miles at its terminus in Tillamook Bay. The watershed of the Kilchis River is similar to that of the Wilson River in that it is dominated by the Coast Range, which is steep forested terrain with shallow soils over impermeable strata. Orographic characteristics of the watershed lead to steep hydrographs with relatively large peak flows during winter rain events. Little gauging has been performed on this river. The OWRD began gauging the river in 1995 and continued this gauge until 1998, whereupon funding was cut and the gauge became idle. At the onset of this feasibility study, it was apparent that better streamflow data would be necessary to model this river. Therefore, the OWRD was funded to continue gauging on the Kilchis River. Gauging began in the spring of 2001 and continued for 2 years until the spring of 2003. The intention of the additional gauging was to capture large storm events to analyze the watershed's response to those events and utilize the information as a boundary condition in the hydrodynamic model. With only 4 years of gauging data, it is difficult to develop statistical relationships for this river beyond the 10%-50% chance of exceedance. The flood of 1996 approximately represented a 2% chance of exceedance event on the Wilson River, and the peak flow on the Kilchis River for this event was approximately 15,971 cfs. Based on the inherent locations and geology of the two watersheds, it was assumed that they behave very similarly. Also, looking at the estimates of discharge-frequency from the 1978 FEMA Flood Insurance Study, their estimate of 13,895 cfs for the 50-year event on this river is approximately 14% less than the peak of 1996, while the Wilson peak from their estimate (35,000 versus 33,000 cfs) also was underestimated. Therefore, it was assumed that 16,000 cfs approximately represents the 2% chance of exceedance for the Kilchis River. From this preliminary analysis, it appeared that the expected probability of the Wilson and Kilchis Rivers are linearly related; Table 4 shows the resulting exceedance probability statistics as compared to the 1978 FEMA study.

Table 4. Kilchis River near Tillamook, Oregon - Annual Peak Discharge-frequency Values from Historic Studies

Study/Date	**Discharge in cfs for Indicated Annual Percent Chance of Exceedance**				
	50%	**10%**	**2%**	**1%**	**0.2%**
USACE/2002 (based on 0.457*Wilson Peak)	8,100	12,700	16,500	18,000	21,600
FEMA (CH2M Hill)/1978 (estimated)	NA	10,240	13,895	15,360	18,965

Miami River

The Miami River has a drainage area of 36.4 square miles at its terminus with Tillamook Bay. Much like the Kilchis, Wilson, and Trask Rivers to the south, the Miami has its origins in the mountainous Coast Range and responds quickly to intense precipitation and often producing steep hydrographs with significant peak flows relative to the size of its watershed. The Miami River has been gauged near Moss Creek by the OWRD intermittently since 1975. Although a significant amount of gauge data exists, the Corps was only able to obtain data from the OWRD for the years 1995-1998 and 1999-2002. With only 7 years of data, it was difficult to develop sufficient discharge-frequency relationships beyond the 10-year event. During the period 1995-2002, the largest event occurred on February 7, 1996 with a recorded flow of approximately 9,900 cfs. However, this reading is suspect because the gauge was washed out during this flood. Other large floods of note during the period include the November 1999 flood where the gauge recorded a peak flow of approximately 5,600 cfs. Another large flow of 6,200 cfs occurred in November 1995. Discharge-frequency curves were not developed for this gauge. Table 5 shows the Tillamook River discharge-frequency values (based on USGS regional methods) from the 1978 FEMA Flood Insurance Study.

Table 5. Miami River at Mouth of Miami Cove – Annual Peak Discharge-frequency Values from 1978 FEMA Study

Study/Date	**Discharge in cfs for Indicated Annual Percent Chance of Exceedance**				
	50%	**10%**	**2%**	**1%**	**0.2%**
FEMA (CH2M Hill)/1978	NA	5,650	7,220	7,900	9,400

MIKE11 MODEL

The MIKE11 model is a one-dimensional, unsteady flow model developed by the Danish Hydraulic Institute. The hydrodynamic model solves the Saint Venant equations for fluid momentum and continuity by a finite difference scheme utilizing an alternating grid. Thus, at each point in the model grid, the model solves for either stage (H) or flow (Q) on an alternating basis. The model also is able to solve general hydraulic equations for hydraulic structures as internal boundary conditions such as weirs and culverts. Basic input to the model includes river cross-sections, structural geometries and geographical networks. It utilizes branches to model rivers and floodplains that consist of nodes (points along the branch) with corresponding cross-sectional dimensions. As with all unsteady flow models, it requires a boundary condition at all upstream branches and downstream branches of a model network. In the case of Tillamook, flow gauges were utilized at all upstream ends of the five rivers and the downstream boundary consisted of tidal conditions in Tillamook Bay.

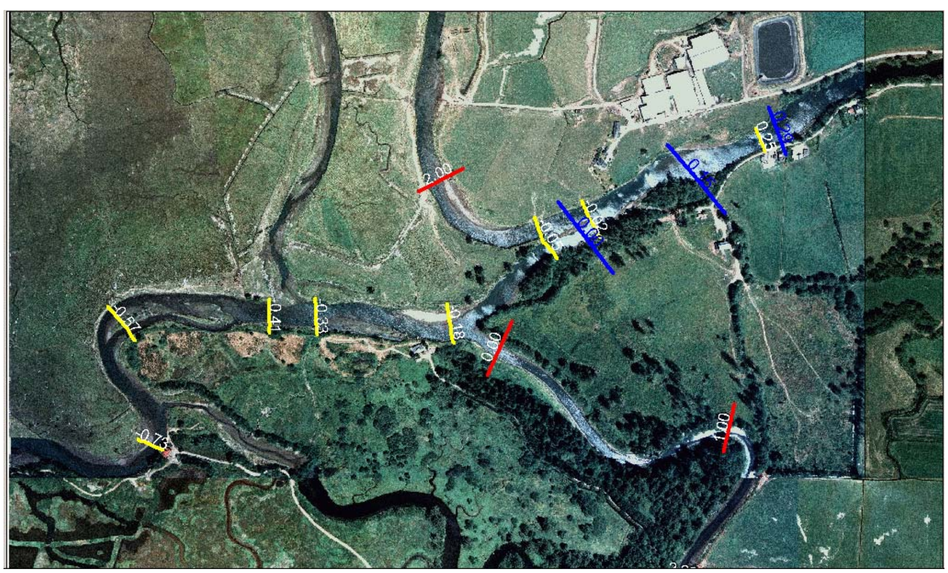
Tillamook Area MIKE11 Model Overview

Geometric Data Collection

River Cross-sections

The MIKE11 modeling of the rivers of Tillamook Bay for this feasibility study included a vast database of nearly 300 physical river cross-sections. Cross-sections for the base hydraulic model of the rivers in the Tillamook area were laid out initially in the summer of 1999 by the Corps. Cross-sections were laid out based on hydraulic properties of the channel including channel junctions, expansions and contractions. Cross-sections were laid out at approximately each 0.25-river mile along the Wilson, Trask, Old Trask, Tillamook, Kilchis and Miami Rivers, as well as several in Dougherty, Hall and Hoquarten Sloughs (Figure 5). Four sections were surveyed at all area bridges to account for bridge hydraulics. The vast majority of cross-sections were surveyed by the Tillamook County Surveyors Office in the summer and fall of 2000. Surveys were performed utilizing GPS techniques, which were later archived in a GIS database for visualization and spatial placement. A mapping study of the Lower Wilson River including Hoquarten and Dougherty Sloughs was performed by FEMA in 1999. Cross-sections from that study were used on Hoquarten Slough, Dougherty Slough and the Wilson River from RM 0.0 to approximately RM 5.0. Supplemental cross-sections were gathered by the Corps from 2000-2001 utilizing GPS techniques for several areas including Hall Slough, the Lower Wilson River, the Kilchis River and Dougherty Slough.

Figure 5. Example of River Cross-sections at the Mouth of the Wilson River



Floodplain Mapping

The Corps performed floodplain mapping of the lower river floodplain areas to be modeled for this feasibility study. Floodplain mapping was performed utilizing aerial photogrammetric techniques. Aerial photographs of the area were made in September 1999 with some re-flight of the lower Wilson, Tillamook and Trask Rivers in March 2000. Mapping of the resulting aerial photographs was performed to a two-foot contour level of accuracy (accurate to ± 1 foot.) From the ortho-rectified mapping, three-dimensional points were extracted. Three-dimensional (x-y-z) points formed the backbone of the mapping. Within a Geographical Information System (GIS) the three-dimensional points were triangulated. Triangulation of the three-dimensional points resulted in a triangulated irregular network (TIN) of the floodplain areas to be modeled. The resulting TINs were utilized for cutting of floodplain cross-sections, measuring of volumes, mapping contours, and visualizing flooded areas. Figure 6 shows the process used to create floodplain mapping for this study.

River Structures

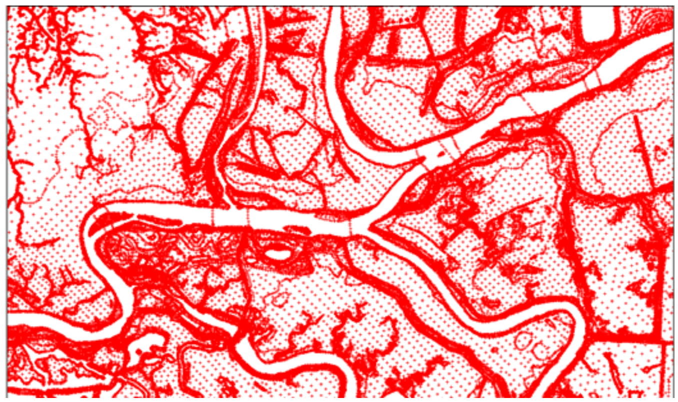
River structures for this study include bridges, culverts, levees and tidegates. Bridges were surveyed by the Tillamook County Surveyors office (river cross-sections) and by the Corps. Generally, four cross-sections were obtained at each bridge: one upstream of the bridge at the river's unobstructed contraction point; one at the upstream face of the bridge; one at the downstream face of the bridge; and one located downstream of the bridge at the river's fully expanded flow point. Other information about each bridge including its hydraulic properties was obtained by the Corps from field survey, photographs, and previous studies.

Because all area rivers are tidally influenced, there are many tidal dikes in the region to control tide waters from inundating the floodplain. Dike dimensions including elevations were derived from the floodplain mapping TINs previously discussed. This methodology was acceptable in most instances. However, several dikes had thick vegetation on and/or around them. In these locations, aerial mapping was not accurate. Several tidal dikes appeared to flood in normal tidal conditions. Dikes were raised to a reasonable level based on local channel cross-section information and tidal heights.

Interior drainage in the Tillamook region is provided by hundreds of tide-gated culverts throughout the lower river system. Because there are so many private culverts, it was impossible to survey them all for this study. The Tillamook County Watershed Council in cooperation with the National Estuary Project at Tillamook Bay had recently completed a cursory inventory of all the culverts of the area. Data for each culvert included their size and if the culvert was tide-gated or open. This data was used to develop the initial models. Other necessary data for each culvert included its elevation, length, Manning's roughness and entrance properties. Some culvert lengths were listed in the Tillamook County report, while others were estimated based on the floodplain mapping. Most elevations of culverts were estimated from floodplain mapping. In some instances, culvert data was too important to estimate. At those locations, a local contractor (Nehalem Marine) was hired to survey approximately 20 culverts. Other data was gathered from Nehalem Marine's records of recent culvert replacement and installations.

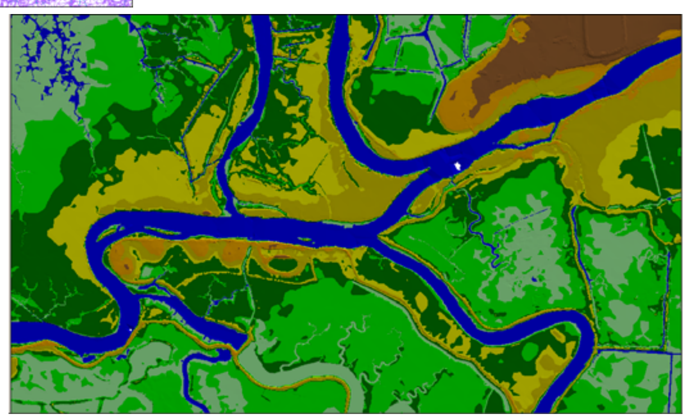
Figure 6. Diagram of Floodplain Mapping for Tillamook, Oregon

From the aerial photography, three-dimensional points were extracted.



From the three-dimensional points, a TIN was created.

From the TIN, a three-dimensional picture of the floodplain was created.



Boundary Condition Data Collection

Boundary data refers to hydrologic data that is necessary throughout the hydraulic model at each point within the model that is either an end to a reach, a beginning of a reach or a source or sink of water within a reach. For each major river in the study area, a boundary condition was necessary at the upstream end of the river and at the downstream end of the river. For the major rivers in the Tillamook models, stream flows were used as upstream boundaries and tidal elevations of Tillamook Bay were used as downstream conditions. Boundary conditions were estimated based on existing gauge data as well as gauges installed specifically for this study. Tables 6 and 7 show the existing and historic stream and tide gauges in the Tillamook region.

Table 6. Historic Stream Gauges in the Tillamook Region

Stream	River Mile	Period of Record	Agency	Parameters
Miami River	1.7	1975-2003	OWRD	h, Q, temp
Kilchis River	3.0	1995-1998, 2000-2002	OWRD	h, Q, temp, WQ
Wilson River	11.5	1931-2003	USGS	h, Q
Trask River	11.0	1932-1956, 1962-1972	USGS	h, Q
Trask River	10.95	1996-2003	USGS	h, Q
Tillamook River	6.90	1973-1977, 1995-1998, 2000-2002	OWRD	h, Q, temp
Killam Creek	2.1	1975-2002	OWRD	h, Q

Note: h = gauge height, Q = discharge, temp = water temperature, WQ = water quality (parameters vary)

Table 7. Historic Tide Gauges in the Tillamook Region

Location	Period of Record	Agency	Parameters
Astoria	1925-Present	NOAA/NOS	h
Garibaldi	1970-1981	NOAA/NOS	h
Yaquina	1967-2004	NOAA/NOS	h
North Jetty	1970	Corps	h
Kincheloe Point	1970	Corps	h
Bay City	1970	Corps	h
Dick Point	1970	Corps	h

Note: h = gauge height; NOS = National Ocean Service

The USGS stream gauge on the Wilson River, which has been in operation for over 72 years, has the longest period of record of all the gauges in the Tillamook region. Another stream gauge in operation for many years is on the Trask River, also operated by the USGS. This gauge was removed in 1972 and replaced with a nearby gauge after the flood of 1996. Thus, many of the more recent large flood events were not captured on the Trask River, giving a less reliable flow-frequency relationship than that of the Wilson River. Stream gauges on the smaller rivers have been operated sporadically by the OWRD, except for the gauge on the Miami River which has been maintained for 28 years. Stream gauging on the Kilchis and Tillamook Rivers has been more sporadic. For the last 8 years, a gauging program was initially funded by the Tillamook Bay National Estuary Project on the Tillamook and Kilchis Rivers. Funding for these two gauges was exhausted in 1998; this study funded operation of those two gauges for the past 2 years of data collection.

Streamflow boundary conditions for upstream reaches were either used directly from these gauges for historic events or estimated from gauge data. Upstream boundary conditions for the MIKE11 model included the USGS gauges on the Wilson and Trask Rivers and the OWRD gauges on the Kilchis, Miami and Tillamook Rivers. Tillamook Bay is the downstream boundary for all five rivers in the study area. The Pacific Ocean controls the stages in Tillamook Bay with its jettied connection at its northern entrance. The only long-term record for Tillamook Bay stages was collected at Garibaldi between 1970 and 1981 by NOAA. During 1970, a physical modeling study was completed for Tillamook Bay by the Corps' Waterways Experiment Station (WES) that included placement of four tidal gauges in Tillamook Bay for model calibration. Gauges were placed at the North Jetty, Kincheloe Point, Bay City and Dick Point to determine tidal elevations throughout the bay.

Recent sedimentation in Tillamook Bay created an uncertainty as to tidal elevations throughout the bay. Therefore, a gauging program was established as part of this study. Purchase and placement of tidal gauges in Tillamook Bay was performed through cooperation between the Corps and Tillamook County. Gauges were placed at five locations throughout the bay during the spring of 2001. A fully automated (i.e. satellite telemeter) gauge was placed at Garibaldi at the U.S. Coast Guard boat house in March 2001. This gauge has been in operation since installation and records tidal stage in feet MLLW every 15 minutes. Data for this gauge is stored in the Corps' Columbia River Operational Hydrometerological System (CROHMS) database under the name 'TLBO.'

Recording gauges also were placed at various locations in Tillamook Bay for model boundary conditions and calibration (Table 8). This gauge data is physically downloaded and stored by the Corps. Gauges were located at or near river mouths to get a better understanding of tidal forcing conditions. All gauges measure tidal stage in feet using the North American Vertical Datum of 1988 (NAVD88) and water temperature every 15 minutes.

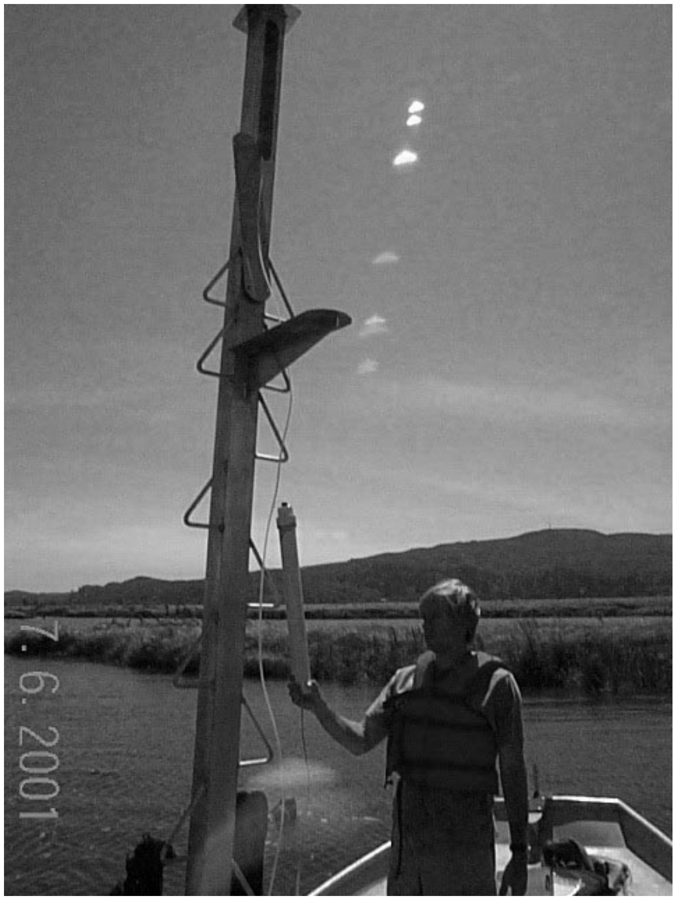
The Tillamook Bay at Garibaldi gauge was determined to be close enough to the mouth of the Miami River to not necessitate placing another gauge there. For the Kilchis River, a gauge was placed near the Kilchis River mouth at Kilchis Cove in April of 2001 (Figure 7). This gauge is a logging device that is located on a piling. The gauge is only accessible by boat. For the Wilson River, a logging gauge was placed in the river just before it splits into three branches at its mouth at approximately RM 0.30. This gauge is located on the right river bank on private property (Gienger Farms Inc.), which is leased by the Corps for gauging purposes. For the Trask River, a logging gauge was placed near its mouth at a boat dock at Carnahan Park near RM 1.2. The gauge is located on a pier of the boat dock and is accessible by car through the park. For the Tillamook River, a logging gauge was placed near its mouth in Tillamook Bay at Dick Point. The gauge is located on a pier at the same location as the gauge placed in 1970 in Tillamook Bay, and is only accessible by boat.

Table 8. Stage-recording Gauges Installed by the Corps

Location	Period of Record	Parameters
Tillamook Bay at Dick Point	2000-2003	h, temp
Tillamook Bay at Garibaldi	2000-2003	h
Tillamook Bay at Kilchis Cove	2000-2003	h, temp
Wilson River at Gienger Farm	2000-2003	h, temp
Trask River at Carnahan Park	2000-2003	h, temp

Note: h = gauge height, temp = water temperature

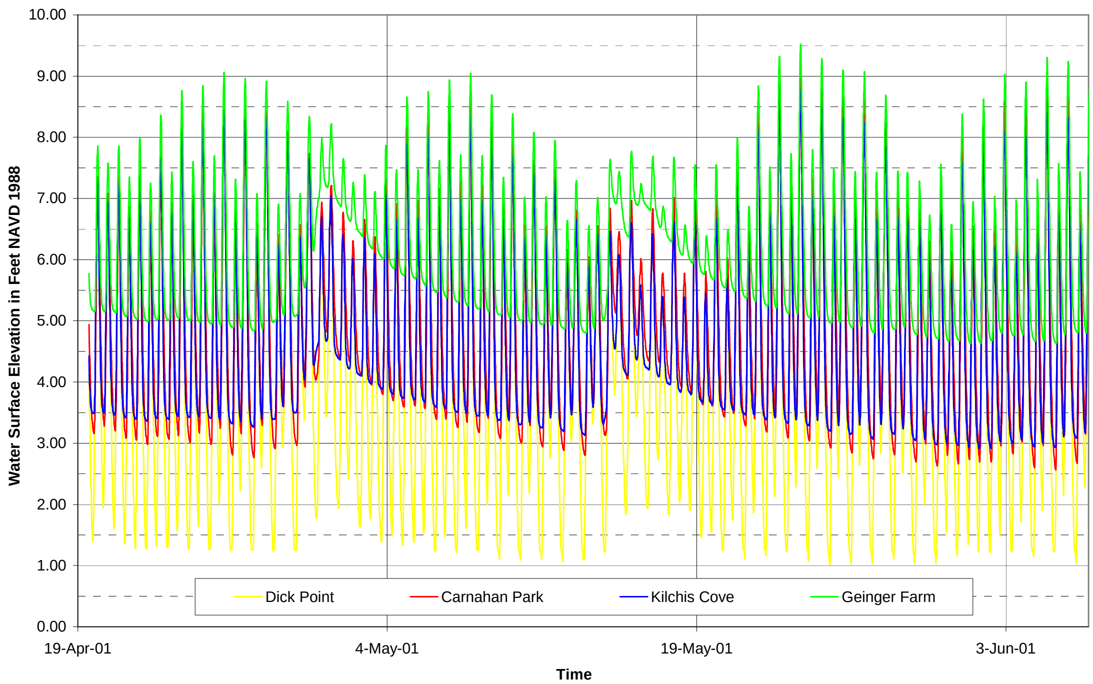
Figure 7. Tide Gauge on the Kilchis River at Kilchis Cove



Note logging device being held next to gauge housing.
Tidal range is approximately 10 feet at this location (Kilchis River at Kilchis Cove).

Figure 8 shows the tidal stage variation at the southern end of Tillamook Bay from data collected during the first four months of gauging. Note the variation of tidal prism from Dick Point to locations near the river mouths. Also, the Wilson River at Gienger Farm gauge shows a truncated tidal range in comparison to the other river gauges during ebb tide. This would indicate that a severe contraction occurs between the bay and the Gienger gauge. This contraction appears to be the result of sedimentation at the mouth of the Wilson River.

Figure 8. Tidal Stages of Gauges at the Southern end of Tillamook Bay



Calibration Data Collection

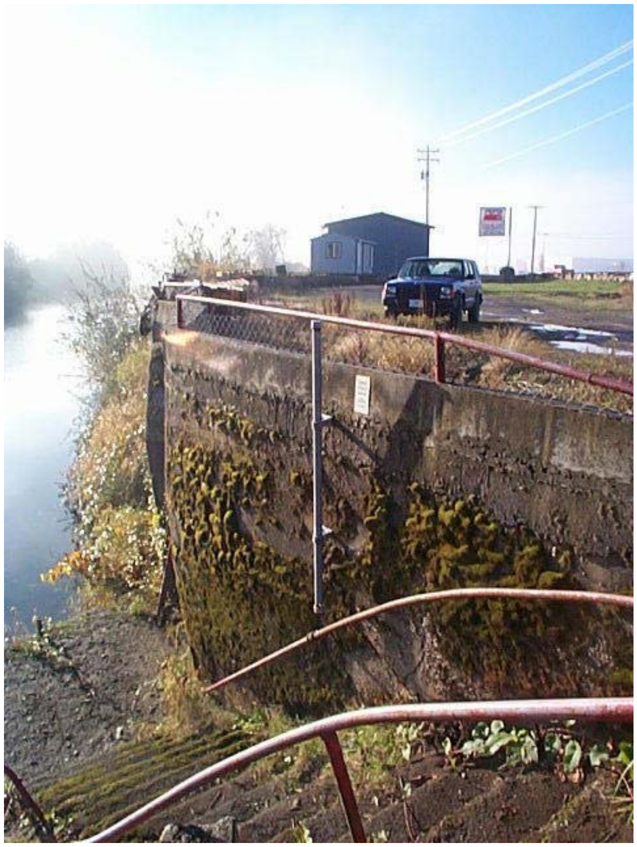
<u>Crest Stage Gauges</u>

Crest gauges consist of a pipe that is mounted to a fixed object in the floodplain at an elevation that is at the 'best-guess' for flood levels. Inside the pipe, a graduated rod rests along with ground cork that sets at the bottom of the pipe. Holes drilled into the bottom of the pipe allow floodwaters to fill the pipe. Cork floating on top of the water sticks to the rod as the flood recedes. After the flood, the rods are retrieved and read.

A network of crest stage gauges was placed in the region by the Corps at the onset of this study to obtain flood stage data to utilize in model calibration. Nineteen crest gauges were placed along Tillamook area rivers and sloughs in November 1999. Approximately 2 weeks later, the gauges were successful in capturing the maximum stages that occurred during the Thanksgiving flood. This data was utilized as the primary source of flood calibration for this study. Since this flood event, several other smaller events have occurred and have been documented from the crest gauge network. All floods captured (with the exception of the 1999 Thanksgiving flood) have been on the order of annual 2-year flood events.

Eighteen crest gauges were given to Tillamook County in the summer of 2001. These gauges were installed by the county throughout the Tillamook area to collect more flood-related stage data for this study and future management. Gauges were generally located on private properties with permission granted for inspection and data collection. A small flood event in January 2002 was captured by these gauges and was entered into the Corps' database.

Figure 9. Crest Stage Gauge Located on the Lower Wilson River



<u>Highwater Mark Surveys</u>

Other calibration data collected included the placement and survey of highwater marks. Approximately 50 highwater marks were placed by the Corps with noted time along all five rivers during an in-bank event on April 30 and May 1, 2001. The highwater marks were then surveyed on May 9-10, 2001. This data was used to develop a snapshot of water surface profiles of each river for known flow conditions to test the initial models for accuracy. On November 14-15, 2001, highwater marks also were placed and surveyed along the lower Wilson River and Highway 101 during a bank-full flood event to further calibrate the MIKE11 model for this area.

Tributary Inflows

Tributaries within the modeling limits were added to the MIKE11 model as point source flow boundaries. Therefore, it was necessary to develop hydrographs for 26 tributaries. Tributary boundaries were delineated in a GIS system. Tributary areas were then calculated from the GIS database. Tributary flows were estimated individually based on their area compared to the area of the gauge that was used for estimation. Tributary flows were estimated based on drainage area ratio to that of the measured stream's hydrograph. Gauges used for tributary estimation included all five river gauges used for upstream boundary conditions. The specific gauge used was dependent on the model run. For some model runs, gauge data did not exist for each river. If gauge data did exist for that river, then generally the tributary flow was estimated from the gauge data for the river that it contributed to. It was determined that the tributaries did not contribute enough in the overall flow to make a difference for flood conditions. Therefore, if gauge data did not exist for the river, then other data was developed based on the individual model run.

The timing in the simulations of the local tributary inflow was assumed to be the same between the tributary inflow point to the river and the upstream boundary condition. Initial sensitivity tests indicated that the timing of the inflow did not significantly affect the overall water surface results. This is due in part to the magnitude of the small tributary inflows relative to the large, main river flows.

Model Boundaries

The original study area, as defined in the Congressional Authority for the study, included Tillamook Bay and all the watershed area encompassing the bay. This vast area was too large to study in detail. Therefore, the 1999 reconnaissance study identified areas that were of greatest concern to the local community in terms of flooding problems and environmental concerns. Tillamook County requested that all five rivers of Tillamook Bay be modeled to the same extent. The area's rivers are all tidally influenced and are fed by the Coast Range Mountains. As the rivers flow from the Coast Range, their valleys widen and there slope decreases to create large coastal floodplains that have been utilized for agriculture for the past 150 years.

It became obvious that an unsteady model was necessary to analyze the hydraulics of the area and that the areas with the majority of flooding problems and environmental concerns were located in the coastal floodplains of each river. As unsteady flow models are only useful in areas with low slopes, it was determined that an unsteady flow model would be created for each of the five rivers within the coastal floodplain of each river. The Danish Hydraulic Institute's MIKE11 model was chosen for this study and this model was adapted to each of the rivers.

It was recognized that the Wilson, Trask, and Tillamook Rivers were all interconnected at their mouths; therefore, these three rivers would be modeled together. The Kilchis and Miami Rivers behaved independently and were modeled independently. It was determined that the Corps would coordinate all model development and obtain all necessary data for the modeling effort. The model for the Wilson, Trask, and Tillamook Rivers was contracted with WEST Consultants, Inc. The Corps developed the models for the Kilchis and Miami Rivers at the same time. Model boundaries included modeling from Tillamook Bay to RM 11.4 on the Wilson River, to RM 10.95 on the Trask River, to RM 6.90 on the Tillamook River, to RM 4.95 on the Miami River, and to RM 5.88 on the Kilchis River. Figures 10 to 12 show the model boundaries for the MIKE11 model.

Figure 10. Area Encompassing the Wilson, Trask and Tillamook River MIKE11 Model (shown by dashed line)

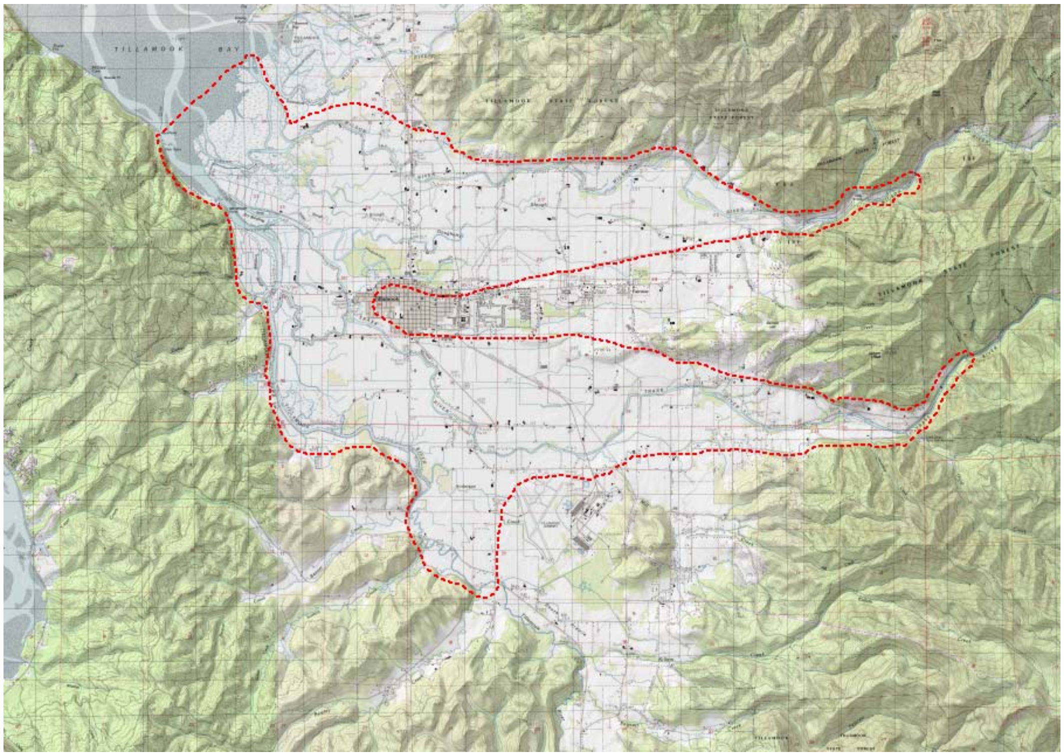


Figure 11. Area Encompassing the Miami River MIKE11 Model (shown by dashed line)

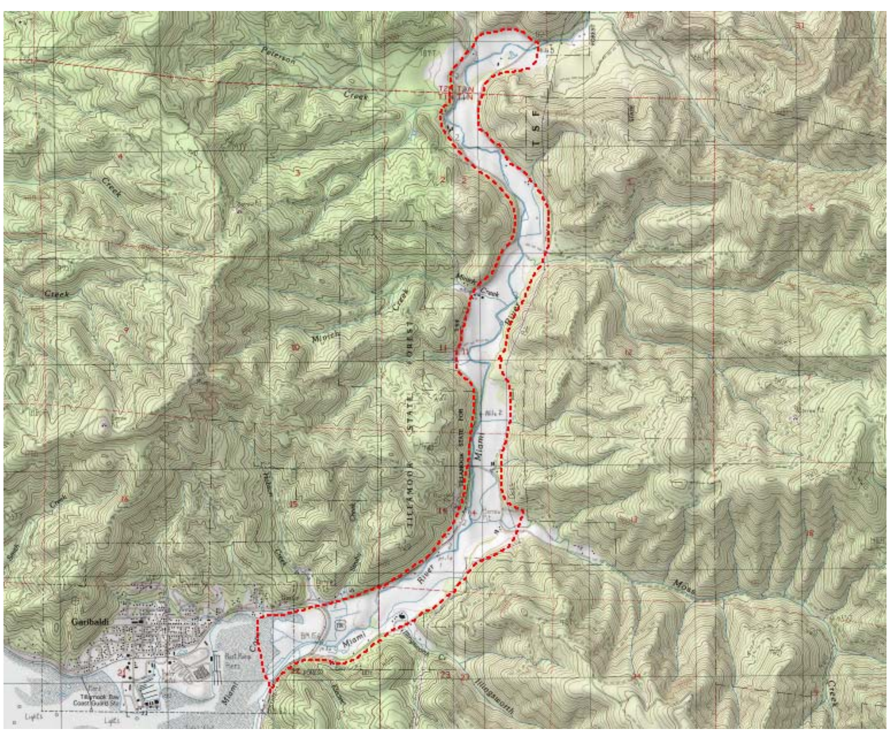
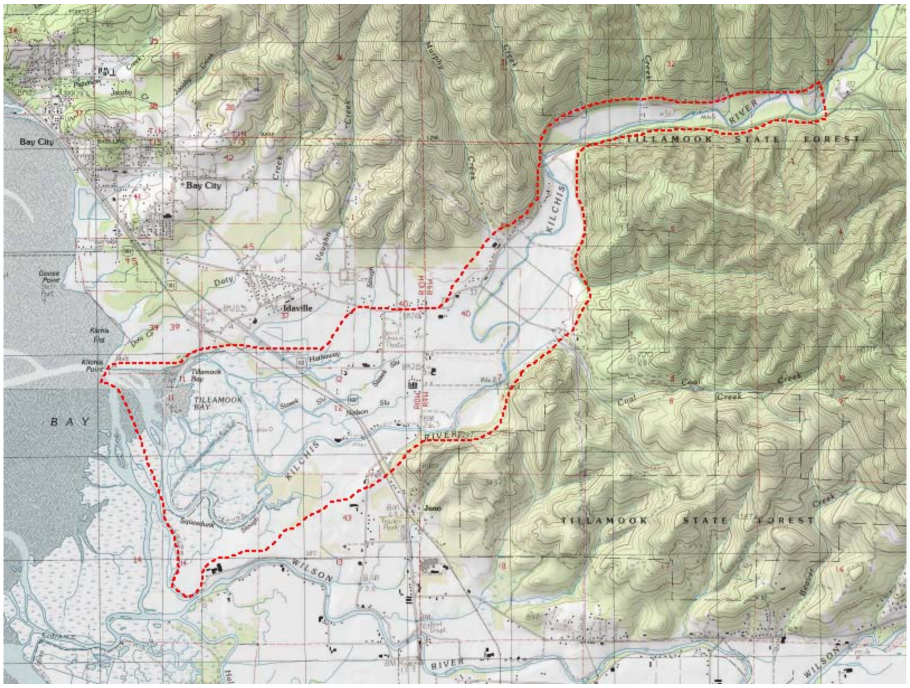


Figure 12. Area Encompassing the Kilchis River MIKE11 Model (shown by dashed line)



Alternative Analysis with the MIKE11 Model

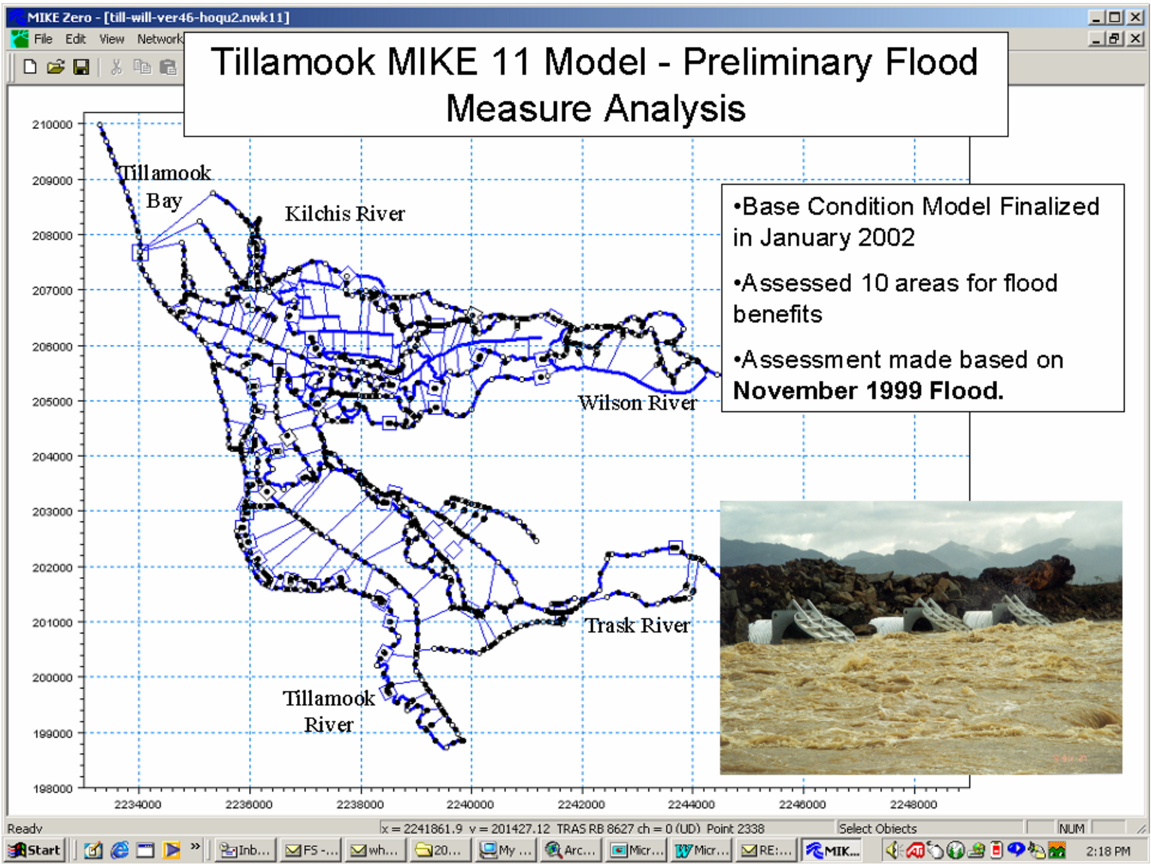
Overview of Alternative Analysis

Alternatives were formulated during final base condition model construction in the winter 2001-2002. Alternatives were formulated by focus groups composed of staff from the Corps, Tillamook County, regulatory agencies, and local citizens. Alternatives were based on the four objectives of the study: reduced in flooding, reduced sedimentation, improved water quality, and improved salmonid habitat. Fifty-nine preliminary alternatives were recommended by the group. At the request of the county, alternatives without flood reduction benefits would not studied further. Therefore, as a first task, each alternative was screened to see if it had any potential flood reduction benefits. If not, then the alternative was dropped from further consideration.

This initial screening left 33 alternatives for further study. At this time, it was determined that with the remaining budget, only alternatives with potential to both resolve the sponsor's immediate concerns of flood reduction along with ecosystem restoration benefits would be studied in detail. The reasoning for this decision was based on budgetary and time constraints along with the inherent desire of the local community to improve flood conditions. Therefore, the remaining 33 alternatives were evaluated based on engineering and biological judgment for their significance. It was determined by the sponsor that the area of focus should be in and around the City of Tillamook, thereby the alternatives on the Miami and Kilchis Rivers were tabled with the exception of evaluating the lower Kilchis River. This left approximately 14 alternatives to be modeled with MIKE11 (Figure 13). The alternatives were modeled under several configurations and combined with other alternatives to evaluate their response to flooding. Thus, there were many model runs made to evaluate each area and its response to flood conditions. Of these alternatives, it was determined that six alternatives areas provided flood reduction on a scale that met the sponsor's requirements. These six alternatives were further evaluated.

Discussion of each alternative followed between the local citizens, the sponsor, resource agencies, and the Corps. From these discussions, three alternatives remained for design to determine costs and benefits. Other alternatives were not evaluated further based on environmental concerns, little to no flood reduction benefits, high costs, or a lack of local support.

Figure 13. MIKE11 Schematic from the MIKE11 Base Condition Model of the Wilson, Trask and Tillamook Rivers



City of Tillamook Area Flood Conditions

An evaluation of flooding problems around the City of Tillamook was performed by the Corps in order to define alternatives that could possibly alleviate flooding in the area. In order to understand the flooding, an evaluation of the topography was performed. Figure 14 shows the topography of the lower Wilson, Trask and Tillamook Rivers near Tillamook. As shown in Figure 14, the rivers of Tillamook are perched above their floodplains. Their high sediment loads spill out during flood events and are deposited near their banks. The floodplains are lower and are reconnected to the river system through a network of sloughs. However, for agricultural use, the floodplains have been diked along their rivers and sloughs to not allow for tidal inundation. Therefore, when floodwater exits the Wilson, Trask, Kilchis and Tillamook Rivers, it is trapped in the floodplains behind the natural and constructed tidal dikes. A network of 'flood cells' was delineated in lower Tillamook area, which gave the modeling team a way to identify and compare floodplain areas during modeling (Figure 15). Flood cells were delineated based on their independence of one another in flooding condition. Each flood cell acts independently because it is diked from its neighboring flood cell, slough, or river.

Figure 14. Lower Tillamook Area Topography, Color Coded by Elevation.

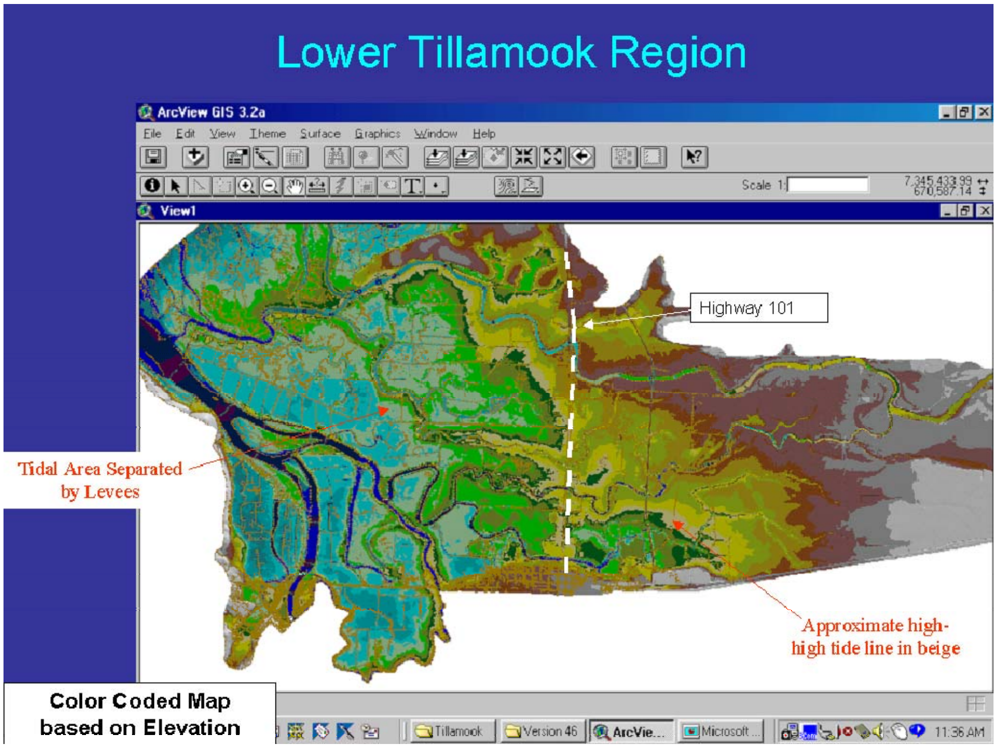
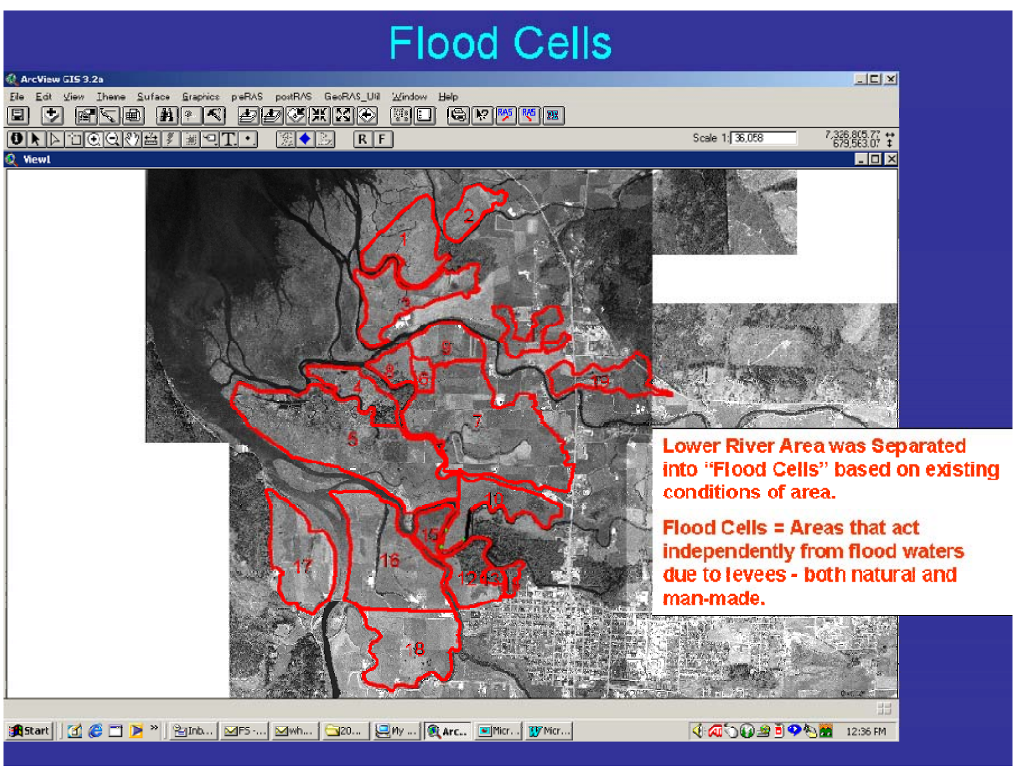


Figure 15. Flood Cells in the Lower Tillamook Region



Both natural and constructed dikes have separated the rivers and sloughs of Tillamook from their floodplains. The complex nature of flooding in the Tillamook region has not been analyzed in floodplain development including the placement of tidal dikes. The result is a system of channels that are disconnected and create increased flood problems, including standing water when floods recede, and increased flood stages within channels. Man-made features such as levees, dikes and roads, along with land use practices may have caused flooding in areas that did not historically flood. The rivers have been forced to evacuate all floodwater; however, they will never have the capacity to do so. In analyzing the peak flows from gauges in the region for the November 1999 flood event, it was apparent that the lower rivers do not have the capacity to carry the floodwater, and depend largely upon the floodplain to carry the floodwater to the bay. Table 9 lists the peak discharge of each river and its capacity through its downstream reach to the bay as determined by MIKE11 for the base condition model (November 1999 flood event).

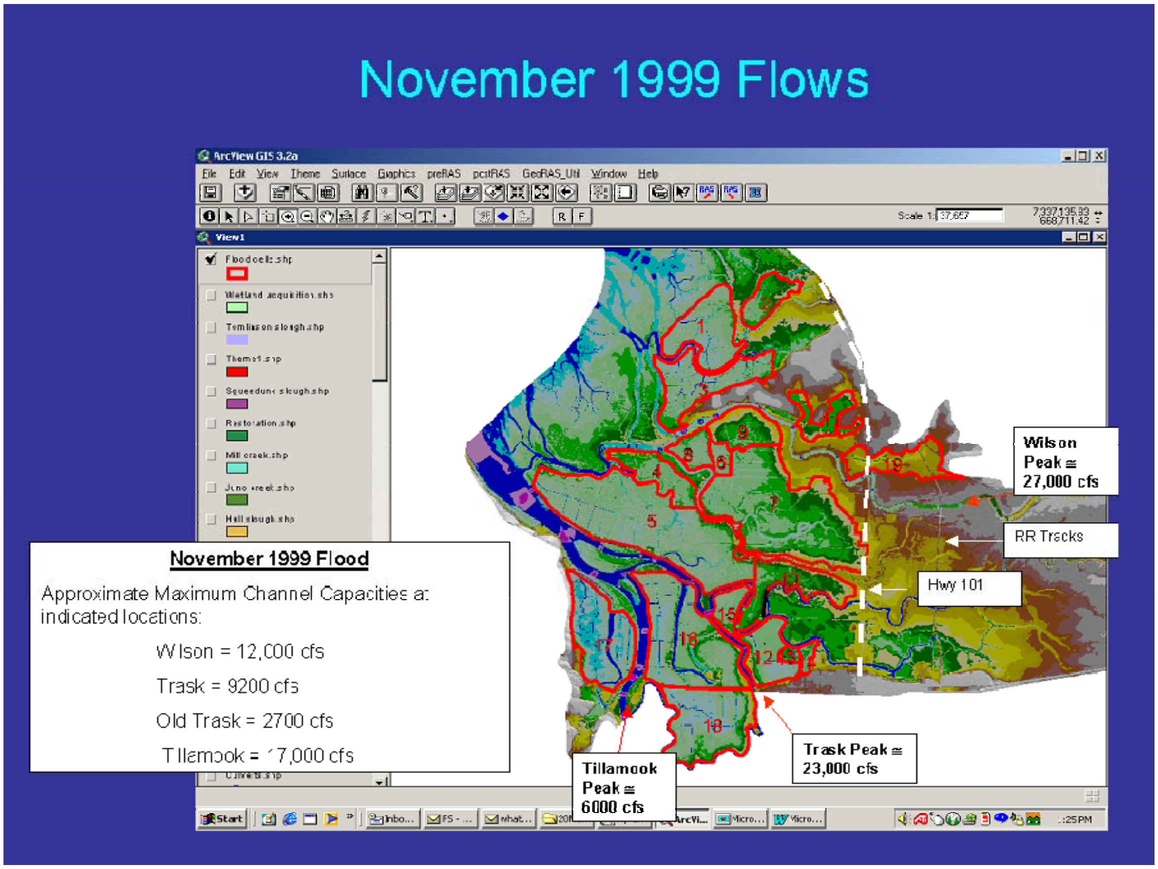
Table 9. November 1999 Flood Flows for Tillamook Area Rivers as Compared to Channel Capacity

River	November 1999 Peak Flow	MIKE11 Peak Channel Capacity at Downstream Reach	Difference
Wilson River	27,000 cfs (approx. 10-yr. peak)	12,000 cfs	-15,000 cfs
Trask River	23,000 cfs (approx. 20-yr. peak)	9,200 cfs	-13,800 cfs
Tillamook River	6,000 cfs (approx. 5-yr. peak)	17,000 cfs	+11,000 cfs

As shown in Figure 16, the lower Wilson and Trask Rivers do not have the capacity to move their floodwaters to Tillamook Bay. The Wilson River has approximately 12,000 cfs capacity and the Trask combined with the 'Old Trask' has approximately 11,900 cfs capacity. It is natural for rivers to not have the capacity to take flood flows within their banks. Their bankfull discharge (or channel forming discharge) is that discharge that the river can move before it overflows its banks. The bankfull discharge of a river is typically on the order of an annual or bi-annual event. For the Wilson River, 12,000 cfs capacity represents approximately the 90% chance of exceedance flow for any given year. For the Trask River, 11,900 cfs capacity represents approximately the 60% chance of exceedance flow for any given year.

However, the Tillamook River is an anomaly among the three rivers because its lower reach is broad in comparison to its flow, and it has more capacity than the river typically flows. The reason for this is that the Trask River flows towards and into the Tillamook River through floodplains and the Old Trask River adding large amounts of floodwater to the Tillamook River near its mouth. From this evaluation, a reasonable approach to managing Tillamook's floodwater would be to increase channel capacity at the lower reaches of the Trask and Wilson Rivers, and to reconnect the floodplains in the area. This was analyzed in the alternatives as discussed in the following section.

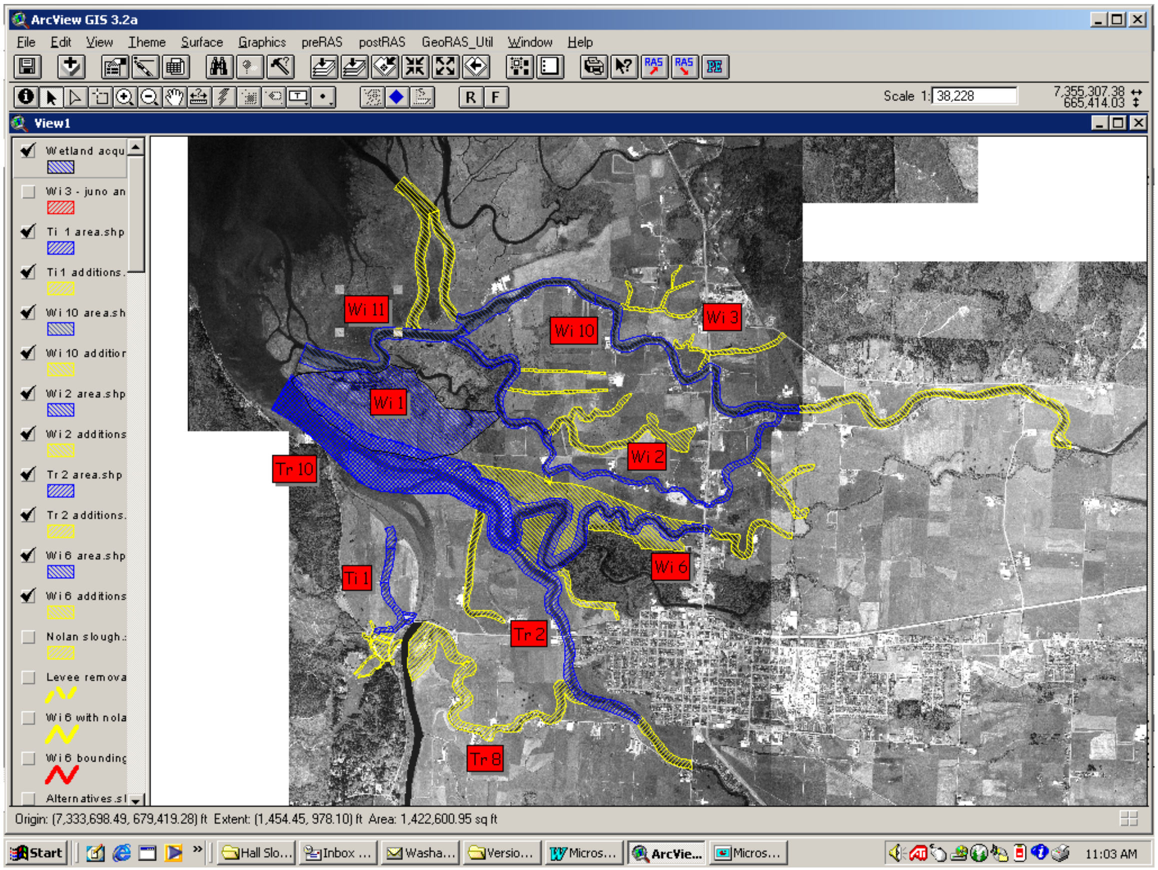
Figure 16. November 1999 Flood Flows of Tillamook Area Rivers



PRELIMINARY MIKE11 MODELING OF ALTERNATIVES

Preliminary modeling of alternative areas took place to evaluate each area's effectiveness for reducing flood impacts in Tillamook County (Figure 17). Preliminary alternatives were minimally designed and were initially modeled with trapezoidal channel cuts and large channel changes to analyze the area's effectiveness in providing flood reduction benefits. The alternatives were modeled using MIKE11 with the November 1999 flood, and model results were compared to base condition results. After running several scenarios in each alternative area, results were summarized and discussed with the Feasibility Advisory Council. This section discusses each of the initial alternatives evaluated and the MIKE11 modeling results.

Figure 17. Areas of Lower Tillamook Area Rivers Modeled For Flood Reduction

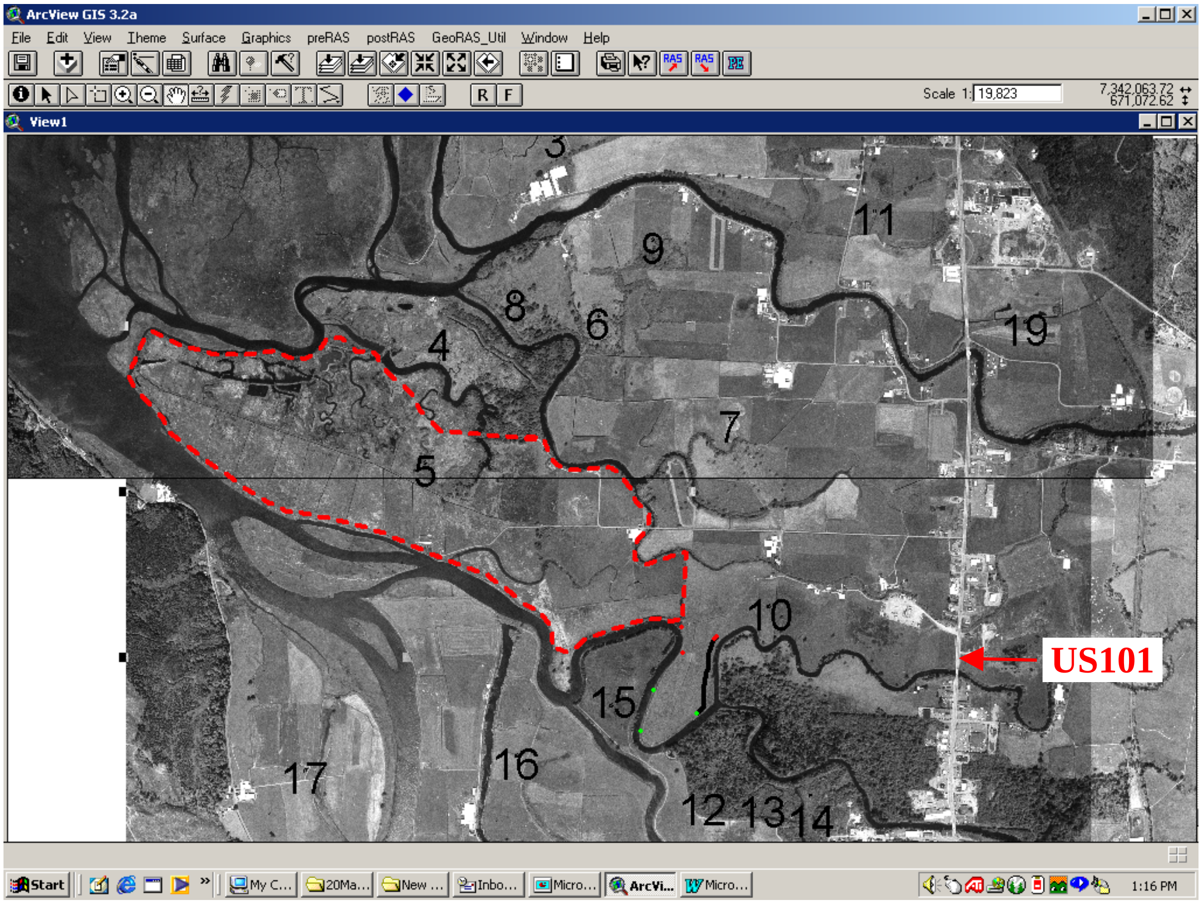


WI 1 – Wetland Acquisition Area

The Wetland Acquisition area (WI 1), as shown in Figure 18, is an area owned by the Tillamook County Performance Partnership in conjunction with Tillamook County that is slated for ecosystem restoration. The area is located between the mouths of the Wilson and Trask Rivers and Tillamook Bay. This area is critical in terms of flooding in the Tillamook area. This area was modeled using MIKE11 by Phillip Williams and Associates (PWA) for Tillamook County. The area is currently cut-off from the rivers and bay by levees that surround the property. Alternatives for this property included levee setback and levee removal.

Results from PWA's modeling of alternatives in this area alone concluded that the removal of levees and setting back of levees on this property resulted in slightly increased peak flood stages at the Highway 101 business district. As this area recently had 10 culverts with tidegates installed in the levee bordering Tillamook Bay, it was determined that the area currently helps alleviate flooding by storing floodwaters during flood tide and releasing floodwaters during ebb tide. It was determined that this property could be included in other alternatives and possibly more favorable results would occur with some modifications (see Wetland Acquisition/Swale).

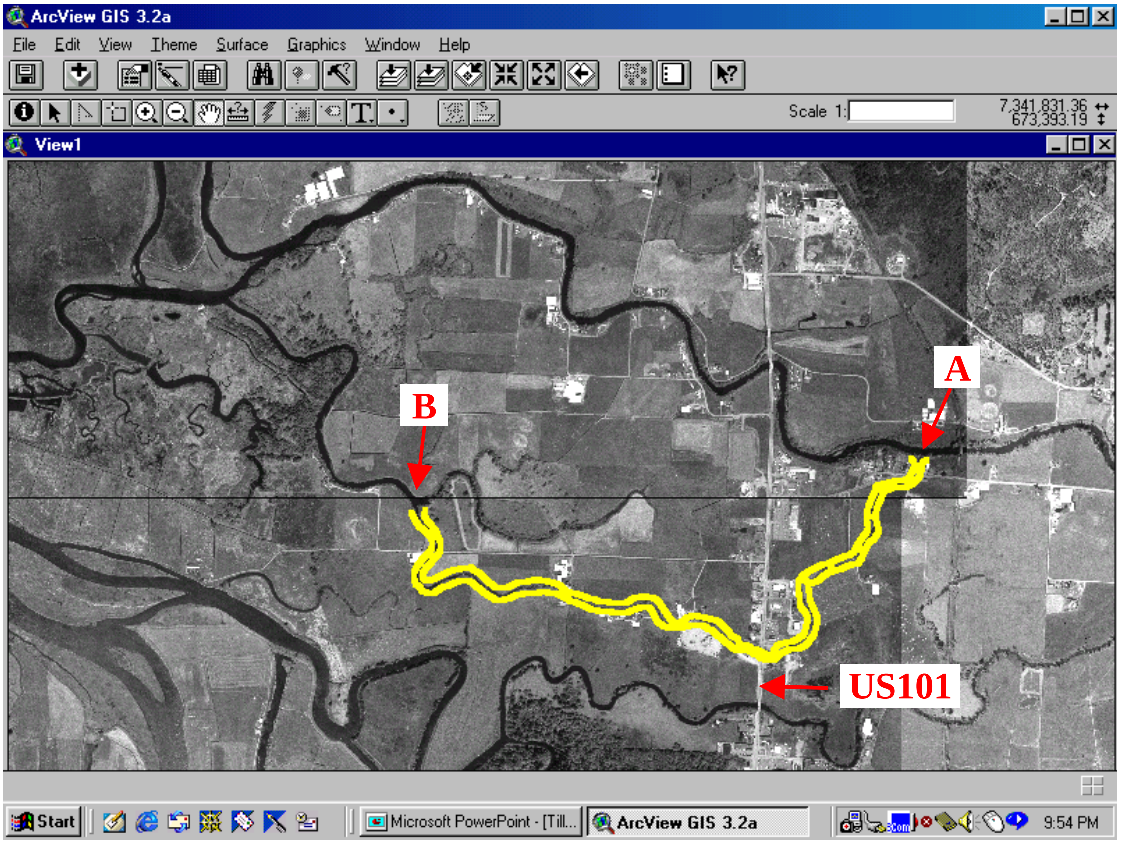
Figure 18. WI 1 – Wetland Acquisition Area



WI 2 – Hall Slough

As shown in Figure 19, Hall Slough is a side channel of the Wilson River. The slough's origins are upstream of Highway 101 near the Wilson River Loop Road (A) and its downstream end comes back into the Wilson River approximately 2 miles downstream near the mouth of the Wilson River (B). Hall Slough was connected to the Wilson River at its upstream end before 1950. At that time a bridge was in place that crossed Hall Slough on the Wilson River Loop Road. Since then, the slough has been filled at its upstream end, the bridge was removed, and a small culvert was placed through the Wilson River Loop Road to drain the area behind it. This area currently represents the area of the Wilson River that overtops first during a flood event. Floodwater flows over along the left bank of the Wilson River near this historic Hall Slough entrance and flows west down the Wilson River Loop Road to Highway 101 where it flows south along the highway eventually crossing and flooding it. These so-called nuisance floods occur annually and may be controlled by reestablishing the historic Hall Slough. Alternatives were formulated and evaluated with MIKE11 that included connecting the slough to the Wilson River at the upstream end, setting back levees, establishing new levees along the slough, and deepening the slough.

Figure 19. WI 2 – Hall Slough Alternative



Initial modeling results of Hall Slough showed that the slough would carry approximately 1,000 cfs of floodwater that had previously flooded Highway 101. This alternative also lowered the duration of flooding on Highway 101 during the November 1999 flood by approximately 4-hours. Although the alternative would not cure flooding for all floods in excess of the nuisance floods, it would help control the common flooding in the Highway 101 area. The alternative also would reestablish Hall Slough and prove to be environmentally beneficial.

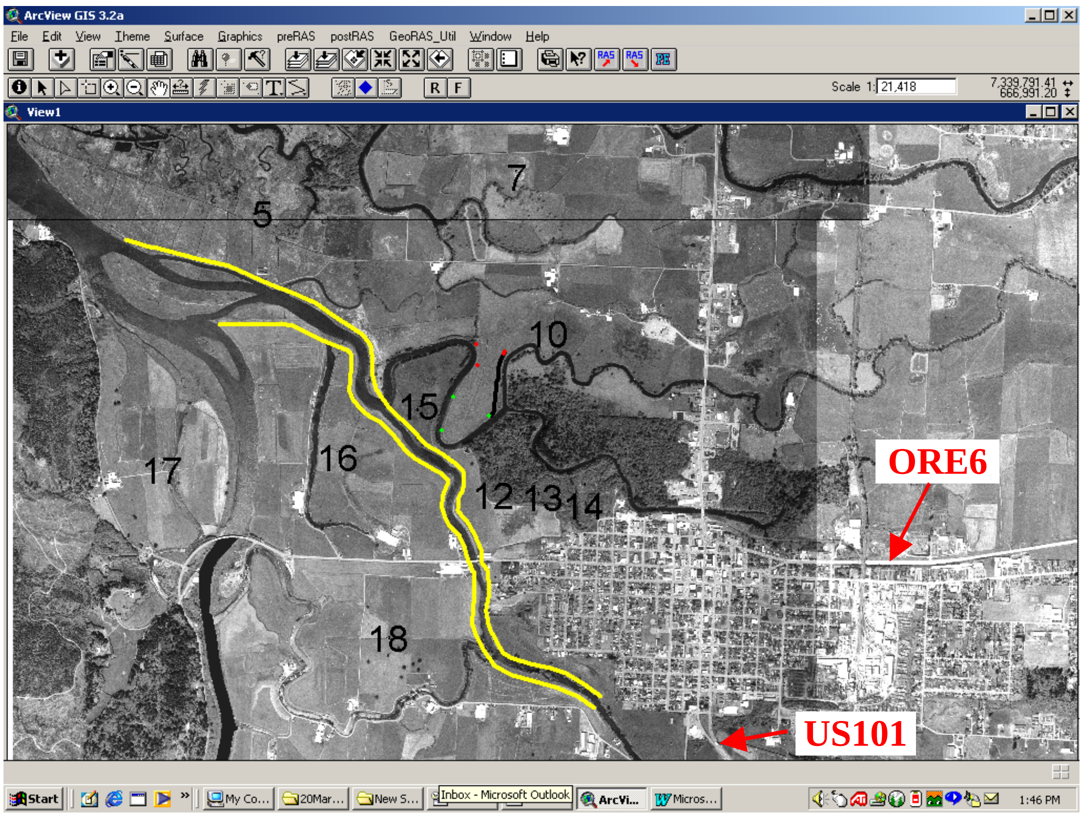
TR 2 – Lower Trask River

As shown in Figure 20, the Lower Trask River alternative is located along the Trask River between RM 2 and the downstream confluence with the Tillamook River. This area represents a constriction in the Trask River. This area represents a constriction in the Trask River because the lower river was rerouted and channelized. The current river channel has a much lower capacity in this reach than in both its upstream and downstream reaches. Furthermore, the reach lacks riparian habitat and channel complexity. This reach of river is essentially a tidal flume devoid of riparian vegetation other than its grazed, trapezoidal banks. Alternatives were modeled for this reach that included setting back levees along with widening and deepening the channel.

Initial modeling results showed that modifying the channel had the most profound effects on flood stages, whereas dike modification provided minimal flood reductions. Channel modifications were initially modeled as large cuts on the maximum side of what would be realistic to actually perform.

This was done to determine the largest flood reduction benefit attainable and to determine if further development of the alternative would be warranted. For the November 1999 flood modeled, water surface elevations were significantly reduced in the reach, as well as upstream of the reach. Stages in the Tillamook-Trask Drainage District, an upstream area that is frequently flooded, were reduced by 1.3 feet. At the same time, the Trask River was carrying approximately 6,000 cfs more flow through this reach of river. From a flooding standpoint, this alternative increased flow through the reach and decreased flood stages. Although the channel modification was modeled on the extreme side in terms of channel geometry, the possibilities for minor flood reduction benefits in this area were shown.

Figure 20. TR 2 – Lower Trask River Alternative



TR 8 – Old Trask River

As shown in Figure 21, the Old Trask River is a branch of the Trask River, possibly representing its former mouth. This reach flows between the Trask River and the Tillamook River near Trask RM 1.8. This reach of river helps alleviate flooding on the Trask River. The reach is currently has levees along both sides. The Stillwell Drainage District is on the north side of the channel and the Tillamook-Trask Drainage District is on the south side. The Stillwell levee provides approximately 50-year protection while the Tillamook-Trask levee only protects for tidal flows. Therefore, the area to the south gets flooded often. Modeling using MIKE11 included modifying the channel by widening and deepening, as well as setting back the levees along the channel and combinations of the two.

The Old Trask River alternative had similar results to that of the Lower Trask River (TR 2), but on a smaller scale. Setting back levees showed minimal benefits, whereas setting back the levees along with modifying the channel provided the largest flood reductions. Although channel stages were only slightly reduced, an increase in channel capacity of approximately 2,400 cfs was obtained from the combined measures when modeled for the November 1999 flood.

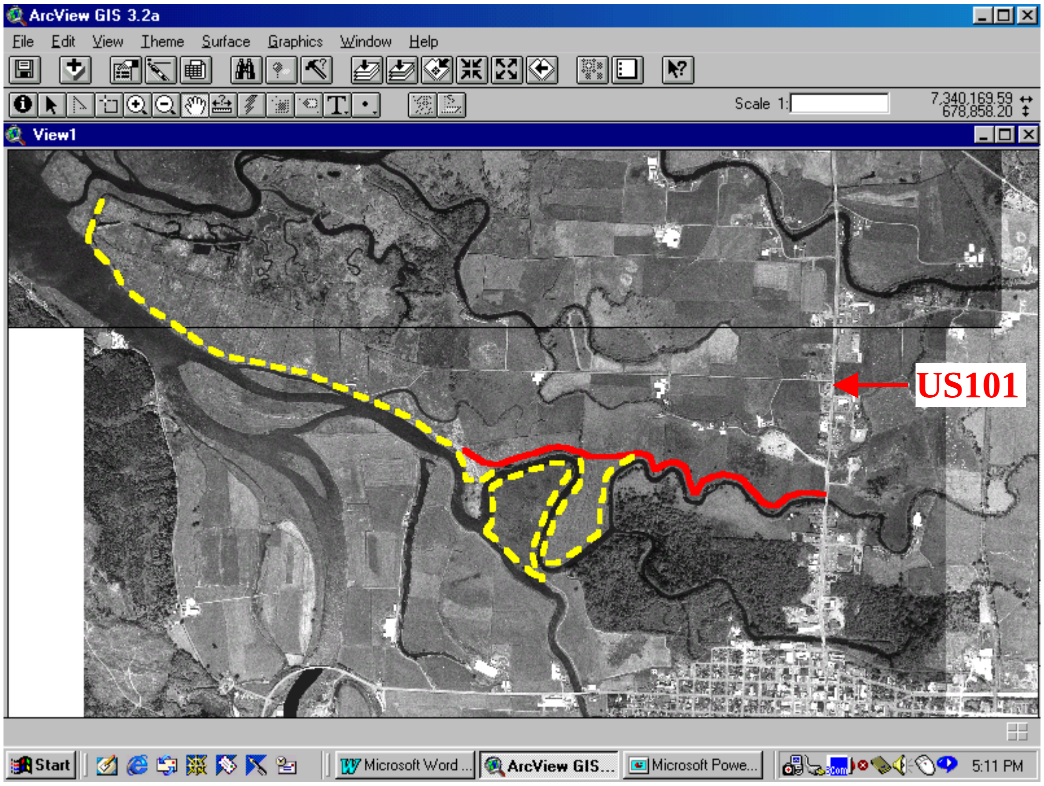
Figure 21. TR 8 – Old Trask River Alternative

WI 6 – Dougherty Slough

Dougherty and Hoquarten Sloughs below Highway 101 (west) represent a critical area in terms of both flood problems in the Highway 101 business district and environmental concerns. Several alternatives were modeled to assess possible solutions to flood problems in the area. Measures included removal of existing levees, setback levees, channel modification, and combination of alternatives in downstream reaches including WI 1 and TR 2. The area evaluated for possible flood alternatives is shown in Figure 22. It became apparent during modeling that if modifications only were performed in Dougherty and Hoquarten Sloughs downstream of Highway 101, very little effect would be had on flood levels at Highway 101. However, if the alternative incorporated levee setbacks and channel modifications from TR 2 and WI 1, then significant flood reductions could be achieved at Highway 101.

Channel modifications included benching one side of Dougherty and Hoquarten Slough from the Dougherty's bridge at Highway 101 to the Trask River along with lowering cross levees along Hoquarten Slough and setting back the Trask River levee in the Wetland Acquisition Area. Also, an alternative was modeled with channel modifications in the Trask River from TR 2. All modeled alternatives showed some improvement in flood conditions at Highway 101. The greatest improvements were while TR 2 was implemented with all other measures along the sloughs. This scenario reduced the November 1999 flood at Highway 101 near Dougherty Slough by approximately 1.1 feet, and the duration of the flood was reduced by 14 hours at this location.

Figure 22. WI 6 – Dougherty Slough Alternative

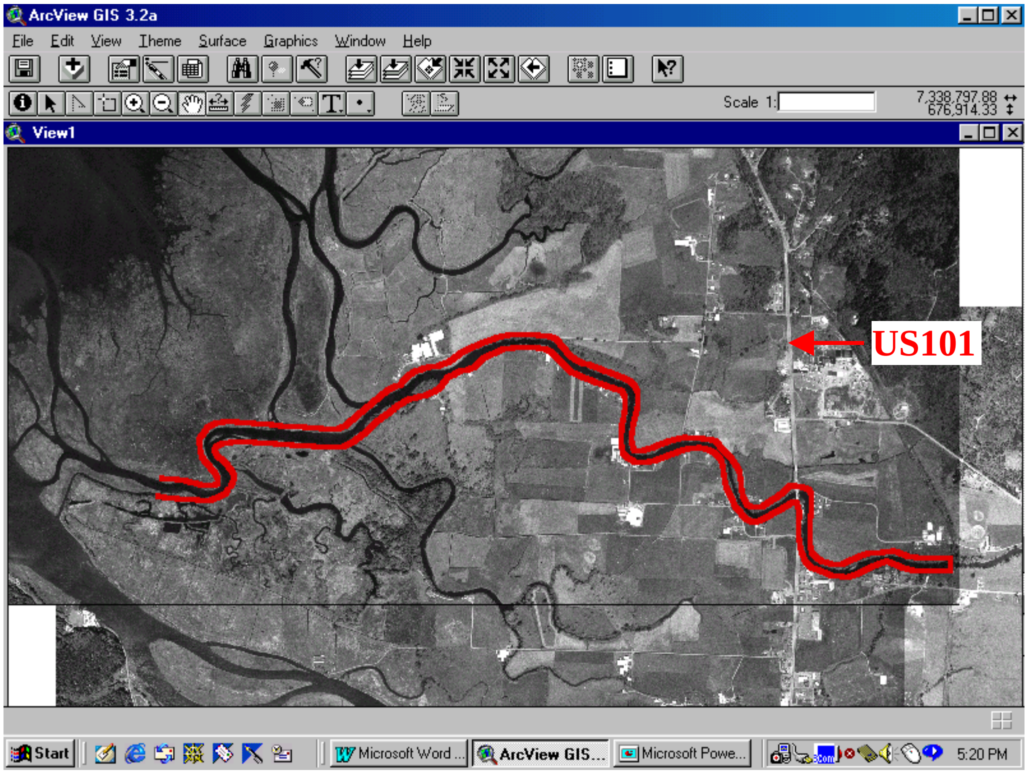


WI 10 – Lower Wilson River

The Lower Wilson River alternative was similar to those discussed previously. The main objective for this alternative was to increase flood conveyance to Tillamook Bay in this reach of river. The alternative reach is between the railroad bridge over the Lower Wilson River and Tillamook Bay on the Wilson River mainstem (Figure 23). The channel was modified throughout this reach to increase channel conveyance by a combination of deepening and widening.

The channel was initially modified as a trapezoidal channel with a bottom width of 80 feet and 2:1 side slopes. This modification only was performed for narrow areas as some areas of the reach were already this large. The bottom also was deepened such that a positive slope occurred throughout the reach. The majority of deepening occurred below the 'Big Cut' to Tillamook Bay where sedimentation has occurred. Model results for the 1999 flood event showed that flows could be increased by approximately 2,000 cfs in this reach and channel stages were reduced from 0.3 feet at the railroad bridge to 1.3 feet near the bay. Adjacent flood cells to this reach had reduced water surface stages and flood durations. This channel modification showed some flood benefits to the lower Tillamook region.

Figure 23. WI 10 – Lower Wilson River

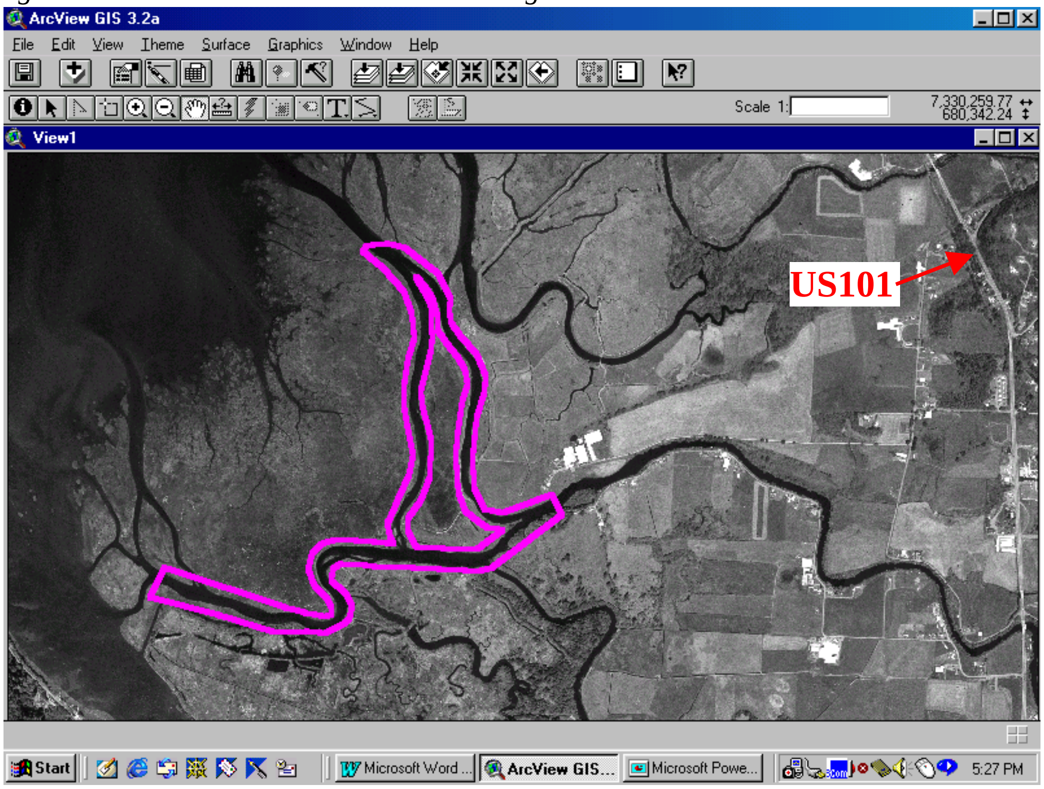


WI 11 – Lower Wilson River Dredge

As shown in Figure 24, the Wilson River branches into three reaches before its terminus into Tillamook Bay. It is apparent from bathymetric data and historic accounts that this area has been aggrading for some time. Large sediment and woody debris deposits have been left in the area. This reach represents a very dynamic area in terms of sedimentation and plan form morphology. At the tidal interface, sediments are deposited as the Wilson River slows. Historically, the river would have aggraded and changed course as a delta was formed. However, development has created a condition in which the river is not allowed to change course in the area. Therefore, sedimentation and natural tidal interface functions are viewed as a problem. The MIKE11 model was used to determine the extent of impact on flood conditions from recent sedimentation. The area was dredged and the three channels were deepened to determine if the recent sedimentation was causing flooding problems upstream, and if dredging would alleviate those problems.

Utilizing a trapezoidal channel, the three branches of the Wilson River were dredged. The 'Little Cut' and the 'Big Cut' were dredged with an 80-foot bottom width and the mainstem of the Wilson was dredged with a 100-foot bottom width. Side slopes were 2:1. Dredging depths ranged from 0 to 5.5 feet as a positive slope to the bay was achieved. Dredging was performed from RM 0.25 to the mouths of the three branches.

Figure 24. WI 11 – Lower Wilson River Dredge



Results of modeling the Wilson River Dredge alternative with the November 1999 flood showed that there was stage reduction in the Wilson River at the dredge location and in nearby flood cells of up to 1 foot. However, upstream the stage reduction was reduced until it was null at Highway 101 across the Wilson River. The reasoning for this appears to be the channel constraints that exist between Highway 101 and the mouth of the Wilson River. These constrictions in the channel control the water surface slope during flood conditions. The next step in this process was to combine WI 10 with WI 11 to determine the extent of increased stage reduction when the Lower Wilson River channel was modified and the three branches were dredged.

WI 10 and WI 11 – Lower Wilson River Channel Modification Combined with Lower Wilson River Dredge

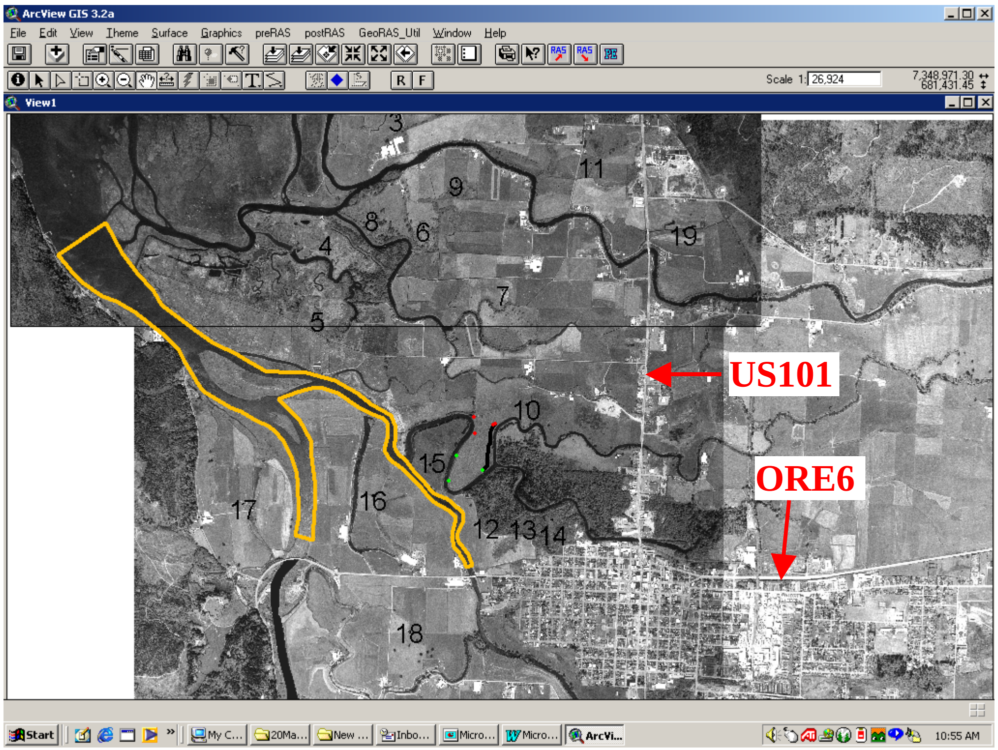
This alternative combined the Wilson River channel modification (WI 10) from the railroad bridge at RM 2 to the mouth and included full dredging of the Wilson River, the 'Big Cut' and the 'Little Cut' as described in WI 11. Results of the modeling showed that no further stage reduction from alternative WI 10 was realized at Highway 101 during flood conditions (modeled in the November 1999 flood). Some minor stage reduction did occur near the dredged area as shown in WI 11. The results showed that stages at or above Highway 101 during highwater conditions are controlled by the capacity of the Wilson River channel, and not by tidal conditions or sedimentation at the mouth of the river.

TR 10 – Lower Trask and Tillamook River Dredging

Similar to the Wilson River, the lower Trask and Tillamook Rivers have been aggrading at their tidal interface with Tillamook Bay. This alternative analyzed dredging the sediments in the lower Trask and

Tillamook Rivers to view the effects on flooding at upstream locations in the Tillamook region (Figure 25). The Tillamook River was dredged from RM 0.86 to the bay and the Trask River was dredged from RM 1.14 to the bay. The Tillamook River was dredged with a bottom width of 215 feet and depths varying between 0.6 to 5.2 feet. The Trask River was dredged with a bottom width of 80 feet and depths varying between 0 to 3.0 feet. The MIKE11 model was run with the November 1999 flood to evaluate flooding effects.

Figure 25. TR 10 – Lower Trask and Tillamook River Dredging



Results of alternative TR 10 were similar to those of alternative WI 10. Water surface stages during flooding were reduced in and near the dredged area. This included stage reductions of up to 1.6 feet on the Tillamook River near the Netarts Highway bridge, and up to 0.8-feet on the Trask River near its mouth. Adjacent flood cells had a stage reduction from 0.3 to 0.5 feet. Also, an increase in discharge from the Trask River was observed. The Trask River had an approximate 1,200 cfs increase in flow at it peak. However, at locations upstream including Highway 101 at Hoquarten Slough, impacts from dredging were minimal. From these results, it appeared that a project on the Trask River may be beneficial to flood stages if it included either TR 2 or WI 6 or some combination of the alternatives.

Table 10 provides a summary of the flood stage and duration benefits by alternative.

Table 10. Summary of Flood Stage and Duration Benefits by Alternative

Alternative	Summary of Results	Major Flood Cell Improvements
Wetland Acquisition Area (WI 1)	See results from PWA assessment.	Generally, removal of the entire levee system in the wetland acquisition area may not be beneficial to flooding in neighboring areas including the Highway 101 business district. It appears that a combination of levee removal, enhanced channels, setback levees, lowering of levees and updated culverts may suit both ecosystem restoration and flood reduction goals for this area.
Hall Slough (WI 2)		
20-meter (65.6 feet) cut	Flow redirected from the Hall right bank to Hall Slough. Duration of Highway 101 overtopping reduced by ≈ 4 hours.	None
Levees lowered	Duration of total flood event extended. Peak stage decreased by up to 0.1 meter (0.32 feet) along Hall Slough.	Peak stage decreased by up to ≈ 0.1 meter (0.32 feet) in cells 4, 5, 6, 8, & 9.
Levees lowered & 20-meter (65.6 feet) cut	Same as above (levees lowered) except Highway 101 overbank reduced by 6 hours and stage decrease of approx. 0.1 meter (0.32 feet) in Highway 101 area.	Peak stage decreased by up to ≈ 0.1 meter (0.32 feet) in cells 4, 5, 6, 8, & 9.
Increased upstream capacity (culverts)	Increase flood duration on Hall Slough and adjacent flood cells. Wilson River decrease of <0.1 meter with receding limb of hydrograph reduced by 5 hours.	Same stage as base case, but with longer flood duration.
Lower Trask River (TR 2)		
40-meter (131.2 feet) cut	Peak water surface stage lowered in the Trask River upstream of Netarts Hwy ≈ 0.6-0.7 meter (1.9-2.3 feet). Peak water surface elevation lowered in the overbank between Trask & Tillamook Rivers ≈ 0.4 meter (1.3 feet). Hydrograph duration significantly lowered on Trask River system.	Peak stage decreased by ≈ 0.1 meter (0.32 feet) in cells 4, 5, 10, 12, 13, 14, & 15.
60-meter (196.8 feet) setback (left levee)	Peak water surface elevation lowered in the overbank between Trask & Tillamook Rivers ≈ 0.1 meter (0.32 feet).	None
Levee lowered (right levee)	No significant benefits other than to flood cell 5.	Peak stage decreased by ≈ 0.2 meter (0.65 feet) in cell 5.
Old Trask River (TR 8)		
30-meter (98.4 feet) cut	Flow redirected to Old Trask approx. 1,700 cfs and Tillamook-Old Trask overbank from Trask River. Trask River peak stage lowered ≈ 0.15 meter (0.5 feet) near Old Trask confluence.	None
30-meter (98.4 feet) setback	Redirects ≈ 700 cfs increase in Old Trask flow. No significant change in stage.	None

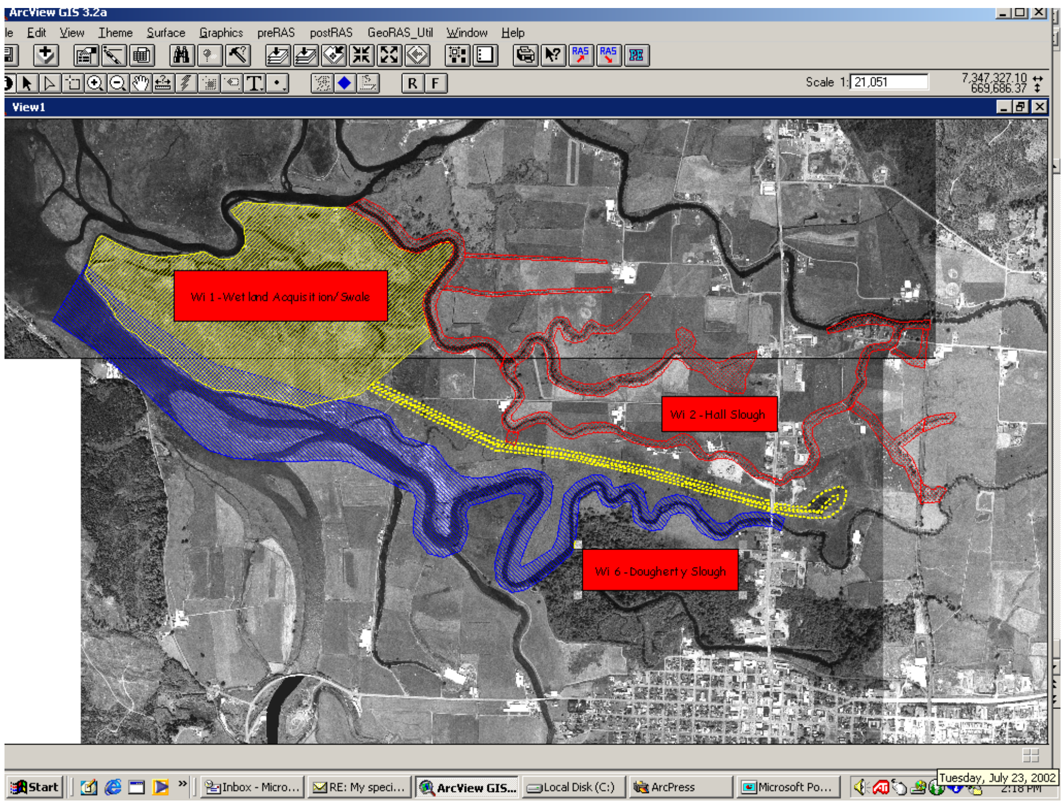
Alternative	Summary of Results	Major Flood Cell Improvements
30-meter (98.4 feet) setback and 30-meter cut	An additional 2,400 cfs redirected to Old Trask and Tillamook-Old Trask overbank from Trask River.	None
Lower Wilson Dredging (WI 11)	Wilson River, Big Cut peak stage lowered between 0-0.3 meters (0-1 feet) in the area of dredging. No significant change in Wilson upstream of dredging.	Adjacent flood cells 6, 8, 9, 11 and 19 are truncated 1 to 6 hours on the rising limb of the hydrograph, and 2.5-7.5 hours on the falling limb.
Lower Wilson River (WI 10)	Wilson River peak stage lowered between 0.1-0.4 meters (0.32-1.31 feet). Approximate overall channel capacity increased from 9,400-11,300 cfs.	Flood cells 6, 8, 9, 11 and 19 are lowered ≈ 0.3 meter (1-foot.) Rising limb of the hydrograph is delayed 4-10 hours. Pool drainage time shortened as much as 10 hours.
Included WI 11 measures	Essentially the same results as WI 10 for the upper Wilson River. Additional stage reduction of approx. 0.1 meter (0.32 feet) for lower Wilson River.	Slight improvement in hydrograph duration, up to 1.5 hours shorter, in addition to results for WI 10 for flood cells 6, 8, 9, 11 and 19.
Lower Trask/Tillamook River Dredge (TR 10)	Trask peak stage reduction from 0-0.25 meter (0-0.80 feet) at most cross sections altered in the channel modification. Tillamook peak stage reduction of up to 1.6 feet in the vicinity of the dredged area. Flow increase in Trask of 1,200 cfs.	Peak stage is decreased between 0.1-0.15 meters (0.32-0.5 feet) in flood cells 5, 12, 13, 14, & 15. Time to drain reduced 6-12 hours for pools 12, 13, 14, &15. Rising limb of the hydrograph delayed 1-2 hours for cells 5, 12, 13, and 14.
Included TR 2 measures	Stages in Trask at dredge are increased as more flow is allowed in channel. Flow increased 3,900 cfs in Trask. Stages upstream of dredge are reduced by up to 1.4 feet. Overall significant decrease in flood duration.	Flood cells in the vicinity of the lower Trask and lower Tillamook Rivers would likely be significantly reduced; however not yet analyzed. Expect similar results to TR 2.
Lower Dougherty & Hoquarten Sloughs (WI 6)		
Levee modifications only	Both a slight reduction in stage and duration occurred for Dougherty Slough at Highway 101 [0.1 meter (0.4 feet) and 1-hour on each end], as well as a minor reduction in stage at Hoquarten Slough at Highway 101. The Trask River was approximately the same as the base case.	Flood cells in the vicinity of Dougherty Slough (cells 10, 12, 13, 14 and 15) would likely be very moderately reduced; however not yet analyzed.
Channel Modification and TR 2 measures	Up to a peak stage reduction of 0.34 meter (1.1 feet) at Highway 101. The duration of flooding at Highway 101 in the vicinity of Dougherty Slough is drastically reduced by approx. 6 hours on the rising limb and 8 hours on the falling limb of the hydrograph while the slough is carrying approx. 530 cfs more water than the base condition.	Flood cells in the vicinity of Dougherty Slough and the lower Trask River (cells 5, 10, 12, 13, 14 and 15) would likely be significantly reduced; however not yet analyzed.
Flood Cell Analysis, Cells 4 through 11 and 19, WEST Consultants	See results of individual alternatives.	Not analyzed individually.

Alternative	Summary of Results	Major Flood Cell Improvements
Corps' Flood Cell Analysis		
Cell 12	As flood waters recede, cell 12 remains flooded longer than surrounding waterways indicating the need for improved connection to local sloughs. Setback or removal of levee along Trask River also may improve Trask River conveyance.	Connection to cells 13 and 14 through breaching of levees would improve habitat diversity. Removal of levees provides limited flood benefits to adjacent areas.
Cells 13-14	Cells 13 and 14 already have good links to Hoquarten Slough through levee breaches; removal of levees reduces stages in Hoquarten Slough only slightly.	Any reductions would show changes in immediate vicinity only.
Cell 15	Removal of levees provides increased conveyance for Hoquarten Slough reducing flood levels on Dougherty and Hoquarten Sloughs at Highway 101 (see WI 6).	See WI 6.
Cells 16 and 18	Setback levees along with increased channel capacity in Trask River vicinity provide very significant reductions in flood levels. Setback levees along with increased channel conveyance in the Old Trask channel provide moderate reductions in flood levels. Lowering all levees reduces flood levels in surrounding channels only slightly.	Area currently does not flood less than approximately 50-year flood.
Cell 17	Removal of entire levee allowed the Tillamook River at Netarts Highway bridge to drop by approx. 0.2 meter (0.65 feet). The water level within the leveed area also showed dramatic improvement from retaining water to following the Tillamook's rise and fall. Improved connections would remove standing flood waters. Setback levees would slightly improve flood conditions on the Tillamook River.	Locations other than the immediate vicinity would have limited benefits from modifications to this cell.

REFINED ALTERNATIVE ANALYSIS

The preliminary model results were presented to the Feasibility Advisory Council and interested citizens in Tillamook on March 27, 2002. Discussions ensued as to which alternatives were to remain for further evaluation and cost analysis. From the modeling results, it appeared that some of the potential alternatives would not provide many benefits for flood damage reduction. The sponsor decided that these alternatives would no longer be considered for further evaluation. Three alternatives remained to be studied as they appeared to have the greatest chance at providing both ecosystem restoration benefits and flood reduction benefits (Figure 26). Those areas considered for further MIKE11 analysis included Hall Slough (WI 2), the Wetland Acquisition Area (WI 1), and Dougherty Slough (WI 6).

Figure 26. Areas Selected for Further MIKE11 Analysis

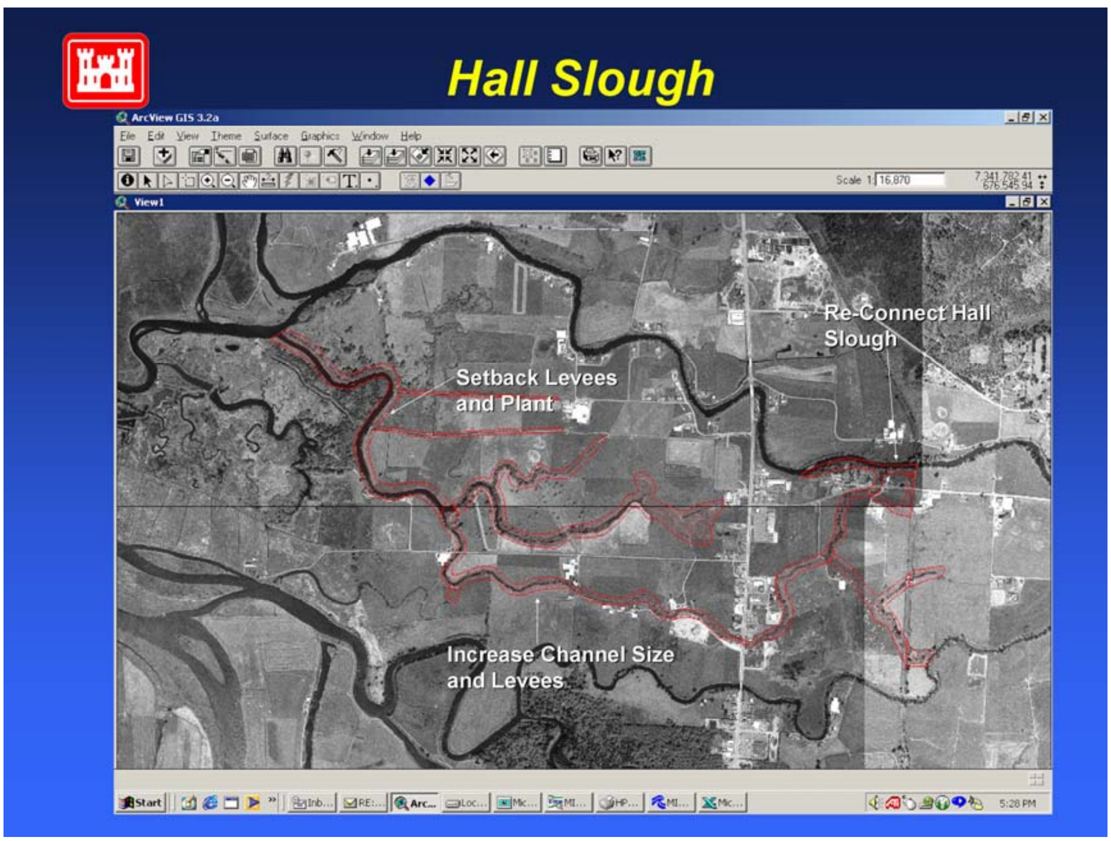


Hall Slough

The goals for the Hall Slough alternative were to restore fish habitat in upper Hall Slough, collect overflows from the Wilson River into a channel for passage to Tillamook Bay, and to take excess floodwater (above 1,000 cfs) in the area and direct it around Highway 101 to the greatest extent possible. At its upper end, Hall Slough was historically connected to the Wilson River. Years ago the upper end of Hall Slough was disconnected and sediment has filled much of the upper channel. As floodwater overflows the Wilson River, it flows out towards the historic upper slough connection, but ends up flowing down roads and fields including Highway 101. Hall Slough is not large enough to contain all floodwater, but it could contain flows up to approximately 1,000 cfs, which is approximately the amount of overflow that occurs for an annual flood. The nuisance floods that disrupt Highway 101 could be controlled with this alternative.

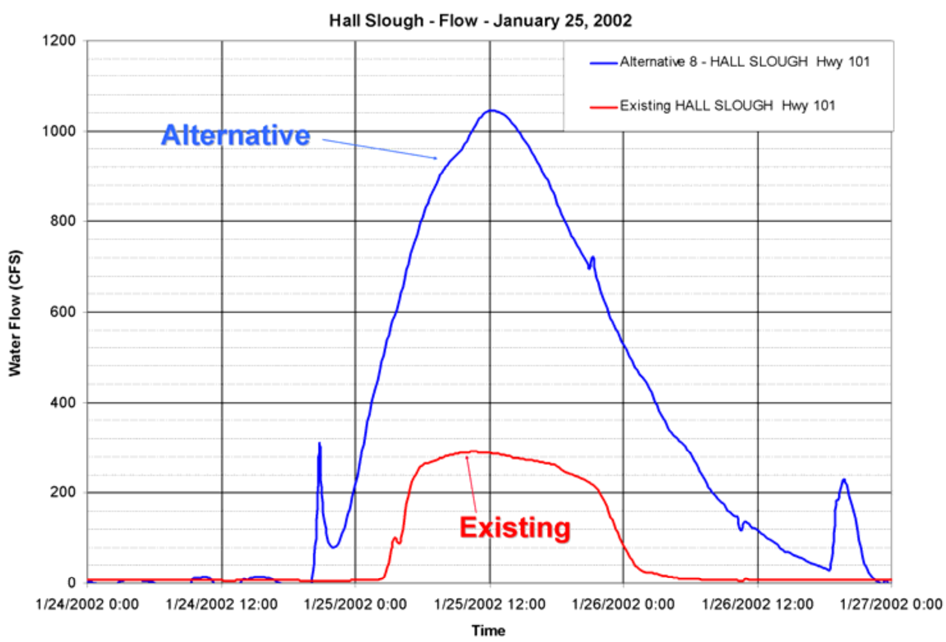
For additional MIKE11 modeling, the slough was deepened throughout to maintain a positive slope to the bay and to be tidally active throughout its length (Figure 27). A conceptual overflow structure was placed at the slough's upper end to allow flows from the Wilson River to enter Hall Slough when the river reached elevation 15.4 feet NAVD88. Wilson River flows would then be allowed in Hall slough via a weir structure. In order for increased flows in Hall slough to remain within the slough, the slough was widened and deepened from its upstream end down to the Goodspeed Road bridge. Also, small levees were needed in a few low spots along the slough. The Hall Slough bridge at Highway 101 was lined with vertical concrete walls and deepened to allow for 1,000 cfs of flow. Hall Slough downstream of Goodspeed Road was unchanged other than the levee on the right bank was setback for riparian plantings.

Figure 27. Hall Slough Alternative



Modeling was performed using the January 25, 2002 flood, which represents an annual event on the Wilson River. Modeling results showed that overflows from the January 2002 flood, which had flowed across Highway 101 and into fields behind Fred Meyer, were contained in Hall Slough with the alternative measures in place. Figure 28 shows the change in flow in Hall Slough for the January 2002 flood with and without the alternative measures.

Figure 28. Results of Additional MIKE11 Modeling of the Hall Slough Alternative



The Hall Slough alternative was split into four reaches based on the preliminary design. Detailed sheets were created to assist in the development of the cost estimate and to discuss the reaches with the sponsor, landowners, and community members. The project extends the length of Hall Slough from the confluence with the Wilson River to the upstream end. Reaches are numbered starting at the downstream end.

Reach 1 extends from the Wilson River to 800 feet downstream of Goodspeed Road. Reach 1 design features consisted of levee modifications and a low level overflow to Blind Slough. Hall Slough is currently 100 feet wide and deep enough for tidal flushing in this area, making excavation unnecessary. The right bank levee is setback and raised and the left bank levee is raised along the existing private road. The levees are high enough to contain 1,000 cfs. If possible, the Fuhrman house should be acquired and removed. If this is not possible, a ring levee will be required around the Fuhrman house at the end of the private road. The levees are designed to contain the 75% chance exceedance flood. All larger floods will overtop the levees.

The biological focus group requested 150-foot levee setbacks throughout the project. In some locations, the levee setback may be less if existing structures are too close to the slough or if an individual landowner negotiates a smaller setback. The majority of the setbacks must be maintained through landowner negotiations or the project will no long be justified based on ecosystem restoration. The landowner negotiations should be coordinated with Corps' biologists to ensure the project maintains positive ecosystem benefits.

Reach 2 extends from Reach 1 to 300 feet downstream of Highway 101. Reach 2 has similar setback levees to Reach 1 and Reach 2 also has channel excavation to allow tidal flushing throughout the reach. The invert of the channel is mean lower low water with a positive slope toward the Wilson River. The top width of the cannel is 90-100 feet and the bottom width is 50 feet.

Reach 3 extends from Highway 101 to Reach 2 and includes the Highway 101 bridge. Replacing the bridge is not cost-effective for this project. To achieve the necessary conveyance through the existing bridge, vertical walls will be constructed at the bridge abutments. The vertical-walled channel would continue downstream to convey the floodwaters past several existing structures near the existing banks, just downstream of Highway 101.

Reach 4 extends from Wilson River Loop Road to Reach 3. The channel will be excavated to allow tidal flushing up to Wilson River Loop Road. The channel will be approximately 75 feet wide in this reach, with an invert slightly above mean low water and sloping towards Reach 3. Reach 4 also contains several large box culverts to convey water under private roads. Levee setbacks in this reach will be determined as described above.

The tidal portion of Hall Slough ends at Wilson River Loop Road. Several large culverts will flow under the road. The flow will come from notches in the bank of the Wilson River just downstream of the railroad bridge. The plan was originally designed with a primary and secondary overflow; however, if the landowner requests, the primary overflow could be expanded to carry all of the flow when the Wilson River stage reaches 15.4 feet NAVD88. The overflow was designed to remove a maximum of 1,000 cfs from the Wilson River during an annual flood event.

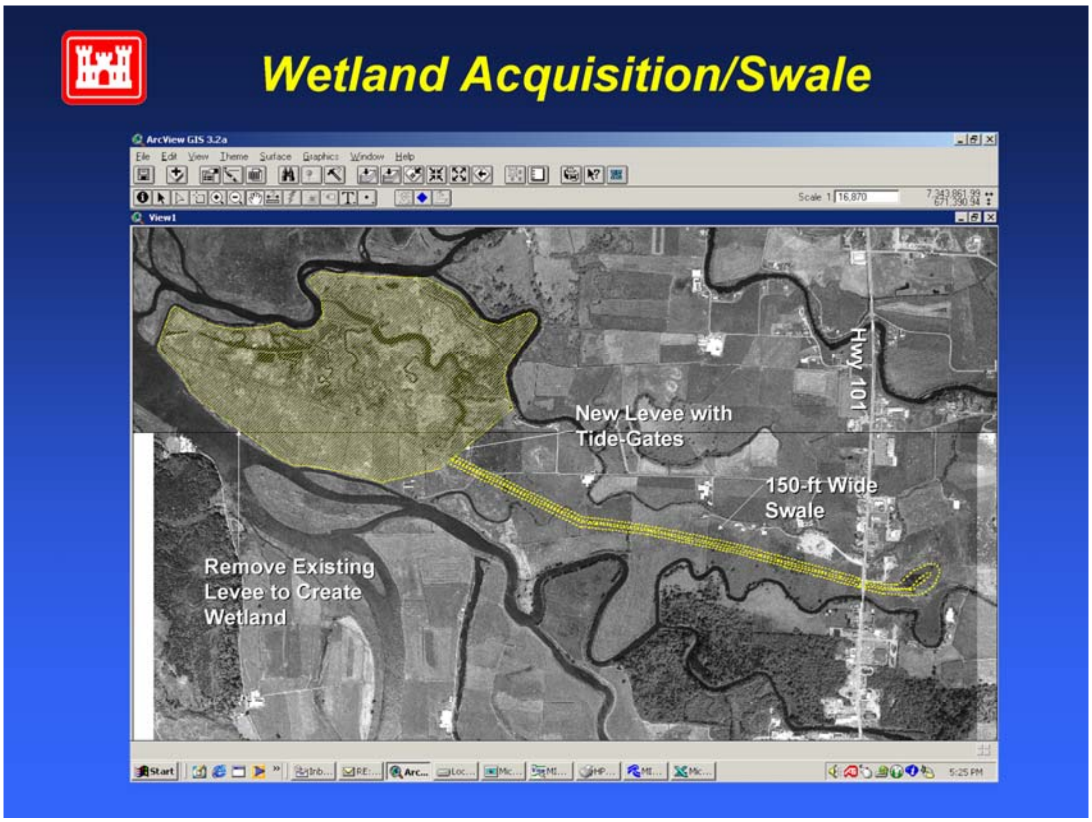
To ensure that the Hall Slough alternative would not increase flood elevations, three additional features were included. Two berms on the right bank of Dougherty Slough were raised. Upstream of the railroad embankment, 1,500 feet of the right bank berm was raised 1.5 feet. Immediately upstream of Highway 101, 1,000 feet of the right bank berm was raised 3.0 feet. These berms were required because the new Hall Slough levees keep more water in the channel, which pushes less water over the levees into the field between Hall Slough and Dougherty Slough. This causes the water level in the field to lower which then draws more water out of Dougherty Slough. The berm modifications described above keep the same volume of water in Dougherty Slough with or without the Hall Slough alternative. The final feature of the alternative is a small swale in the field between Hall Slough and Dougherty Slough. The swale is 30-feet wide and connects two low spots (elevation 9 feet NAVD88) approximately 1,000 feet upstream and downstream of Highway 101.

The Hall Slough alternative was modeled for two flood events. The January 2002 flood has a peak flow of 15,700 cfs. This flood event was considered the design flood event with a 60% chance of being exceeded on the Wilson River each year. For the feasibility study, this flood event is considered an annual, nuisance flood event. The Hall Slough alternative was designed based on the 2002 flood event. This alternative also was modeled with the 100-year flood event to ensure there would be no increases to base flood elevations.

Wetland Acquisition/Swale

The wetland acquisition alternative represents a unique area in the Tillamook Bay watershed. Not only is it at the tidal interface of the two largest rivers in Tillamook Bay, it sets at the downstream end of the area's greatest flood-prone properties in the Highway 101 business district. It appears to be an area with a good likelihood of providing both flood reduction benefits and ecosystem restoration benefits. During preliminary analysis, it was shown that opening up the leveed area to tidal conditions would increase flooding conditions at Highway 101. Since this is not acceptable, other alternatives were formulated. One of these showed some positive results for allowing the wetland acquisition area to be re-connected to tidal conditions of Tillamook Bay by removing and setting back the existing levees, while also reducing flooding at Highway 101. This included adding a swale 150-feet wide that would begin upstream of Highway 101 and continue downstream to the edge of the wetland acquisition area. The concept of the swale was simple in that it would be a large ditch that would remain dry for most of the year. During flood conditions, however, overflows from Dougherty and Hall Sloughs would end up in this area and be swiftly evacuated by the swale to Tillamook Bay during ebb tide. The current situation allows for these overflows to find their way to the bay through businesses, farm fields, fences, and levees. The swale was located in fields currently used for grazing of dairy cattle, and these uses could continue within the swale. Figure 29 shows the measures for the wetland acquisition/swale alternative.

Figure 29. Wetland Acquisition/Swale Alternative



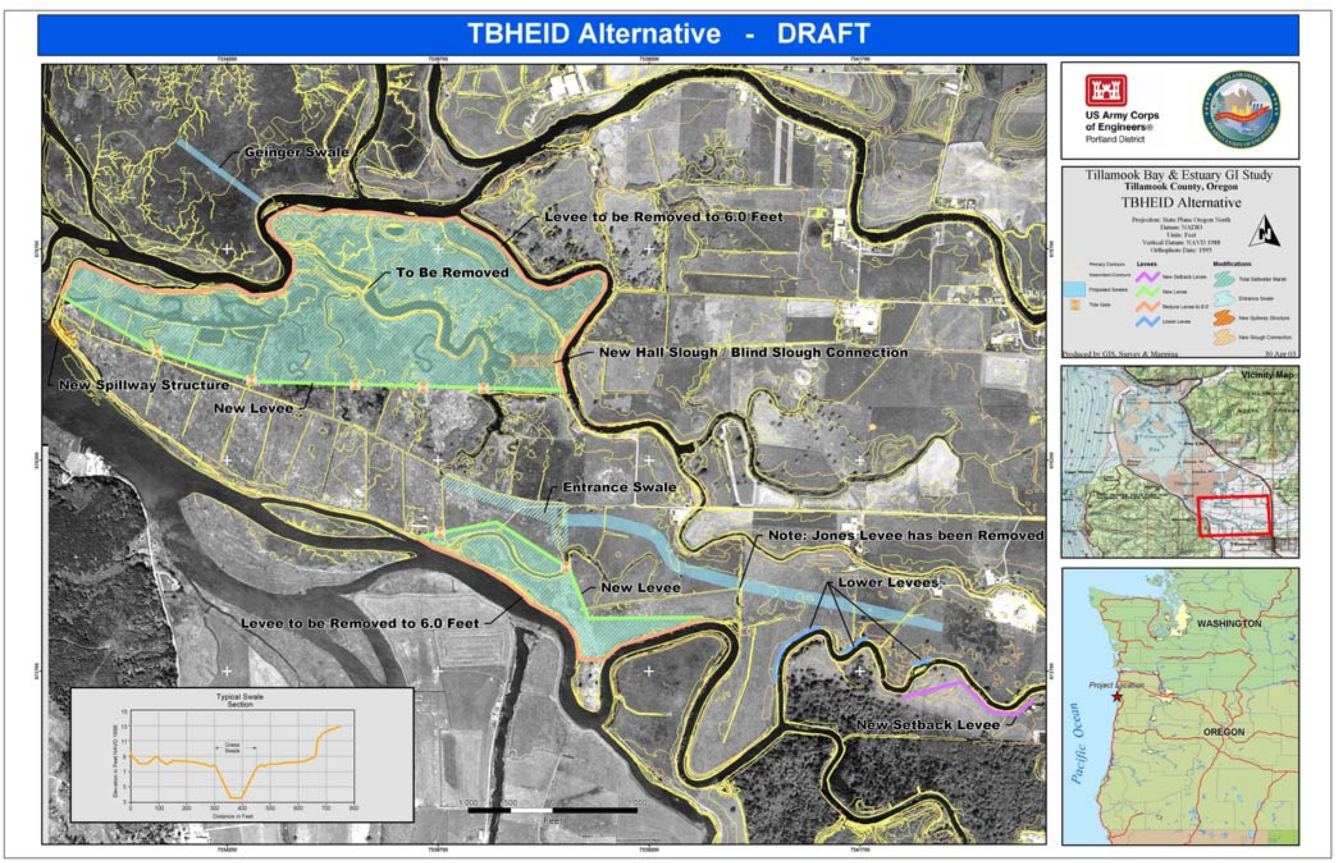
The initial swale design consisted of a long and shallow ditch that would have a minimal slope and an invert elevation of 5 feet NAVD88. The ditch would have a bottom width of 50 feet and a top width that equaled 150 feet with varying side slopes of 10- to 25-feet horizontal to 1-foot vertical. The intention of the swale would be to collect overflows from Hall and Dougherty Sloughs in a central location and to evacuate those overflows in the most expedient manner possible. The swale included a bank of ten 6-feet in diameter tide-gated culverts at its downstream end in the levee for the wetland acquisition area. It also included culverts under Highway 101. Initial model results for this concept showed that for the November 1999 flood, maximum flood elevations at the swale just upstream of Highway 101 would have been 0.3 feet lower, and the duration of flooding would have been 5 hours less with the swale in place.

This alternative was modified after the 100-year flood event was modeled because removing all of the dikes/levees surrounding the Wetland Acquisition area caused an increase in 100-year flood elevations with the swale. Based on the preference of the Biological Focus Group, the levee breaches were limited to a 30-foot wide breach at the northwest end of the main drainage ditch and the removal of the tide gates on the two Blind Slough culverts. This variation removed the increases in the 100-year flood elevations. The sponsor decided to not develop this alternative in more detail and to focus remaining study funds on the Modified Wetland Acquisition/Swale alternative discussed below.

Modified Wetland Acquisition/Swale

The Wetland Acquisition/Swale alternative was modified to represent the Dougherty Slough (WI 6) alternative at the sponsor's request. The Tillamook Bay Habitat and Estuary Improvement District (TBHEID) provided Tillamook County with four documents suggesting numerous concepts to modify the Wetland Acquisition/Swale alternative. The main feature includes a new levee dividing the area in half, east to west, separating a fully tidal area to the north with a flood storage area to the south. Agreement was reached that while flood storage area could be used for ecosystem restoration, it could not be fully tidal and it must be reserved for flood storage and conveyance during flood events. A muted tide concept was discussed. The muted tide gate would allow the flood tide to rise to a specified elevation, for example 5 feet NAVD88, but the tide gate would shut at the specified elevation. The muted tide would allow partial saltwater intrusion on the wetland acquisition property and prevent seawater from reaching the landowners beyond the project boundaries. The concept drawing of the alternative is shown on Figure 30.

Figure 30. Modified Wetland Acquisition/Swale Alternative



The full-time saltwater marsh to the north would be reconnected to the Wilson River by removing the plug in Blind Slough, removing the levee at several historic sloughs, and creating an overflow from the left bank of Hall Slough. Beyond the wetland acquisition property a swale would be required from the project boundary to Averil's property boundary but would not be required to extent upstream of Highway 101. Without the swale, the project caused a rise in 100-year flood elevations at several locations. The swale was included to ensure that the project did not increase flood elevations. An additional ecosystem restoration feature of the flood storage area could be an excavation of the existing drainage ditch and additional excavation to create saltwater marsh that would be inundated with the muted tide.

Dougherty Slough

After the Modified Wetland Acquisition/Swale alternative was developed, there were not enough funds remaining to develop the Dougherty Slough alternative. However, the alternative remains a viable ecosystem restoration project.

KILCHIS RIVER MIKE11 MODEL

The Kilchis River was modeled using MIKE11 from its terminus in Tillamook Bay to RM 5.88. Modeling of the Kilchis River included Squeedunk, Neilson, Stasek, and Hathaway Sloughs. The first step in model creation was to place all the river reaches in a GIS database to extract cross-sectional information, reach lengths, and topographic information from the area's TIN and aerial photography. The main flow paths for the river include the Kilchis River and Squeedunk Slough. The two channels were digitized in ArcView GIS utilizing orthophotogrametric mapping from 2000 aerial photos. Figure 31 shows the Kilchis and Squeedunk channel network after digitization. Once the main river channels were digitized, the major sloughs were added (Neilson, Stasek, and Hathaway). These sloughs are normally tidal, but also serve as a floodplain conveyance network during high flood events.

Once the main river channels and sloughs were added to the model, the major floodplain features were added. Floodplains were modeled in MIKE11 utilizing river branches, which located the route of flood flows in the floodplain areas. Floodplain branches depict ditches and swales that drain the floodplain area. Figure 32 shows the floodplain network added to Kilchis MIKE11 model.

Figure 31. Sloughs Modeled in the Kilchis River Model

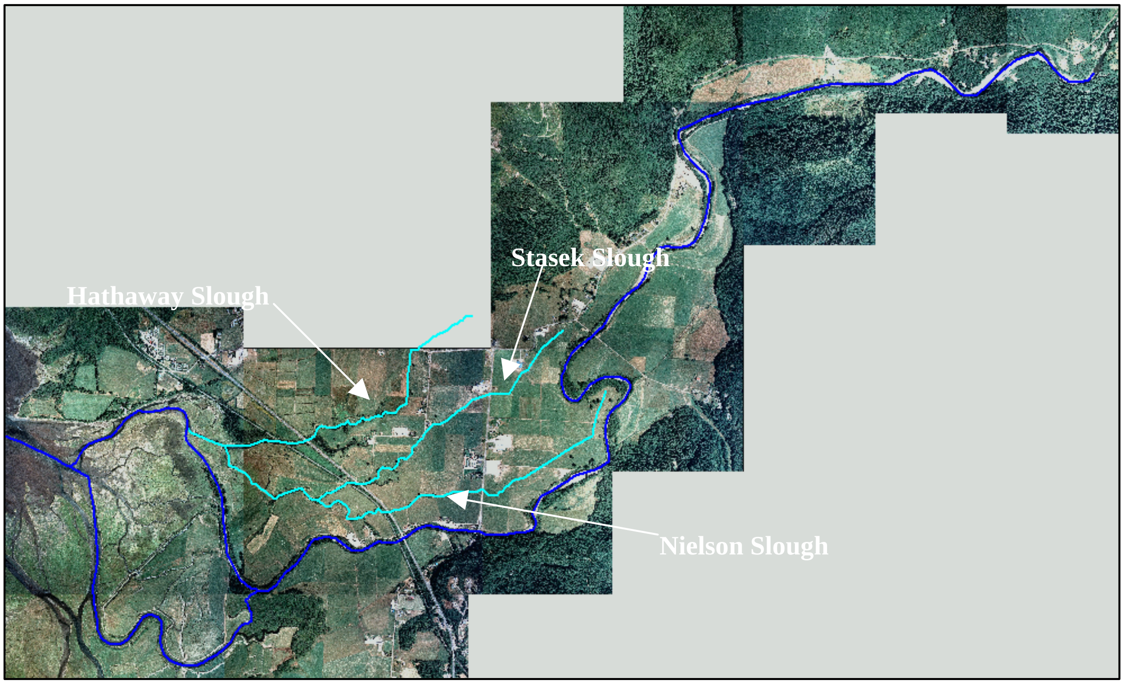
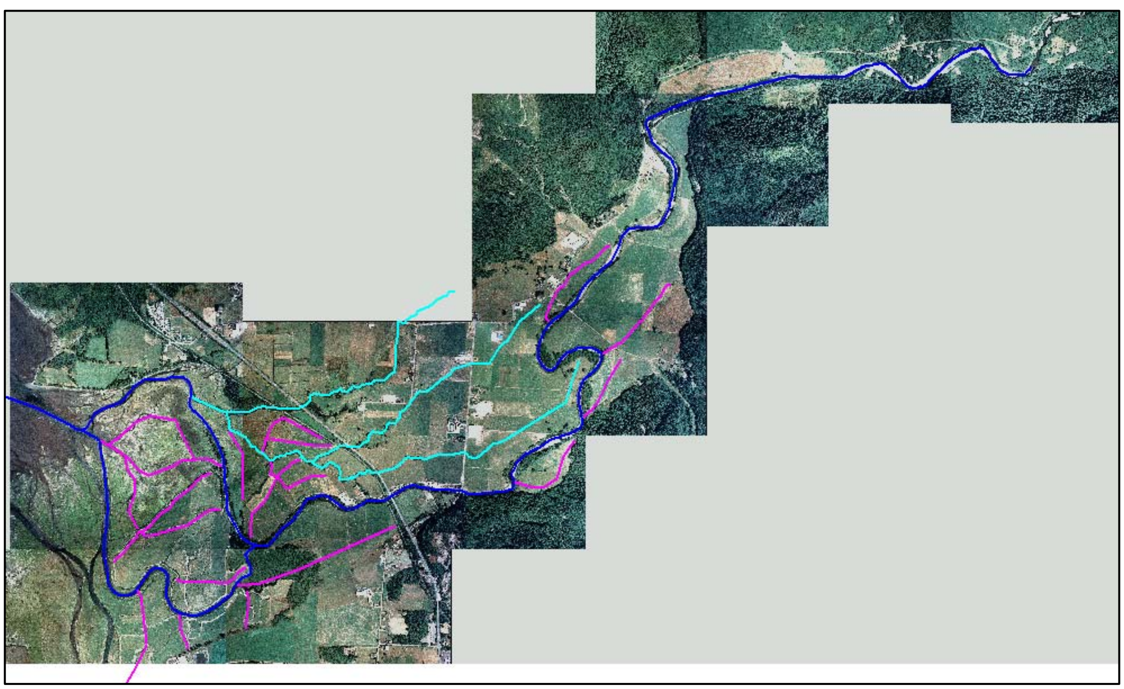
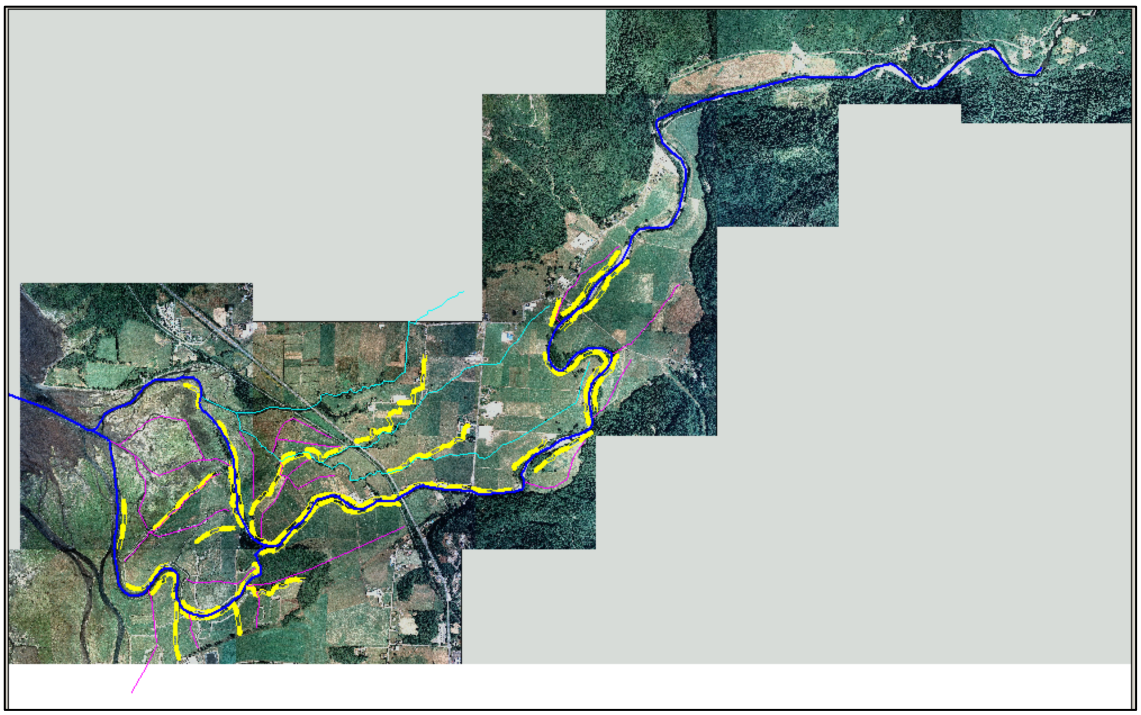


Figure 32. Floodplain Network of the Kilchis River Model



As discussed in the description of the Wilson-Trask-Tillamook River MIKE 11 model by WEST Consultants (Appendix B), link channels were used to tie the floodplains to the river channels. Link channels allow the MIKE 11 model to become a ‘pseudo two-dimensional model’ in that they allow flow to take place laterally to the river branches through weir flow. Link channels connect river branches by defining the high points between branches with an elevation versus distance table in the model. Thus, when water rises just above the threshold of the link channel, water begins to flow between the branches. This flow can take place in either direction. Figure 32 shows the link channels added to tie together branches in the Kilchis River model.

Figure 33. Link Channels in the Kilchis River Model



Cross-sectional Geometry

Cross-sections were added to the model to represent channels, sloughs, and floodplain topography. Cross-sections of the Kilchis River and Squeedunk Slough were surveyed. Cross-sections of floodplain features, as well as secondary sloughs, were estimated from the orthophotographic mapping. The sources for all cross-sectional information are shown below.

<u>Kilchis River Cross-sections</u>

- River Miles 0-3.98: Tillamook County Surveyors Office, survey summer/fall 2000.
- River Miles 3.98-5.50: Gibbs and Olson survey (1995) under contract for the Corps; mapping study by the Corps under contract by FEMA.
- River Miles 4.03-5.88: Corps May 2001 updated many sections of the Gibbs and Olson survey, as well as added new cross-sections.

Squeedunk Slough Cross-sections

- All sections: Tillamook County Surveyors Office, survey summer/fall 2000.

Nielson, Stasek, and Hathaway Sloughs

- Rail Road Openings: Nehalem Marine Inc. survey April 2001.
- All other sections: Orthophotographic mapping 2000.

Floodplains

- All sections: Orthophotographic mapping 2000; sections were 'cut' from a TIN developed by the mapping data utilizing the GeoRAS feature by HEC within ESRI's ArcView GIS software.

Bridges

There are six bridges on the Kilchis River, one on Squeedunk Slough, and two each on Neilson, Stasek, and Hathaway Sloughs. Bridges on the Kilchis River and Squeedunk Slough were initially surveyed by the Tillamook County Surveyor in 2000. Railroad bridges on Neilson, Stasek, and Hathaway Sloughs were surveyed by Leo Kuntz of Nehalem Marine. Additional surveys of bridge details were made by the Corps during subsequent trips in spring 2001. Bridges were modeled with four cross-sections: one at the upstream face, one at the downstream face, and one at both the upstream and downstream contraction and expansion points of each channel. Cross-sections were surveyed by the Tillamook County Surveyor. Bridges were modeled in MIKE11 utilizing the culvert option. Weirs for bridge overtopping were not added to bridges in the Kilchis River model because it was apparent that bridges would not be overtopped in this manner. Culvert dimensions were estimated from survey data and geometric properties of each bridge (piers, abutments, deck, low-cord, etc).

Model Calibration

The Kilchis River model was not initially calibrated to the May 2001 instream event because the flow data recorder was not working at the time. The model was calibrated to the November 1999 flood. Three high-water marks were known for the November 1999 event. Two crest gauge readings were obtained on gauges installed 2 weeks prior by the Corps. The third point was obtained from the OWRD stage gauge at the Curl Road bridge. The model was calibrated to this event by running the flows that were recorded at the Curl Road bridge (RM 3.01) and transforming that gauge data upstream to the start point of the Kilchis River model (RM 5.88).

Transforming the upstream boundary flow required altering the time of concentration and removing inflows from Mapes and Myrtle Creeks. This was performed by drainage area proportion and time of concentration estimates for each creek. Ungauged downstream tributaries were added and included Murphy, Coal, and Vaughn Creeks. Estimates of ungauged hydrographs for each creek were obtained from the Kilchis River hydrograph and drainage area proportion combined with altered time-of-concentration for each watershed. Because there was no gauge in the bay during the event, downstream boundary conditions were estimated as the NOAA estimated tidal signal at Garibaldi in Tillamook Bay for the time period of the event.

Calibration was performed by adjusting the Manning's roughness coefficient in the model at each river section until reasonable water surface elevations resulted. Floodplains in the Kilchis River model were not adjusted, only the main branches of the Kilchis River and Squeedunk Slough. Tables 11 and 12 show the resulting Manning's roughness and calibration results for the November 1999 flood event.

Table 11. Final Manning's Roughness Values by Reach, Kilchis River

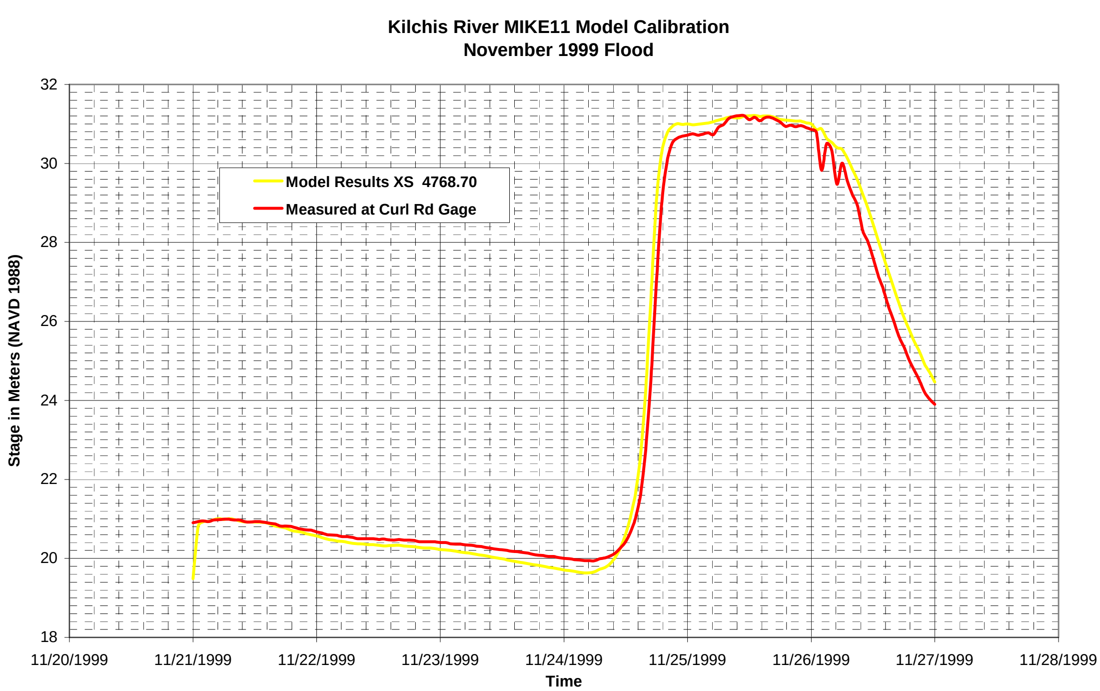
River Reach	Final Manning's Roughness Value
Kilchis River - Clear Creek to Curl Road Bridge (Chainage 0 to 4742)	0.030
Kilchis River - Curl Road Bridge to Old Hwy 101 Bridge (Chainage 4742 to 7402)	0.040
Kilchis River - Old Hwy 101 Bridge to Mouth (Chainage 7402 to 14398)	0.055
Squeedunk Slough - Kilchis River to Mouth	0.055

Table 12. Kilchis River Final Calibration Results, November 1999 Flood Event

Location	Modeled	Measured	Difference
Forest Service Rd Bridge (RM 3.99)	10.98 meters (36.01 feet)	10.88 meters (35.68 feet)	+0.1 meters (+0.33 feet)
Curl Road Bridge (RM 3.02)	9.51 meters (31.19 feet)	9.50 meters (31.16 feet)	+0.01 meters (+0.03 feet)
Old Hwy 101 Bridge (RM 1.35)	6.37 meters (20.89 feet)	6.55 meters (21.48 feet)	-0.18 meters (-0.59 feet)

Calibration data consisted of highwater marks only. In order to evaluate the model's effectiveness over time, results were plotted for modeled stage at the Curl Road bridge versus recorded stage at the gauge as shown in Figure 34.

Figure 34. Kilchis River Model Results Versus Gauge Data, November 1999 Flood Event



Kilchis River Alternative Analysis

The Kilchis River model was used to analyze the effects of dredging the lower Kilchis River and widening the lower river and Squeedunk Slough. The lower river has filled with sediment below its confluence with Squeedunk Slough. Squeedunk Slough has pirated the flow of the Kilchis River and now carries the majority of flow to Tillamook Bay. The base condition model was altered from the railroad bridge down to the bay in the Kilchis River, Squeedunk Slough, and the surrounding floodplains. Alterations included dredging the lower river and widening the slough to increase channel capacity.

Several scenarios were run that included either widening the slough or the lower river, dredging the lower river, removing levees in the lower river, setting back levees in the lower river, and combinations of the above. The scenarios were modeled with the November 1999 flood event and then compared to base condition model runs. Results showed that water surface slopes were reduced in the immediate area of channel dredging and widening. However, not far upstream from the altered channels, the water surface slope matched that of the base conditions. It was determined that dredging the lower river and Squeedunk Slough would not affect the upper river valley.

The next step in model evaluation was to determine where problem areas were located in terms of flooding. Tillamook County could not determine the location of these specific problem areas, and no further alternatives were considered.

MIAMI RIVER MIKE11 MODEL

ArcView GIS 3.2a and the GEO-RAS model were used to export the Miami River channel centerlines used to create the MIKE 11 network file *Miaminet1.nwk*. Mainstem and tributary channel centerlines were first digitized within ArcView based on orthophotos (*miami1.jpg-4.jpg*) and a 2-foot contour theme created from the TIN, *Miamitin*, located at *Tyler\Bay&Est_GI\Design_Files\Mike11 models\GIS themes\miami river*. The centerlines were processed by specifying the digitized line as the channel centerline, creating a flow path, and then specifying the fake tin *blkmiamitin* that was created to encompass the watershed. Branches were exported separately as recommended by Hans Hadley.

Cross-section survey data was collected by Tillamook County surveyors from Miami River mile 0.12 to 4.97, provided to the Corps, and converted to Excel files. All data was converted to metric units and then placed into a MIKE11 cross-section file. The file *Miami River xs.xls* contains all of the cross-section data entered into the MIKE11 model. In order to get the model to run successfully, the most upstream and most downstream cross-sections were copied to the boundaries of the river network (e.g., chainage 0 and chainage 9800). Initial runs of the MIKE11 model utilized dummy inflow data for the upstream boundary condition and measured Garibaldi tide gauge data for the downstream boundary condition.

Bridge dimensions were obtained from drawings provided by Tillamook County and field verified by the Corps. Initially, attempts were made to add bridges at the downstream end of the model (at Highway 101) by using a combination of culverts and weirs. These initial efforts were unsuccessful due to model instabilities. However, the bridge at the most upstream end at RM 4.95 was the only bridge on the Miami River likely to be overtopped during flood events (based on conversations with residents). Therefore, for initial modeling efforts, all bridges were modeled using the Tillamook County survey data measured at the upstream and downstream faces of each bridge. Each surveyed cross-section consisted of an upstream face and opening and a downstream face and opening. The upstream and downstream face sections were the surveyed sections. These sections were placed 1-foot toward the center of the bridge, named the ‘opening’ section, and modified slightly to include pier dimensions. Thus, each bridge consisted of four cross-sections. The final model of the Miami River included the uppermost bridge at RM 4.95 modeled as a culvert and weir.

Inflow Hydrographs and Data Used for Calibration

Inflow data used for further model development and calibration included predicted tide level data obtained by the Tides and Currents program. In the future, tide gauge data also will be available from a tide gauge located at the Garibaldi Coast Guard station (installed by the Corps in March 2001). Gauge height data is available from the OWRD stream gauge located at the Moss Creek Road bridge (RM 1.69). Streamflow was approximated using the OWRD rating curve for the site (dated October 2000). Crest gauge data also is available from the Corps-installed gauge located at the uppermost bridge at RM 4.95. It was originally thought that high water marks measured by the Corps during the May 2001 storm event could be used for in-channel model calibration. Unfortunately, the OWRD stream gauge on the Miami River was not operating from the end of February until the end of May when the gauge was eventually serviced. Therefore, the only storm event that had sufficient data available for calibration (including high water marks at RM 4.95, tide gauge, and streamflow data) was the November 1999 storm event.

The simulation period used for the November 1999 event extended from November 15 through December 6, 1999. Predicted tide gauge data was recorded for this period at 15-minute intervals, streamflow data at the OWRD gauge was approximated based on gauge height (recorded every 15 minutes), and crest gauge data at RM 4.95 was recorded by the Corps in December 1999. All inflow data was compiled and then modified to incorporate significant subbasin inflow locations.

Modification of Inflow Hydrographs

The total area of the Miami River Basin is approximately 23,444 acres; the gauged area is approximately 18,255 acres and the ungauged area is approximately 5,189 acres. Significant subbasin inflow areas were identified and subbasin areas were approximated using ArcView. Subbasin areas were then used to compute the percent area of each subbasin as compared to the gauged area of the Miami River. These percentages were applied to the flow measured at the Moss Creek Road gauge, and individual inflow hydrographs were computed for each of the major subbasin inflow locations. For example, 64% of the gauged area of the Miami River is located upstream of RM 4.95; therefore, 64% of the inflow hydrograph was added at RM 4.95.

In an attempt to address the issue of hydrograph timing, Snyder's lag time was used to determine the relative difference in lag time between the gauged subbasins and the ungauged subbasins downstream. Lag time in hours (tp) = $Ct[(L)(Lc)^{.3}]$, where Ct is a lag coefficient ranging from 1.8 to 2.2 (an average of 2.0 was used), L = length of the basin divide, and Lc = length along the mainstem to a point nearest the centroid. Values for L and Lc were estimated by measuring the distances in ArcView. Approximate lag time for the area upstream of the OWRD gauge was 6.5 hours, and the average lag time of the smaller ungauged subbasins was 2 hours. Inflows for subbasins downstream of the gauge at Moss Creek Road were shifted by the difference in lag time. Inflows for subbasins upstream of the gauge were not shifted since the total flow measured at the gauge takes into account differences in timing of the upstream subbasins (it also was not possible to back-calculate the exact volume and timing of individual subbasin inflows).

Time series files were created for each of the major inflow locations and were added to the boundary condition files.

Overbank Model Development

Orthophotos and *Miamitin* themes were used to estimate flow paths and possible overbank channels in the basin. Results of initial model runs were also looked at to determine areas where streambank overtopping could occur. It was determined that most flows would likely stay within the mainstem stream areas from the upstream end of the study reach to approximately RM 1.9. Additionally, only areas that encompassed a relatively large area (spanning multiple cross-sections along the mainstem) were considered significant enough to add an overbank channel. Overbank side channels were not added to the area downstream of the confluence of Illingsworth Creek since it was apparent that the entire area floods during high flow events.

Overbank channels and large tributary branches in the lower part of the basin were digitized using ArcView and processed in the GEO-RAS model in the same manner as the mainstem channel. Channels were named using the naming convention proposed by WEST Consultants, Inc. For example, a left overbank channel entering into the mainstem at RM 1.31 would be named *Miam-LB MI 1.31*. Cross-sections were digitized across the overbank channels at locations adjacent to the mainstem cross-sections plus some additional locations where it appeared that spacing of the cross-sections was too far apart. The HEC-RAS model was used convert units to metric and to filter cross-section points for the overbank channel cross-sections. Cross sections were then exported to Excel.

A new network was created and overbank channels were added to the mainstem channel. A new cross-section file (*20sept01miamic.xns11)* was created to incorporate the additional branches added to the network. When this was completed, mainstem cross-sections were modified in MIKE11 so that the mainstem cross-sections ended where the overbank channel cross-sections began. Overbank channel cross sections were taken from Excel and placed into the new MIKE11 cross-section file. The ArcView extension profile extractor tool was then used to check for possible low points and link channel locations. Thirteen link channels were digitized along lines cutting perpendicular between each set of overbank channel cross-sections (*linkcuts.shp*). These cross-sections also were cut from *Miamitin,* exported for processing in HEC-RAS, and then exported to Excel. A new MIKE11 cross-section module (*miamilinkxn2.xns11*) was created and link channel cross-sections were taken from Excel so that a depth-width table could be computed. This data was then copied into the overall network module containing the mainstem and overbank channels. Later, depth-width tables were increased vertically (up to a depth of 16.4 feet) to prevent errors from occurring. High points of overbank cross sections also were increased to prevent model errors.

Model Calibration and Fine-tuning

It was initially thought that streamflow data from the February 1996 event could be used for overbank model development, but sufficient data was not available. As with most of the other stream gauges in the area, the Miami River gauge failed to operate during the highest flows of the storm event. Therefore, the only storm event data available for calibration was the November 1999 event.

Initial calibration runs were unsuccessful using the parameter file for initial conditions, so a hotstart file had to be created. Hotstart time series data were created and added to the boundary conditions file *miamiHSOBinflow.bnd11*. For each subbasin time series, flows or gauge heights were held constant for a 4-day period, 3-hour time step at the initial flow level measured during the November 1999 event. Overbank channel inflows needed an initial flow to keep the model operating, so a time series file was created with a constant flow of 1 cfs for all overbanks not associated with tributary inflows. Other initial inflows held constant in hotstart time series files are as follows: mainstem chainage 1508.6 = 44.9 cfs; mainstem chainage 3351.8 = 76.6 cfs; mainstem chainage 4069.7 = 25.8 cfs; mainstem chainage 5874.4 = 23.0 cfs; and mainstem chainage 8594.1 = 19.1 cfs; overbank entering at

RM 0.34 = 28.6 cfs and Moss Creek inflow = 68.9 cfs. The hotstart results file *24sept01hsout.res11* was used as the initial condition input for the final configuration of the Miami River model.

The final configuration of the model consisted of a culvert and weir combination added to the uppermost bridge at RM 4.95. Final HD files were modified so that global values for the mainstem were set as Manning's n = 0.03 and horizontal relative resistance for overbank portions of each mainstem cross-section was set at 1.67. This equates to a Manning's n roughness of 0.05. All other overbank Manning's n values (including overbank channels and link channels) were set equivalent to 0.05. Cross-sections located just upstream of the Highway 101 bridge had relative resistance set at 2.67 which equated to a Manning's n of approximately 0.08. This was done to take into account the fact that flow would be backed up behind the bridge due to the constriction.

Miami River Model Results

Based on results found in the final output file *24sept01out.res11,* the computed peak flow occurred at 1:15 PM on November 25, 1999 for the November 1999 event. The computed high water level at the downstream face of Moss Creek Road bridge was 27.2 feet NAVD88. This is approximately 1.2 feet above the level recorded at the OWRD gauge. Timing of the computed peak was only slightly off from the measured peak, which occurred at 1:00 PM on November 25, 1999. A high water mark recorded by Leo Kuntz (after talking to a local resident) was 26.5 feet at a Moss Creek Road left bank overbank area. For comparison, the MIKE11 model computed flow level near this location at 26.6 feet. Results also were quite close at the upstream end of the model where the peak water level of 84.3 feet was recorded at the Corps crest gauge. The computed high water level at this location was 84.0 feet. Downstream computed water levels did not appear to be as close to actual water levels as those found upstream. A high water mark estimate of 15.6 feet was noted at Highway 101, whereas the peak computed water level was 10.6 feet.

Since water surface elevations at the Moss Creek Road bridge were higher than expected, a HEC-RAS model was set up to compare results with the OWRD rating table and the MIKE11 results. The OWRD rating curve is considerably lower than the flows that would have been predicted by the HEC-RAS and MIKE11 models. Discussions with Ben Scales of the OWRD indicate that the rating curve may not be extremely reliable at flows above 4,000 cfs since most measurements made by OWRD to verify the rating curve rarely take place during flows greater than 2,000 to 3,000 cfs.

The FEMA study showed that for the 100-year flood event, base flood elevation was approximately 84.3 feet NAVD88 near the uppermost bridge at RM 4.95. This is quite close to the results measured during the November 99 event. The FEMA computed 100-year flow was approximately 4,590 cfs, and the 500-year flow was approximately 5,470 cfs. It should be noted that it is not certain whether or not the uppermost bridge was in place when the FEMA study was conducted.

Final result files were created in grid output format and mapped in ArcView. Maps were submitted to Tillamook County for review.

US Army Corps
of Engineers ®
Portland District

Tillamook Bay and Estuary, Oregon
General Investigation Feasibility Report

APPENDIX B

Hydraulic Model Development for the Tillamook Bay and Estuary Study

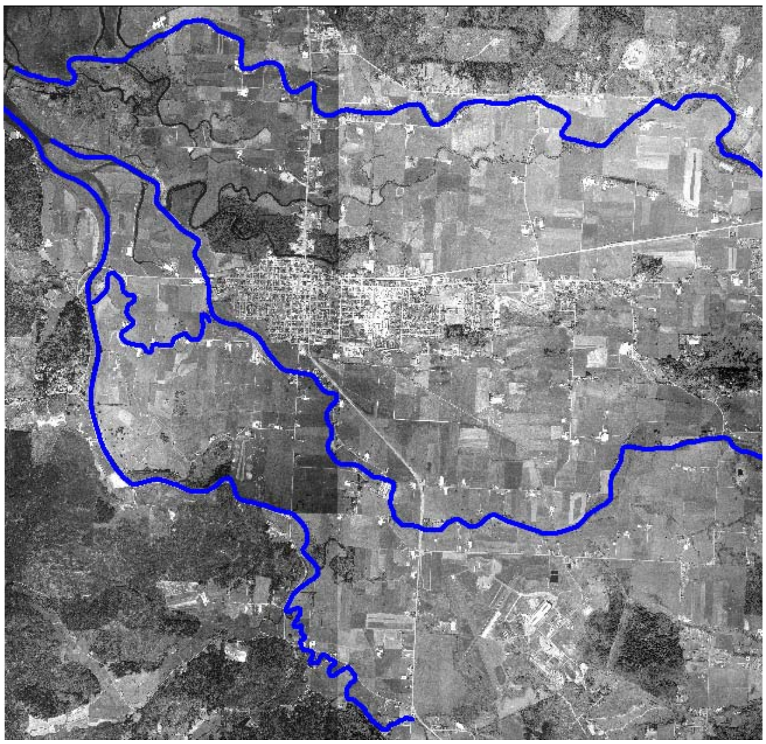
Final Report

Prepared by
WEST Consultants, Inc.
for the
U.S. Army Corps of Engineers
Portland District

March 2004

Hydraulic Model Development for the Tillamook Bay and Estuary Study

FINAL REPORT



MARCH 2004

WEST CONSULTANTS, INC.

Prepared by WEST Consultants, Inc. under contract DACW57-99-D-0003

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FINAL REPORT

Overview

Background

During the past several years, Tillamook County has been devastated by numerous flood events. As a result of the February 1996 flood, Congress authorized a request from Tillamook County to pursue a General Investigation Study of water resource problems in the Tillamook Bay Watershed. The U.S. Army Corps of Engineers, Portland District (CENWP) performed an Expedited Reconnaissance Study during fiscal years 1998 and 1999. The "Recon" study involved review of the many local, state and federal studies, which had recently been completed for the area. The "Recon" study identified the need for further study and laid the foundation for a partnership between CENWP and the project sponsor Tillamook County (County) to further study the environmental issues of Tillamook Bay. A Project Study Plan was formulated to investigate solutions to four identified environmental issues in the Tillamook Bay watershed. The four issues identified are: 1) salmon habitat restoration, 2) reduction of sedimentation, 3) reduction of bacterial contamination in Tillamook Bay, and 4) reduction of the impact of flood events to the region, specifically in Tillamook, Oregon. The General Investigation Study was focused on identifying possible solutions to ecosystem restoration goals that included flood damage reduction as well as providing compatible flood damage reduction solutions to identified problems in the Tillamook Bay region. A key component of the General Investigation Study was the development of a one-dimensional, unsteady-flow model of the five rivers flowing into Tillamook Bay.

Project Description

The study area for this project includes the watershed and estuary of Tillamook Bay. The watershed surrounding Tillamook Bay is dominated by broad valleys along the coastal plain that abruptly rise to the steep mountains of the Coast Range. Elevations vary from near sea level in the coastal lowlands to above 1,100 meters (3,500 feet) in the Coast Range. The majority of watersheds contributing to the bay are located within the mountainous area. Dense forest covers much of the terrain, which overlies impermeable strata in the mountainous watershed.

The Tillamook Bay Watershed contains five principle rivers – the Wilson, Trask, Tillamook, Kilchis and Miami. The Wilson and Trask Rivers are the two largest rivers in the area and contribute to the majority of flooding in the region. The Miami and Kilchis Rivers have similar watersheds and characteristics as the Wilson and Trask, but they are smaller and are located in sparsely populated areas. The Tillamook River, in contrast to the other four, has a relatively low gradient and it's watershed is located mainly along the coastal foothills. The Tillamook River contributes the least to flooding and erosion problems in the region.

WEST Consultants, Inc. (WEST), under contract DACW57-99-D-0003 with the Portland District, U.S. Army Corps of Engineers, was tasked to develop a MIKE11 one-dimensional unsteady flow model of the combined Tillamook, Trask, and Wilson River systems. The District developed models of the Miami and Kilchis River systems.

Hydraulic Model Development

Data Acquisition

Cross-Section Surveys. Surveyed cross-section information, supplied by CENWP to WEST, originated from various sources. This included data from an updated FEMA Flood Insurance Study on the Wilson River and surveys by both CENWP and the County. Cross-sections were provided for the Tillamook (to river mile 6.93), Trask (to river mile 10.95), Wilson (to river mile 9.36) and Old Trask Rivers (complete system provided), and Hall, Dougherty, and Hoquarten Sloughs (complete systems provided). A summary of the data sources for the cross-sections are provided in Appendix A-Table 1.

GIS data. A geographic information system (GIS) triangular irregular network (TIN) was supplied by CENWP to WEST (Figure 1). The TIN was used to define overbank features including floodplain geometry and levee heights for the hydraulic model, and to delineate flooding extents and depths. Aerial mapping for 0.06 meter (two-foot) contour accuracy of the TIN was conducted by CENWP in September 1999 and May 2000. Bathymetric data of Tillamook Bay were collected by CENWP in 1995 and 2000 and provided to WEST in GIS format, from which a TIN was then created.

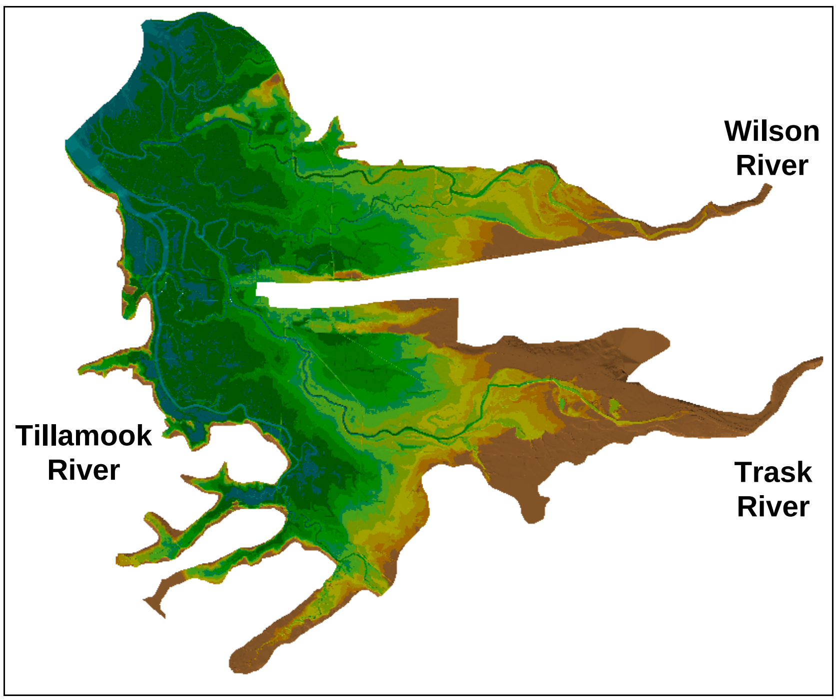

Figure 1. TIN of the Tillamook, Trask and Wilson River valleys (Data source: 2000 aerial photographic mapping to 0.6m (two-foot) contour interval by CENWP).

Stage and Flow Data. Stage and flow data, which was provided by CENWP to WEST, was collected from various sources. Wilson and Trask River hourly stage and flow data, gages #14301500 and #14302480, respectively, were obtained from the U.S. Geological Survey (USGS). Tillamook River flows, gage #14302700, were collected by the Oregon Water Resources Department. Fifteen-minute tidal information at Garibaldi (located near the north end of Tillamook Bay), as well as 15-minute hourly stage data at Kilchis Cove and Dick Point (both in Tillamook Bay), Geinger Farm (on the Wilson River), and Carnahan Park (on the Trask River) were recorded at CENWP gages. Gage locations and descriptions are summarized in Figure 2 and Appendix A-Table 2.

Bridge information. Bridge information was supplied from CENWP surveys, Oregon Department of Transportation (ODOT) bridge scour reports and bridge plans, and the 1999 FEMA Flood Insurance Re-Study. Source information for the major bridges modeled in MIKE11 are tabulated in Appendix A-Table 3.

Culvert data. Culverts included in the model (Appendix A-Table 4) connect the overbank areas to the rivers or sloughs. All these culverts are circular in shape in the MIKE11 model and have tide flaps to restrict the direction of flow when connected to the Wilson, Trask, or Tillamook Rivers. Culvert data were collected and supplied by Tillamook County (USACE, 2001). Upstream and downstream invert elevations were estimated from the TIN when survey data were not available.

Miscellaneous imagery. Orthophotos (color photos dated 2000, and black and white photos dated 1995) were supplied by CENWP. A photo album, by “Best Impressions Picture Company” (Rockaway, OR), and an aerial video of the November 1999 event were also provided by CENWP.

Calibration information. Highwater marks for the November 1999, May 2001, and November 2001 events were provided by CENWP and the County. The CENWP stage data at Dick Point, Geinger Farm, and Carnahan Park, as well as the imagery of the November 1999 event, were also used in calibrating the hydraulic model (see Calibration section).

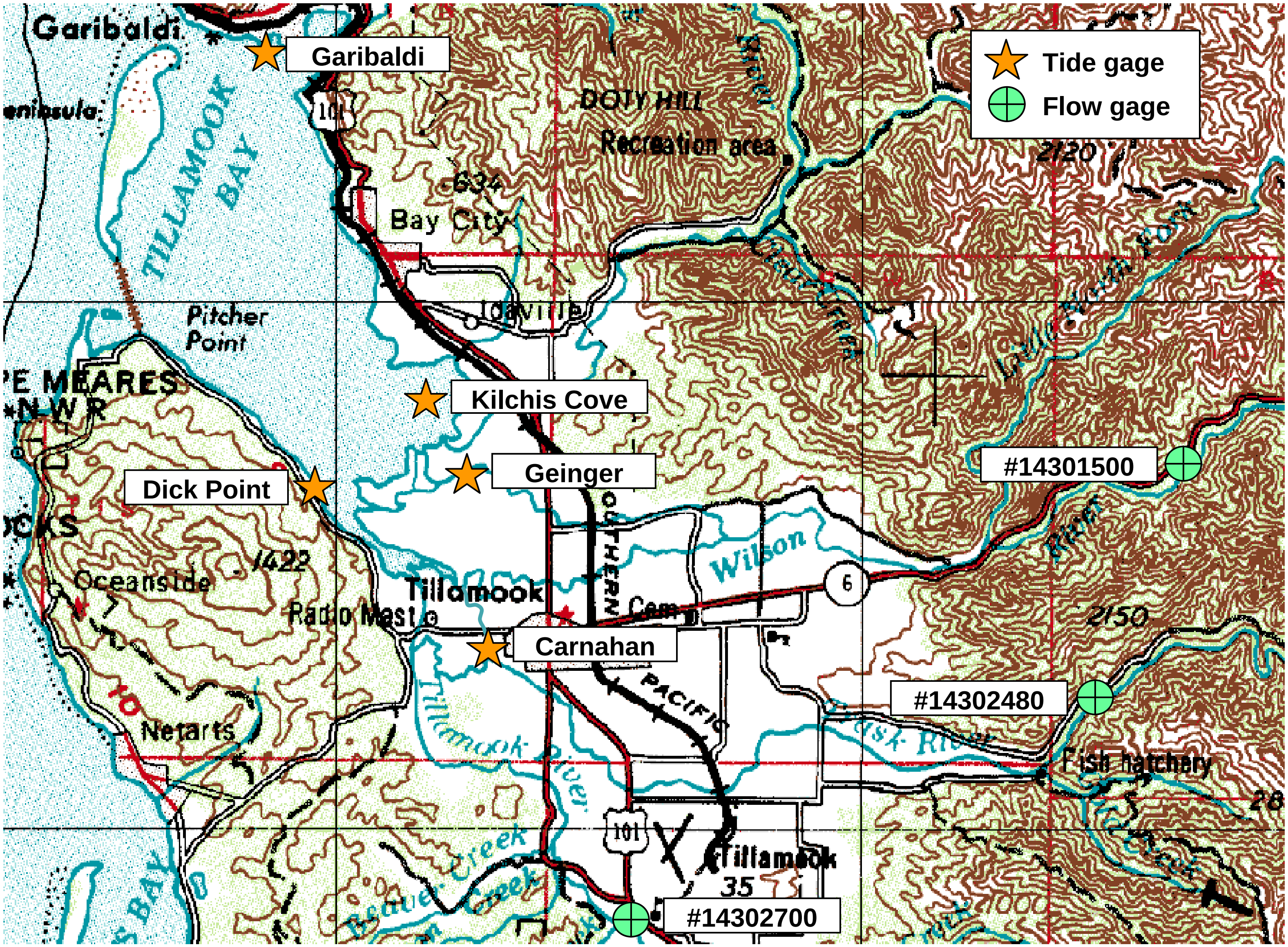

Figure 2. Approximate gage locations.

Model Construction

Hydraulic model. The Danish Hydraulic Institute's MIKE11 2000b (DHI, 2000) model was used for the hydraulic simulations.

Channel branch definition. The hydraulic model was assembled using the CENWP provided cross-sections. The branch orientation and reach lengths (referred to as "chainage" in the MIKE11 model) were determined from the aerial photos and the TIN. There are four primary branches, the Tillamook, Trask, Old Trask, and Wilson Rivers (Figure 3), and a number of secondary branches including the Hall, Dougherty, and Hoquarten Sloughs, and the "Big Cut" and "Little Cut" of the Wilson River (Figure 4) in the hydraulic model. Cross-sections were extended out into Tillamook Bay using bathymetric data supplied by CENWP (Figure 4).

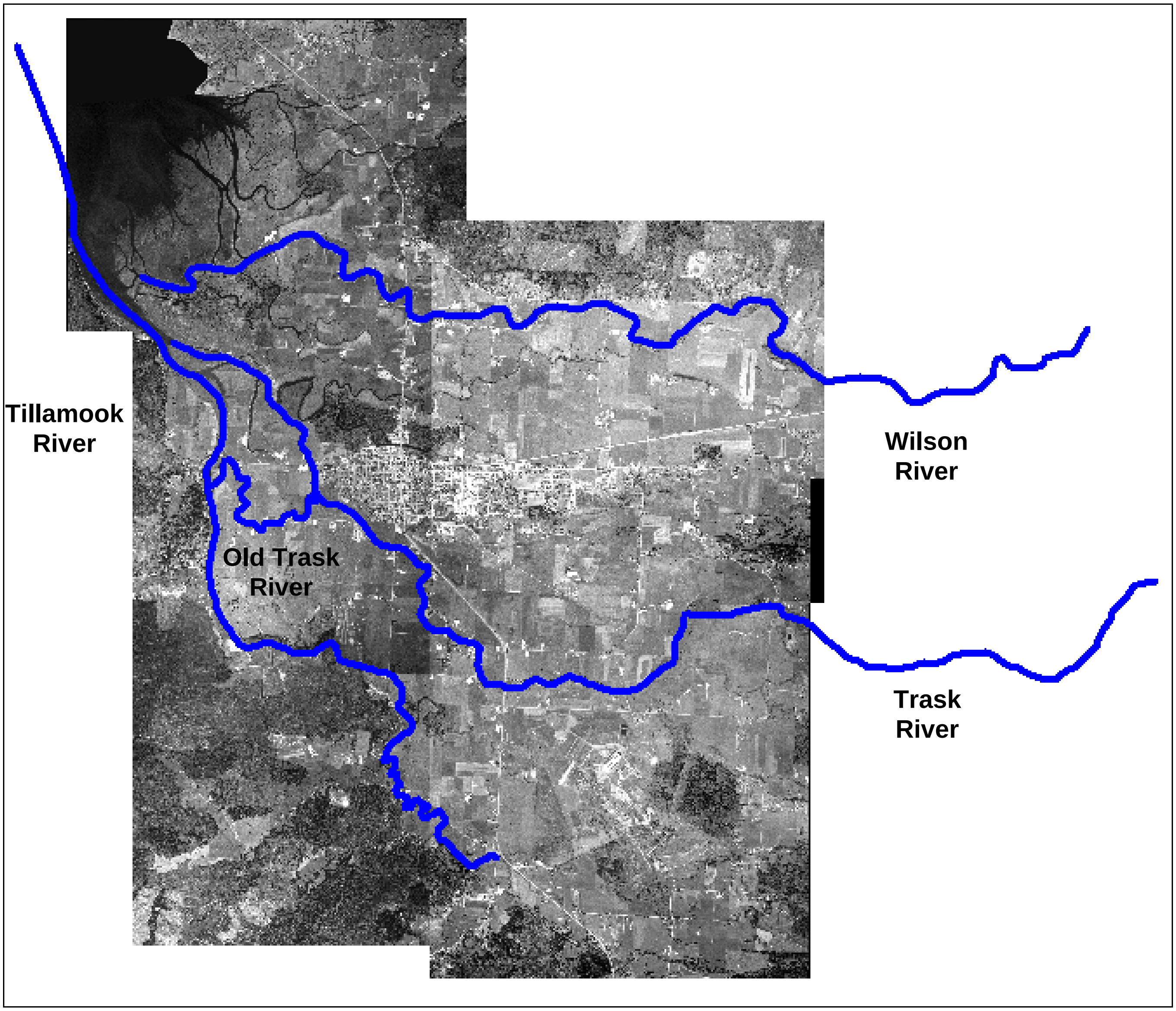

Figure 3. Four primary channel branches in the hydraulic model.

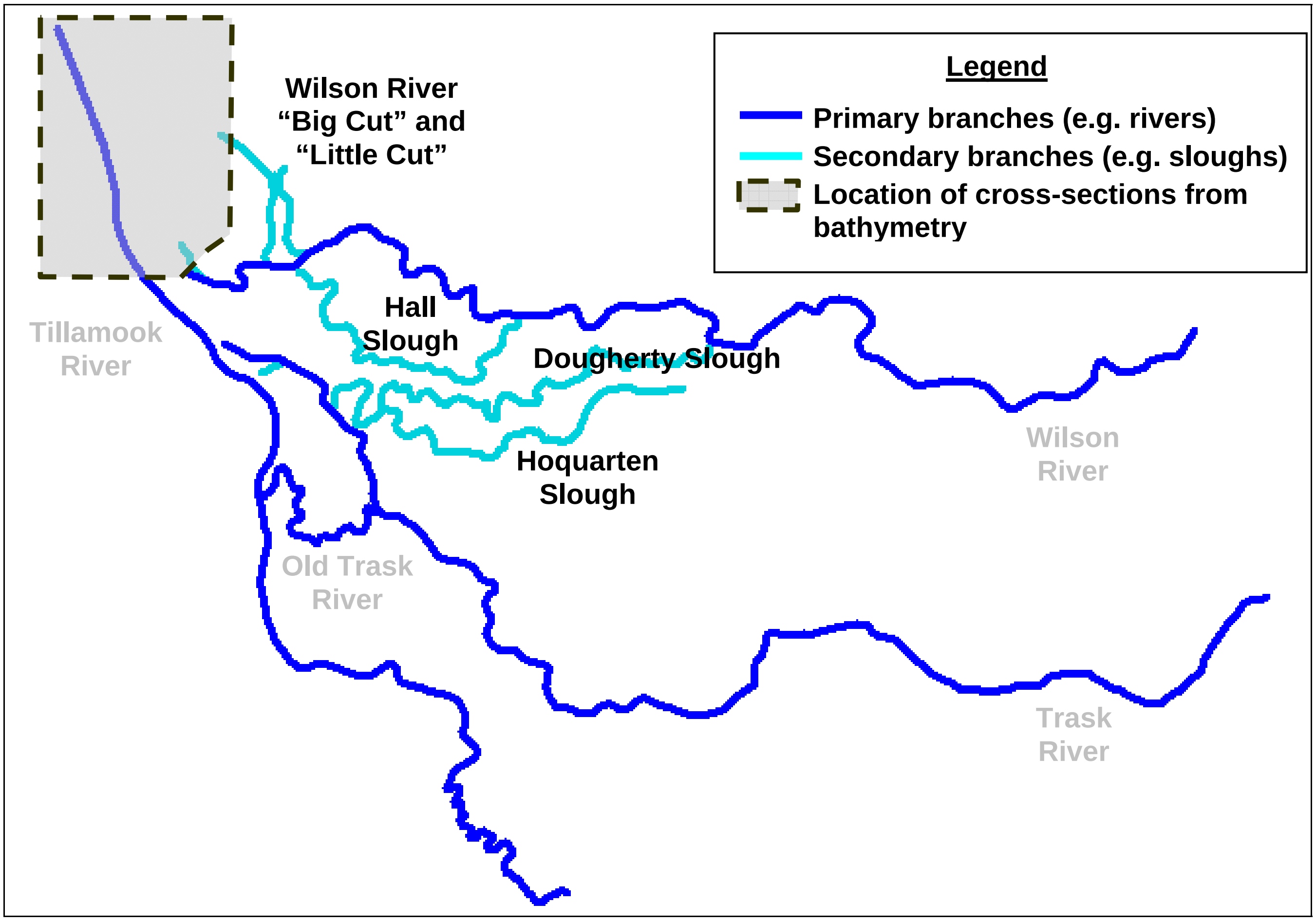

Figure 4. Additional secondary branches and cross-sections from bathymetric data, shown with the four main branches, in the hydraulic model.

Overbank branch definition. Overbank branches, representing those areas on the landward (protected) side of levees, were defined from the TIN geometry since cross-sections were surveyed only for the primary and secondary branches. Overbank branches (Figure 5) were required to define conveyance during out-of-bank events. These flow paths are active only under high flow conditions and are typically separated from the main channel by topographic features such as high ground, levees, dikes, and roads. The TIN was used to define these overbank areas. HEC-GeoRAS (HEC, 2000) was used to "cut" the TIN and specify cross-section geometry. GeoRAS was selected because DHI software, at the time of this study, was limited to use with digital elevation models (DEM's), and it was desired to maintain the TIN data resolution instead of possible resolution loss in conversion from the TIN to a DEM. The GeoRAS "cut" cross-sections were imported into HEC-RAS (HEC, 2001), and then copied into MIKE11.

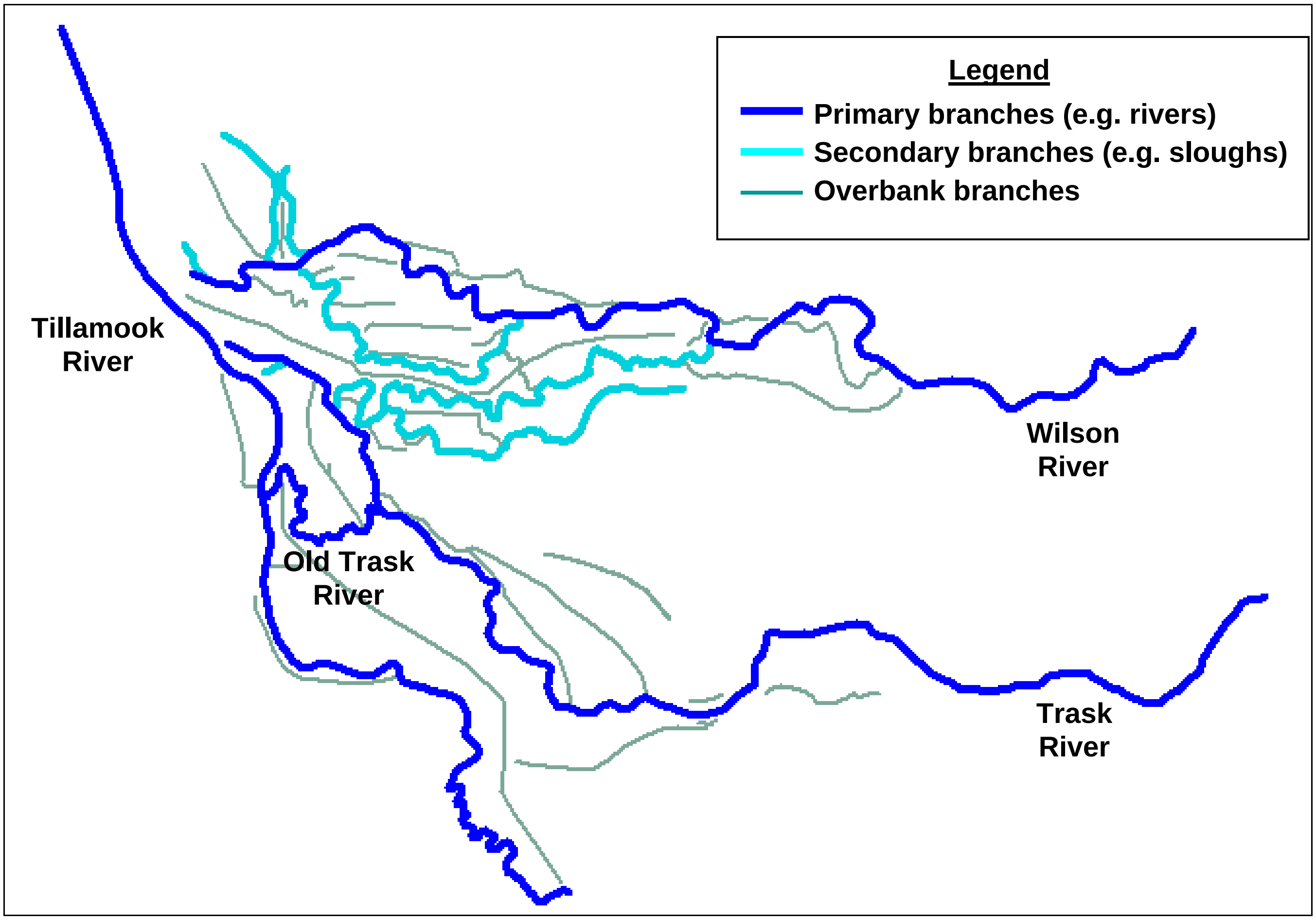

Figure 5. Overbank branches in the hydraulic model shown in their location relative to the primary and secondary channels.

Link channel definition. The primary and secondary channels are typically separated from the overbank areas by localized high ground, dikes, levees, and roads, which obstruct flow from one branch to another until the high ground is overtopped. These areas are modeled as "link channels" (shown in Figure 6) in the MIKE11 model (DHI, 2000). Field visits, observation by locals, the flight video, and the "Best Impressions" photo album of the November 1999 event helped to determine the most significant of these high ground areas. The TIN was used to define the high ground station/elevation data and pairs of depth/width information (as required in MIKE11) for the "link channels." The hydraulic model network of branches and link channels is shown in Figure 7.

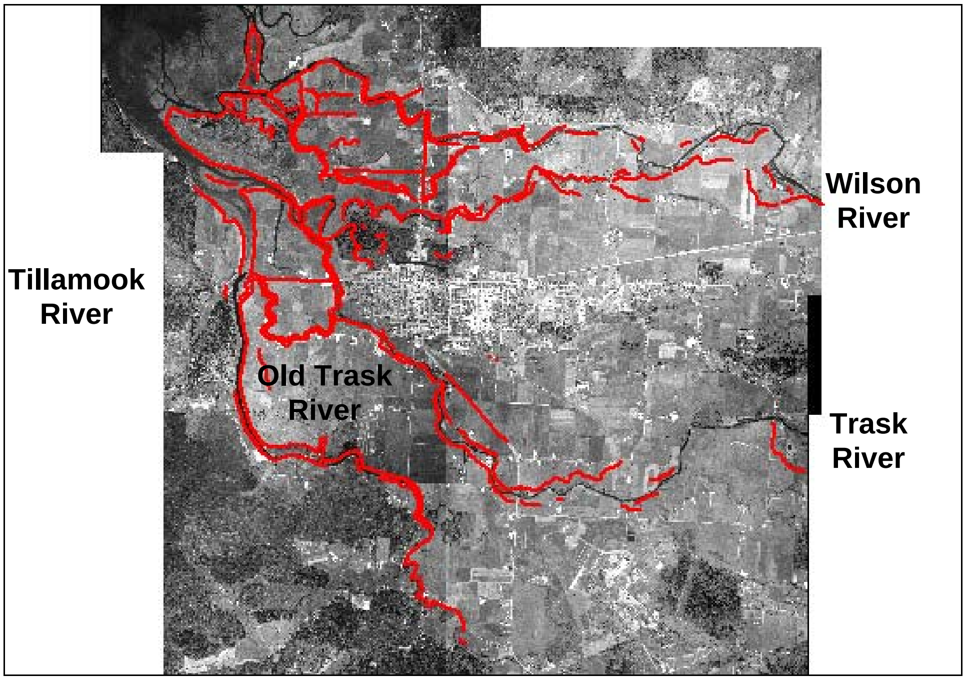

Figure 6. Distribution of "link channels" in the hydraulic model.

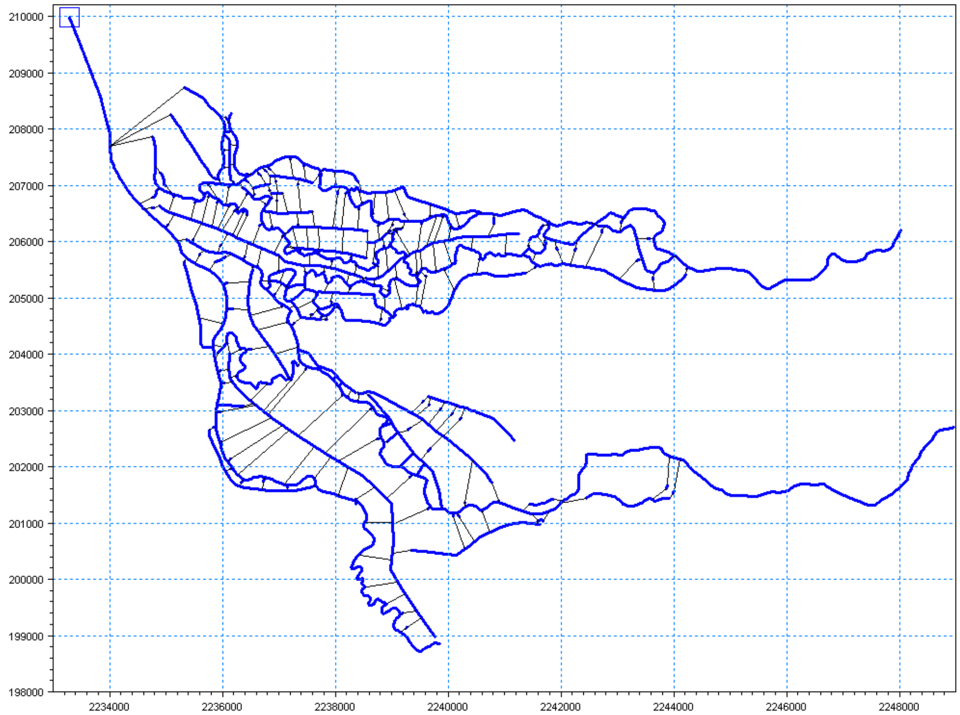

Figure 7. Branch and link channel network in MIKE11 (thick blue lines indicate branches and link channels, thin black lines indicate connections for conveyance).

Bridges and culverts. Bridges were defined as a combination of weirs and culverts (shown in Figure 8) as required in the MIKE11 version (DHI, 2000) available at the time of this study. Bridge geometric information for defining the weirs and culverts were supplied from CENWP surveys, the 1999 FEMA Flood Insurance Study, and ODOT bridge plans and bridge scour reports, as previously discussed. Culverts that drain the overbank branches through the levees ("link channels") to the primary or secondary branches (Figure 5) were also added to the model. The culverts are included at "link channel" locations and require "$LINK" to be specified in the culvert "ID" field (DHI, 2000).

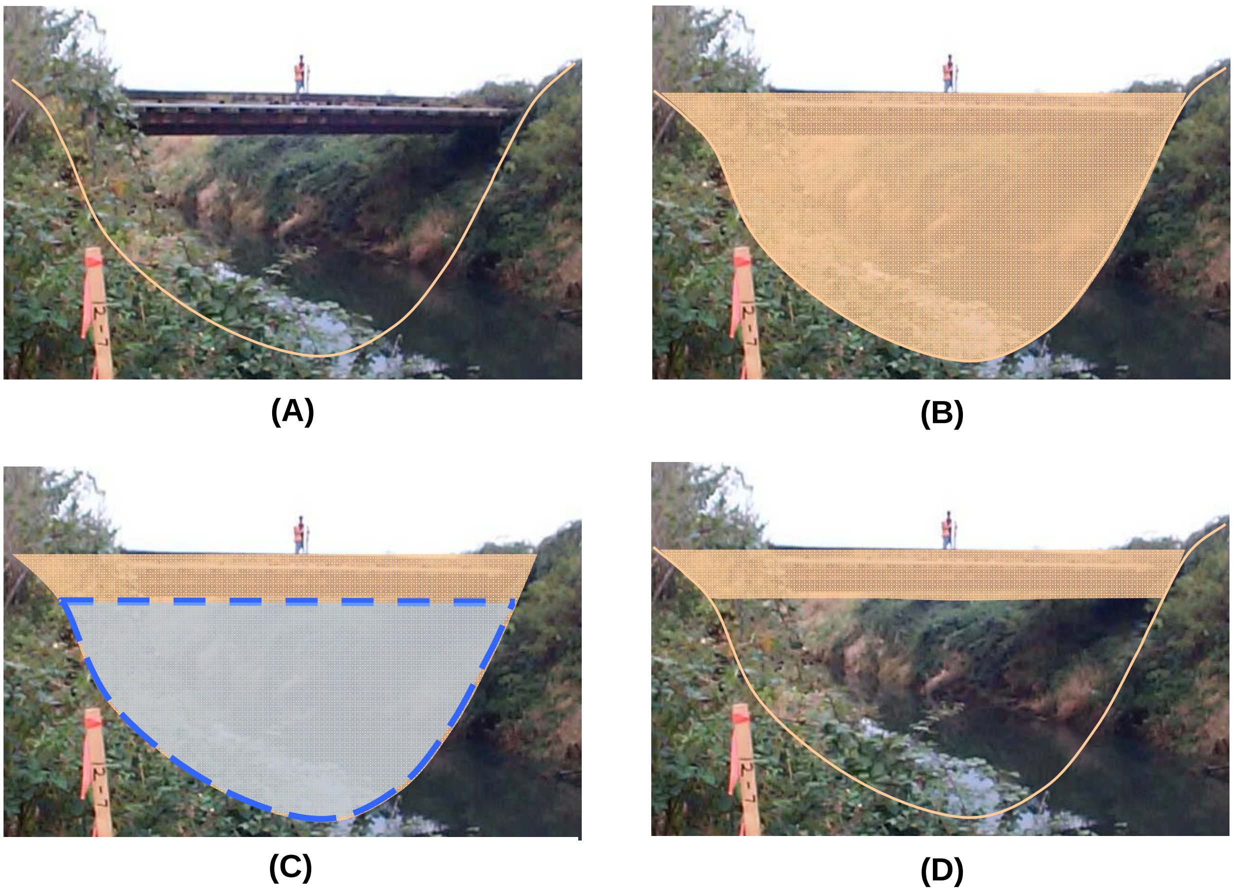

Figure 8. Creating bridges in the hydraulic model: (A) A typical surveyed cross-section at a bridge location, (B) Weir geometry (shown in brown shading) as defined at the cross-section, (C) Irregular culvert shape (shown in blue shading and dashed line) as defined at the cross-section, (D) Resulting weir/culvert combination representing the bridge opening.

MIKE11 branch naming convention. The branch naming convention typically used in the MIKE11 model is as follows:

Type:	Primary branch
Branch Name Description:	Entire river or slough name
Example:	"Tillamook River"

Type:	Secondary branch
Branch Name Description:	Entire river or slough name
Example:	"Hall Slough"

Type:	Overbank branch
Branch Name Description:	Abbreviation for the connecting upstream branch followed by the abbreviation for the connecting downstream branch and the approximate downstream connecting chainage or river mile.
Example:	"Oldt tras 0.32" is the overbank branch connecting the Old Trask River to the Trask River at approximately Trask river mile 0.32. When an overbank branch is connected to another overbank branch, usually a two part abbreviation is used, e.g. "Tras ti-ot 0.00" indicates a connection between the Trask River and the Tillamook-Old Trask overbank branch. If an overbank branch connects at both ends to the same primary or secondary branch, typically only one abbreviation is given. "Wils RB 1.44" is the overbank branch connecting the Wilson River on the right bank back to the Wilson River downstream at river mile 1.44. When "LB" and "RB" are used in abbreviations they stand for "left bank" and "right bank", respectively

Type:	Link channel
Branch Name Description:	"LC", followed by the abbreviation for the upstream connection, the approximate chainage or river mile on the connecting upstream branch, and then the abbreviation for the downstream branch
Example:	"LC WILS 11463 HALL" is the link channel connecting at the upstream end to the Wilson River at chainage 11463 and at the downstream end to Hall Slough.

Boundary Conditions. External boundary conditions were defined at the upstream extents of the Tillamook, Trask, and Wilson Rivers, and at the downstream end of the model. The upstream boundaries of the modeled branches were set at the river gage locations (the Wilson River at the "older" site 2.1 miles downstream of the current site). The upstream boundary conditions for the Trask and Wilson Rivers were defined by the provided measured USGS flow data. Likewise, the upstream Tillamook boundary was defined using the measured Oregon Department of Water Resources data when they were available. For the November 1999 event (see the Calibration section) no data were recorded at the Tillamook gage. Through discussions with CENWP, it was established that the appropriate level of effort for approximating the hydrograph would be to scale either the recorded Wilson River or Trask River flows. A comparison was therefore made between the peak flows and the periods of overlapping continuous flow recorded at the three rivers for data available between November 1995 and November 1998. Through this analysis the Wilson River (vs. the Trask River) was selected as better representing both the shape and peak of the Tillamook hydrograph. Appendix A-Figure 1 and Appendix A-Figure 2 show a scatter plot of the Tillamook peak flows vs. the Wilson and Trask Rivers. A linear line was then fit to the scatter plots and the Wilson and Trask flows scaled by the slope of the line to estimate Tillamook River flows. Appendix A-Figure 3 and Appendix A-Figure 4 show the resulting hydrograph shapes where the Trask and Wilson River flows are multiplied by these factors for two events where all three gages recorded data. The November 1999 Tillamook flow was estimated to be 18% from this analysis.

Inflow from local watersheds contributing runoff within the study area were also added to the model. The drainage areas were determined by GIS mapping conducted by CENWP (Appendix A-Figure 5 and Appendix A-Table 5), and the Wilson River flow scaled by a ratio of drainage areas to define the local watershed runoff hydrograph. It was found that the addition of these inflows had little impact on the results for the events simulated and therefore no timing adjustments were made to the local inflow hydrographs.

Calibration

The MIKE11 model was calibrated using a low flow, in-bank event (May 2001) and a high flow, out-of-bank event (November 1999). Two different geometric representations of the system (i.e., MIKE11 network files) were created, one with and one without overbanks. The May 2001 event was calibrated first and because it was an in-bank event, used the geometry without overbank definition.

Calibration was conducted primarily by modifying the Manning's 'n' value, but as part of the calibration process additional branches or cross-sections were added as necessary to better represent channel or overbank geometry. Manning's 'n' values ranged from 0.03 to as high as 0.15 in some overbank floodplain areas (Appendix A-Table 6). Calibration values were different for the November 1999 and May 2001 event because of different flow conditions (in-bank vs. out-of-bank). As part of the calibration, the estimated Tillamook River flows for November 1999 were increased by 30% because unrealistic Manning's 'n' values were required to meet observed high water marks.

A third bankfull event (November 2001), with peak flows between the May 2001 and November 1999 event, was used to validate the model (Table 1). Manning's 'n' values from the November 1999 event were used in the verification simulation.

Table 1. Peak flows for the three simulated events.

	November 1999		May 2001		November 2001	
	Peak Flow	Approximate Flow Frequency	Peak Flow	Approximate Flow Frequency**	Peak Flow	Approximate Flow Frequency
Wilson River	720 cms	6 year**	60 cms	<1 year**	440 cms	<2 year**
Trask River	640 cms	20 year**	40 cms	<1 year**	220 cms	<2 year**
Tillamook River	160 cms*	(not determined)	15 cms	(not determined)	50 cms	(not determined)

*The Tillamook River discharges were estimated for the November 1999 event.

**Approximate flow frequencies are from "DRAFT Tillamook Bay and Estuary General Investigation Study, Overview of Hydrologic Study including MIKE 11 Model Development" (USACE, 2003)

Both recorded time series data and observed high water marks were used for the May 2001 and November 2001 events. Only high water marks were available for the November 1999 event. Sources for the data included CENWP and Tillamook County (USACE, 2001) as discussed in the following text.

Tillamook Bay

The roughness coefficient for Tillamook Bay was calibrated using the Garibaldi tidal stage data at the downstream boundary, running the MIKE11 simulation, and calibrating to the stage gage at Dick Point at the opposite end of the bay. The Manning's 'n' value for the cross-sections in the bay between these two gages was adjusted until the simulated and observed values matched at Dick Point. Figure 9 shows the comparison of the downstream boundary condition gage (at Garibaldi), the observed Dick Point gage, and the simulated stage at Dick Point (Tillamook River chainage 13866.6).

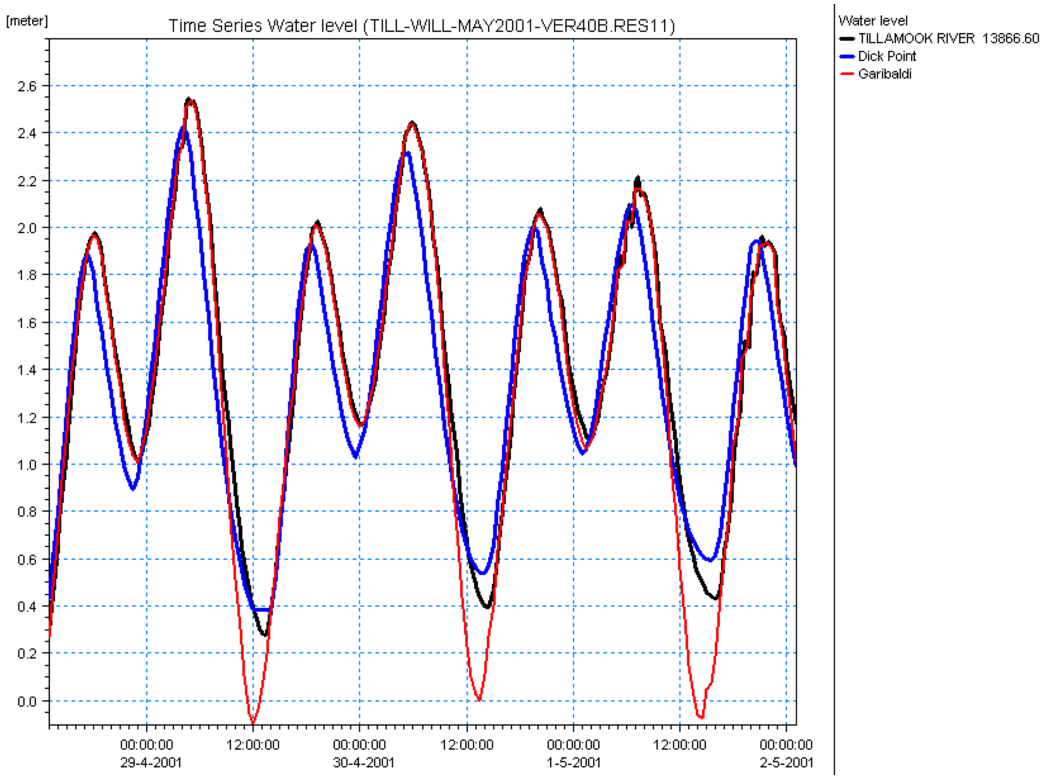

Figure 9. Comparison of downstream boundary condition gage at Garibaldi (shown in red), the observed Dick Point gage (shown in black), and the simulated stage at Dick Point (Tillamook River chainage 13866.6) (shown in black).

May 2001 In-Bank Event

Figure 10, Figure 11, Table 2, and Table 3 show the calibration results for the May 2001 event. The difference between simulated and observed high water marks was ±0.13 meters (±0.4 feet) except for being 0.25 meters (0.8 feet) too high in Hall Slough and 0.48 meters (1.6 feet) too low at the log jam location on the Dougherty Slough. All observed values were provided by CENWP and are listed in Appendix A-Table 7. Table 4 lists the range of calibrated Manning's 'n' values for the simulation.

Note that the program default "resistance radius" (DHI, 2000), and not "hydraulic radius," was selected in the MIKE11 model. An investigation by WEST, and verified with DHI, indicates that a relatively higher Manning's 'n' than the typical published values (e.g., in U.S. Army Corps of Engineers [2001], "HEC-RAS Hydraulic Reference Manual", or Barnes [1987], "Roughness Characteristics of Natural Channels") should be expected for the "resistance radius" type when using the Manning's 'n' equation.

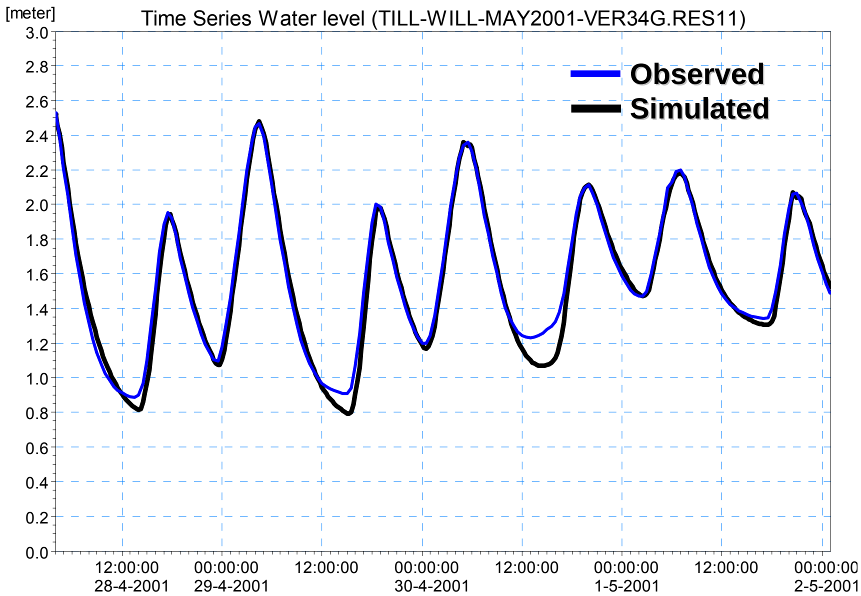

Figure 10. Simulated vs. observed water surface stage at the Carnahan tide gage on the Trask River for the May 2001 Event.

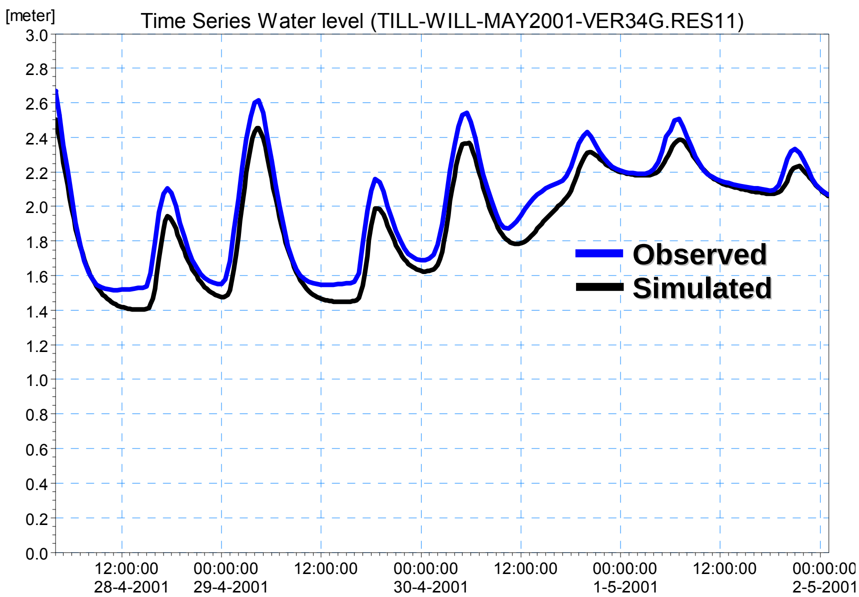

Figure 11. Simulated vs. observed water surface stage at the Geinger tide gage on the Wilson River for the May 2001 event.

Table 2. Difference between simulated and observed high water marks for the May 2001 event in the Tillamook and Trask River system.

Branch	Nearest Chainage (m)	Location	Observed Level* (m) (NAVD88)	Simulated Level (m) (NAVD88)	Diff. (m)	Diff. (ft)
Tillamook River	28.2	River Mile 6.9	4.76	4.67	-0.09	-0.3
Tillamook River	2658.5	River Mile 5.44	2.04	2.02	-0.02	-0.1
Tillamook River	3532.8	River Mile 4.95	1.94	1.98	0.04	+0.1
Tillamook River	5060.3	River Mile 3.96	1.99	1.99	0.00	0.0
Tillamook River	6775.5	River Mile 2.95	2.04	2.01	-0.03	-0.1
Tillamook River	8402.1	River Mile 2	1.98	2.04	0.06	+0.2
Tillamook River	10193	River Mile 0.91	2.08	2.08	0.00	0.0
Trask River	3231	River Mile 8.75	13.06	13.03	-0.03	-0.1
Trask River	6392.9	River Mile 6.95	7.16	7.26	0.10	+0.3
Trask River	9164.6	River Mile 5.26	4.48	4.53	0.05	+0.2
Trask River	10930.55	River Mile 4.2	2.74	2.63	-0.11	-0.4
Trask River	12965.6	River Mile 2.98	2.04	2.08	0.04	+0.1
Trask River	14070.4	River Mile 2.39	1.83	1.89	0.06	+0.2
Trask River	15873.6	River Mile 1.18	1.49	1.49	0.00	0.0

*All observed high water marks provided by CENWP.

Table 3. Difference between simulated and observed high water marks for the May 2001 event in the Wilson River system.

Branch	Nearest Chainage (m)	Location	Observed Level* (m) (NAVD88)	Simulated Level (m) (NAVD88)	Diff. (m)	Diff. (ft)
Wilson River	1299.9	River Mile 8.6	13.10	13.10	0.00	0.0
Wilson River	1650.7	River Mile 8.43	12.41	12.41	0.00	0.0
Wilson River	8942.9	River Mile 3.83	4.42	4.41	-0.01	0.0
Wilson River	11336.5	River Mile 2.4	3.24	3.29	0.05	+0.2
Wilson River	12445.1	Upstream of Hwy 101	2.87	2.79	-0.08	-0.3
Wilson River	14341.9	River Mile 0.63	2.35	2.48	0.13	+0.4
Hall Slough	3100.7	Upstream of Goodspeed Rd	2.03	2.28	0.25	+0.8
Dougherty Slough	0	at Wilson Confluence	4.83	4.89	0.06	+0.2
Dougherty Slough	172	Near log jam	4.61	4.67	0.06	+0.2
Dougherty Slough	690.6	Wilson River Loop Road	4.02	3.54	-0.48	-1.6
Dougherty Slough	4170.7	River Mile 2	1.94	2.04	0.10	+0.3
Dougherty Slough	4684.9	Upstream of Hwy 101	2.01	2.09	0.08	+0.3
Hoquarten Slough	6234.9	Upstream of Hwy 101	1.95	1.99	0.04	+0.1

*All observed high water marks provided by CENWP.

Table 4. Range of Manning's 'n' values for the May 2001 event using resistance radius.

Branch	Manning's 'n'
Tillamook Bay	0.02
Downstream (tidal) secondary branches	0.03 – 0.08
Tillamook River	0.03 – 0.1
Trask River	0.04 – 0.12
Wilson River	0.03 - 0.09
Old Trask River	0.05
Hoquarten Slough	0.04
Dougherty Slough	0.07
Hall Slough	0.04

November 1999 Out-of-Bank Event

Figure 12 shows the locations of the most reliable high water marks for the November 1999 event. Results from the simulation, corresponding to Figure 12, are presented in Table 5 and Table 6. The difference between simulated and observed high water marks was ±0.24 meters (±0.8 feet).

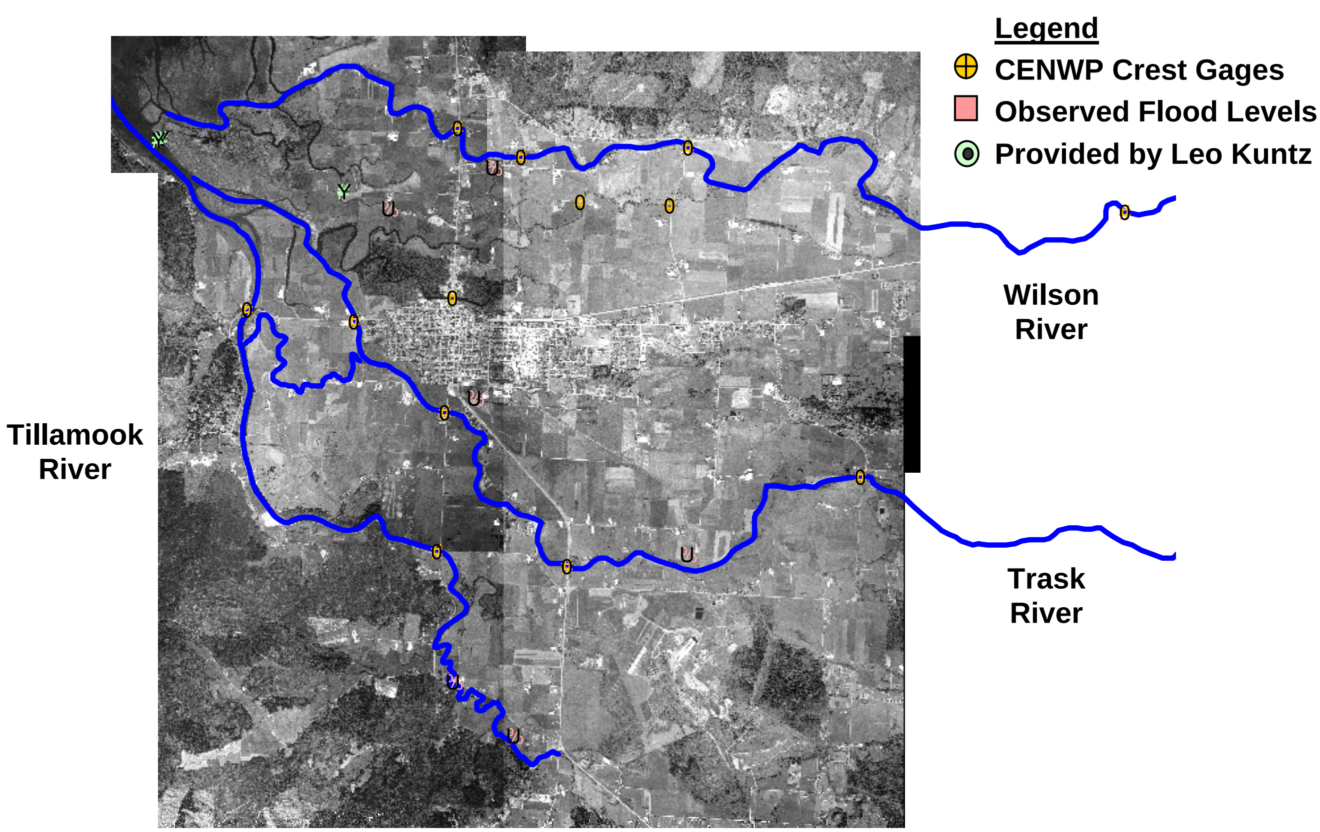

Figure 12. Location of high water marks for the November 1999 event.

Table 5. Difference between simulated and observed water surface elevations for the November 1999 event in the Tillamook and Trask River systems.

Branch	Nearest Chainage (m)	Location	Source	Obs. Level (m) (NAVD 88)	Sim. Level (m) (NAVD 88)	Diff. (m)	Diff. (ft)
Tillamook River	2605.7	Louie Blaser Dairy	Observed Historic Flood Levels	4.30	4.45	0.15	0.5
Tillamook River	12997.0	Tide gate outlet	Leo Kuntz	2.96	3.08	0.12	0.4
Tillamook River	5060.3	Tillamook River Road Bridge RM 3.96	CENWP Crest Gages	4.25	4.16	-0.09	-0.3
Tillamook River	10193	Netarts Highway RM 0.91	CENWP Crest Gages	3.75	3.68	-0.07	-0.2
Tillamook Right Overbank	258	Kevin Pullian Home	Observed Historic Flood Levels	5.50	5.71	0.21	0.7
Tillamook Right Overbank	1045.3	Louie Blaser Dairy	Observed Historic Flood Levels	4.30	4.24	-0.06	-0.2
Tillamook Overbank	3912.6	Tide gate inlet	Leo Kuntz	3.87	3.8	-0.07	-0.2
Trask River	6380.2	Brickyard Road Bridge RM 6.96	CENWP Crest Gages	11.86	11.97	0.11	0.4
Trask River	9164.8	Lethhold Dairy	Observed Historic Flood Levels	9.60	9.58	-0.02	-0.1
Trask River	10954.3	Highway 101 RM 4.2	CENWP Crest Gages	8.14	8.28	0.14	0.5
Trask River	14086.5	Tone Road RM 2.39	CENWP Crest Gages	5.78	5.69	-0.09	-0.3
Trask River	15841.6	Netarts Highway RM 1.18	CENWP Crest Gages	4.51	4.45	-0.06	-0.2
Trask Overbank	2919.4	Dean Tohl Dairy	Observed Historic Flood Levels	6.10	6.11	0.01	0.0

Table 6. Difference between simulated and observed water surface elevations for the November 1999 event in the Wilson River system.

Branch	Nearest Chainage (m)	Location	Source	Obs. Level (m) (NAVD88)	Sim. Level (m) (NAVD88)	Diff. (m)	Diff. (ft)
Wilson River	1313.1	Highway 6 Bridge RM 8.6	CENWP Crest Gages	17.53	17.56	0.03	0.1
Wilson River	8908.9	Sollie-Smith Bridge RM 3.84	CENWP Crest Gages	8.99	9	0.01	0.0
Wilson River	11294.6	RR Bridge RM 2.4	CENWP Crest Gages	7.14	7.23	0.09	0.3
Wilson River	12445.1	Highway 101 RM 1.8	CENWP Crest Gages	6.45	6.4	-0.05	-0.2
Hall Slough	2245.1	Beeler Heffer Farm	Observed Historic Flood Levels	4.20	4.13	-0.07	-0.2
Hall Slough	3100.7	Goodspeed Bridge	Leo Kuntz	4.27	4.03	-0.24	-0.8
Hall Right Overbank	109.7	Aufdermauer Shop	Observed Historic Flood Levels	4.10	4.14	0.04	0.1
Dougherty Slough	696.6	Wilson River Loop Road Bridge	CENWP Crest Gages	8.42	8.35	-0.07	-0.2
Dougherty Slough	2184.3	Kiger Road Bridge	CENWP Crest Gages	6.52	6.29	-0.23	-0.8
Hoquarten Slough	6240.1	Highway 101 Bridge	CENWP Crest Gages	4.78	4.7	-0.08	-0.3

Table 7 presents the range of calibrated Manning's 'n' values used in the model for the out-of-bank event. Note that the program default "resistance radius" (DHI, 2000), and not "hydraulic radius," was selected in the MIKE11 model. An investigation by WEST, and verified with DHI, indicates that a relatively higher Manning's 'n' should be expected for the former radius type when using the Manning's 'n' equation. The 'n' value for the MIKE11 link channels was set to 0.30 as part of the calibration to help reduce the amount of weir flow. With a 'n' value for the link channels less than this too much flow enters the overbank areas, reducing the amount of water in the main channel and therefore reducing the main channel stage below the observed highwater marks.

Table 7. Range of Manning's 'n' values for the November 1999 event using resistance radius.

Branch	Manning's 'n'
Tillamook Bay	0.02
Downstream (tidal) secondary branches	0.03 – 0.05
Tillamook River	0.04 – 0.045
Trask River	0.04 – 0.06
Wilson River	0.04 - 0.055
Old Trask River	0.09
Hoquarten Slough	0.09 – 0.12
Dougherty Slough	0.12 – 0.15
Hall Slough	0.12
Overbanks	0.07 – 0.15

November 2001 Event

The November 2001 event, which overtopped the banks in many locations on the Wilson River and was near bankfull on the Trask and Tillamook, was used to verify the MIKE11 model (Figure 13, Figure 14, Figure 15, and Table 8). All observed values were provided by CENWP The difference between the observed and simulated values ranged from –0.64 to +0.64 meters (±2.1 feet). There were some known errors in the recorded stage at the Carnahan gage as the values were unrealistically high. The entire Carnahan gage datum was therefore adjusted by a constant value (compare the resulting stage at Carnahan, Figure 14, to Geinger, Figure 13).

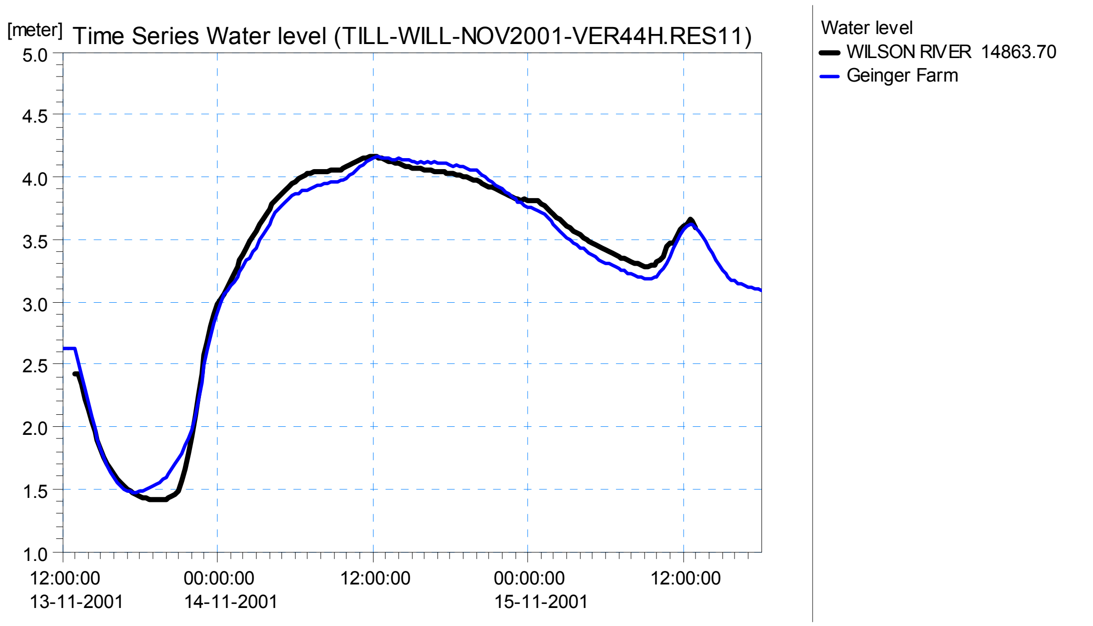

Figure 13. Simulated (in black) and observed (in blue) stage at Geinger Farm for November 2001.

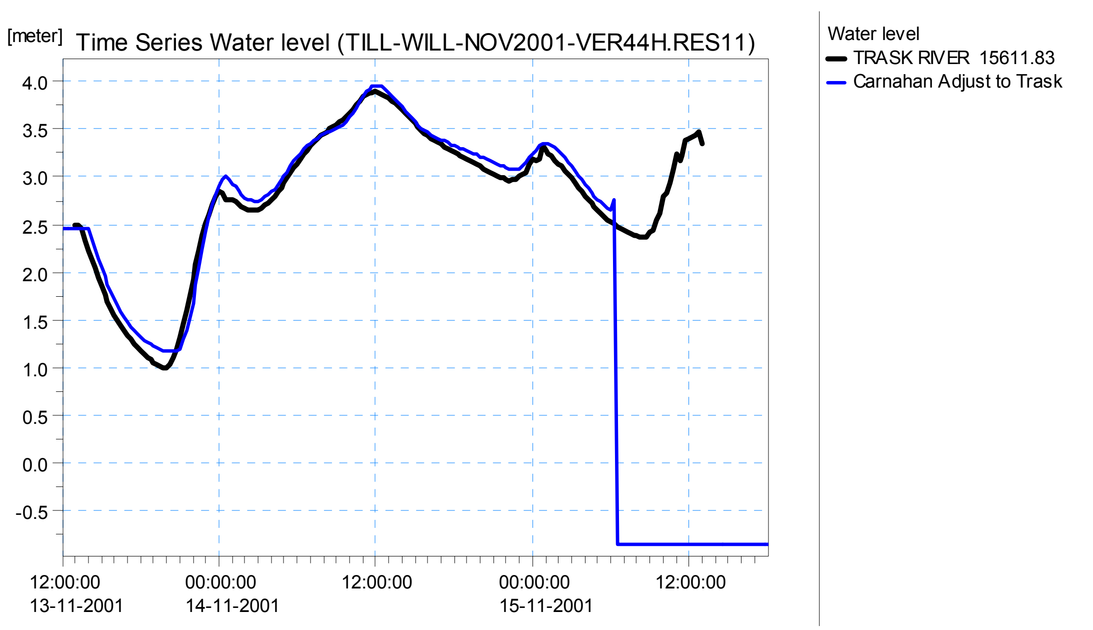

Figure 14. Simulated (in black) and observed (in blue) stage at Carnahan for November 2001.

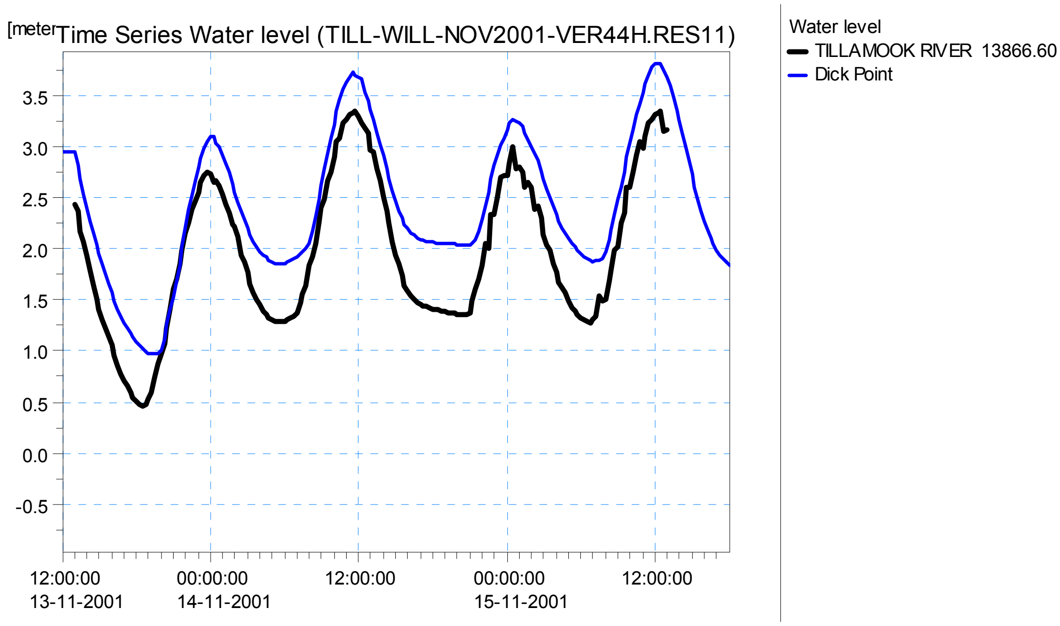

Figure 15. Simulated (in black) and observed (in blue) elevations for the November 2001 event.

Table 8. Difference between simulated and observed water surface elevations for the November 2001 event.

Branch	Nearest Chainage (m)	Location	Obs. Level* (m) (NGVD 88)	Sim. Level (m) (NGVD 88)	Diff. (m)	Diff. (ft)
Tillamook River	10193	Netarts Highway RM 0.91	2.75	3.38	0.63	2.1
Trask River	15873.6	Netarts Highway RM 1.18	3.96	3.8	-0.16	-0.5
Old Trask River	2796.6	River Km 2.8	3.14	3.43	0.29	1.0
Wilson River	1299.9	Highway 6 Bridge RM 8.6	16.06	16.17	0.11	0.4
Wilson River	1650.7	Upstream boat ramp RM 8.43	15.51	15.54	0.03	0.1
Wilson River	5010.1	River Km 5.0 Donaldson	11.26	11.47	0.21	0.7
Wilson River	8908.9	Sollie-Smith Bridge RM 3.84	8.82	8.55	-0.27	-0.9
Wilson River	11294.6	SPRR Bridge RM 2.4	7.08	6.97	-0.11	-0.4
Wilson River	12445.1	Highway 101 RM 1.8	6.42	6.37	-0.05	-0.2
Wilson River	12759.2	Boquist Road	5.69	6.09	0.40	1.3
Hall Slough	1275.1	Highway 101	4.5	4.35	-0.15	-0.5
Hall Right Overbank	345.2	Shilo Inn	5.04	4.41	-0.63	-2.1
Dougherty Slough	690.6	Wilson River Loop Rd. Bridge	7.96	7.63	-0.33	-1.1
Dougherty Slough	2157.0	Kiger Road Bridge	6.03	5.96	-0.07	-0.2
Dougherty Slough	4684.9	Highway 101 (upstream)	3.76	4.11	0.35	1.1
Dougherty Slough	4730.6	Highway 101 (downstream)	3.86	4.08	0.22	0.7

*All observed high water marks provided by CENWP.

Discussion

The MIKE11 model was calibrated to an in-bank event (May 2001) and out-of-bank event (November 1999). In both cases the simulated vs. observed peak values compared relatively well, differing by 0.12 meters (±0.4 feet) and 0.24 meters (±0.8 feet), respectively, for the two events. The model represents relatively well the observed water surface elevations, simulating equally as well both the main rivers and sloughs. The simulated values also replicate relatively well the timing of the events as can be observed in the hydrograph time series plots discussed in the Calibration section.

The verification run (November 2001), using the November 1999 Manning's 'n' values and geometry, varied by ±0.64 meters (±2.1 feet). However, the November 2001 discharge values were between those in the November 1999 and May 2001 simulations, and different Manning's 'n' values were used when calibrating these two latter events. Therefore, the Manning's 'n' values should likely be modified as well to better calibrate this "in-between" flow. A verification run of magnitudes similar to those of the November 1999 and May 2001 events would better verify the MIKE11 model parameters.

This would indicate that the model is best suited for simulating events similar to those used in the calibration, then using the corresponding calibrated Manning's 'n' values for that type of event (e.g. May 2001 or November 1999). Caution should be used when applying this model for other flows unless the model has been calibrated for an event of that other magnitude.

As a whole, the Manning's 'n' values typically increase moving in an upstream direction for the Wilson, Trask, and Tillamook Rivers. Manning's 'n' was increased to reflect, in part, the additional losses in the more sinuous sections of the river (e.g. downstream portions of the Wilson River). The sloughs, which are typically more heavily vegetated, usually have higher Manning's 'n' values than those in the main channels. The Manning's 'n' value at the upstream end of the Dougherty Slough was raised to reflect the blockage and turbulence caused by the log jam at this location.

Areas of potential improvements to the model include making modifications and additions to the culverts and levees. Only the apparently significant culverts were included in the model, and many of the invert elevations of these were estimated from the TIN. Additional culverts and surveyed invert elevations may be necessary to perform more detailed modeling in any specific location. Levee ("link channel") elevations were also estimated from the TIN. Surveying the levee elevations and modifying the MIKE11 model accordingly may yield more accurate results.

Alternatives

Once calibrated, the MIKE11 hydraulic model was then used to model a number of flood control alternatives. The November 1999 event was used to simulate the effects of flood control measures including channel dredging, levee removal and levee setback. A summary of the flood control alternatives and their purpose is shown in Table 9. Figure 16 and Figure 17 show the location of these alternatives and the location of flood cells where impacts were analyzed, respectivley. Further description of these alternatives and preliminary results from these simulations are provided in Appendix B. Flood Control Alternatives Modeled in MIKE11.

Table 9. Difference between simulated and observed water surface elevations for the November 2001 event.

Alterative	*Goal*	*Result Highlights*	*Significant/Major Flood Cell Changes*
Wi2 - 20m cut	Reduce frequency of "nuisance" floods.	Flow redirected from the Hall right bank to the Hall Slough Duration of Highway 101 overtopping reduced by ≈ 4 hours in Hall right overbank	
- levees lowered		Duration of total flood event extended Peak stage decreased by up to 0.1 m along Hall Slough	Peak stage decreased by up to ≈ 0.1 m in Cells 4, 6, 7, 8, & 9
- levees lowered & 20m cut		Nearly identical to levees lowered only alternative. Duration of Highway 101 overtopping reduced by ≈ 6 hours in Hall right overbank	Nearly identical to levees lowered only
- increased US capacity		Increased duration of Hall Slough flushing flows	Duration of flooding increased in Cells 6, 7, 9, 11, & 19
Tr2 - 40m cut	Reduce flood levels. Restore channel complexity and increase channel capacity.	Peak water surface stage lowered in the Trask R. upstream of Netarts Hwy ≈ 0.6 - 0.7 m Peak water surface elevation lowered in the overbank between Trask & Till ≈ 0.4m	Peak stage decreased by ≈ 0.1 m in Cells 4, 5, 10, 12, 13, 14, & 15
- 60m setback (left levee)		Peak water surface elevation lowered in the overbank between Trask & Till ≈ 0.1 m	None
- levee lowered (right levee)		No significant benefits other than to Flood Cell #5	Peak stage decreased by ≈ 0.2 in Cell 5
Tr8 - 30m cut	Reduce flood stages and flooding of surrounding area.	Flow redirected to Old Trask (approximately 47 cms) and Till-OltT 0.85 overbank from Trask River Trask R. peak stage lowered ≈ 0.1 m near Old Trask confluence	None
- 30m setback		Redirects ≈ 20 cms increase in Old Trask flow No significant change in stage	None
- 30m setback & 30m cut		Flow redirected to Old Trask and Till-OltT 0.85 overbank from Trask River	None
Wi11	Determine if dredging improves flood conditions.	Wilson River, Big Cut peak stage lowered between 0 to 0.35 meters.	Flood cells 6, 8, 9, 11 and 19 are truncated 1 to 6 hours on the rising limb, and 2.5 to 7.5 hours on the falling limb.

Alterative	*Goal*	*Result Highlights*	*Significant/Major Flood Cell Changes*
Wi10	Increase flood conveyance by widening and deepening the channel.	Wilson River peak stage lowered between 0.1 to 0.4 meters. Approximate overall channel capacity increased from 265 cms to 320 cms.	Flood cells 6, 8, 9, 11 and 19 are lowered ≈ 0.3 meters. Rising limb of the hydrograph is delayed 4 to 10 hours. Pool drainage time shortened as much as 10 hours.
- included Wi11 measures		Essentially the same results as Wi10 for the upper Wilson River. Additional stage reduction of approximately 0.1 meters for lower Wilson River.	Slight improvement in hydrograph duration, up to 1.5 hours shorter, in addition to results for Wi10 for flood cells 6, 8, 9, 11 and 19.
Tr10	Determine local and upstream effects of channel dredging.	Peak stage reduction from 0 to 0.2 at most cross sections altered in the channel modification.	Peak stage is decreased between 0.1 and 0.15 meters in flood cells 5, 12, 13, 14, & 15. Time to drain reduced 6 to 12 hours for pools 12, 13, 14, & 15. Rising limb of the hydrograph delayed 1 to 2 hours for pools 5, 12, 13, and 14.
- included Tr2 measures		Discharge through the Trask increased by approximately 70 cms over Tr10 results. Trask stage higher than in Tr10 but still lower than for base condition.	Up to 2 hours duration added to either end of the hydrograph when compared to Tr10, but duration still less than base condition.
- included Tr2 measures and 60m levee setback		Discharge through the Trask increased by approximately 20 cms over Tr10+Tr2 results.	None beyond Tr10+Tr2 results.

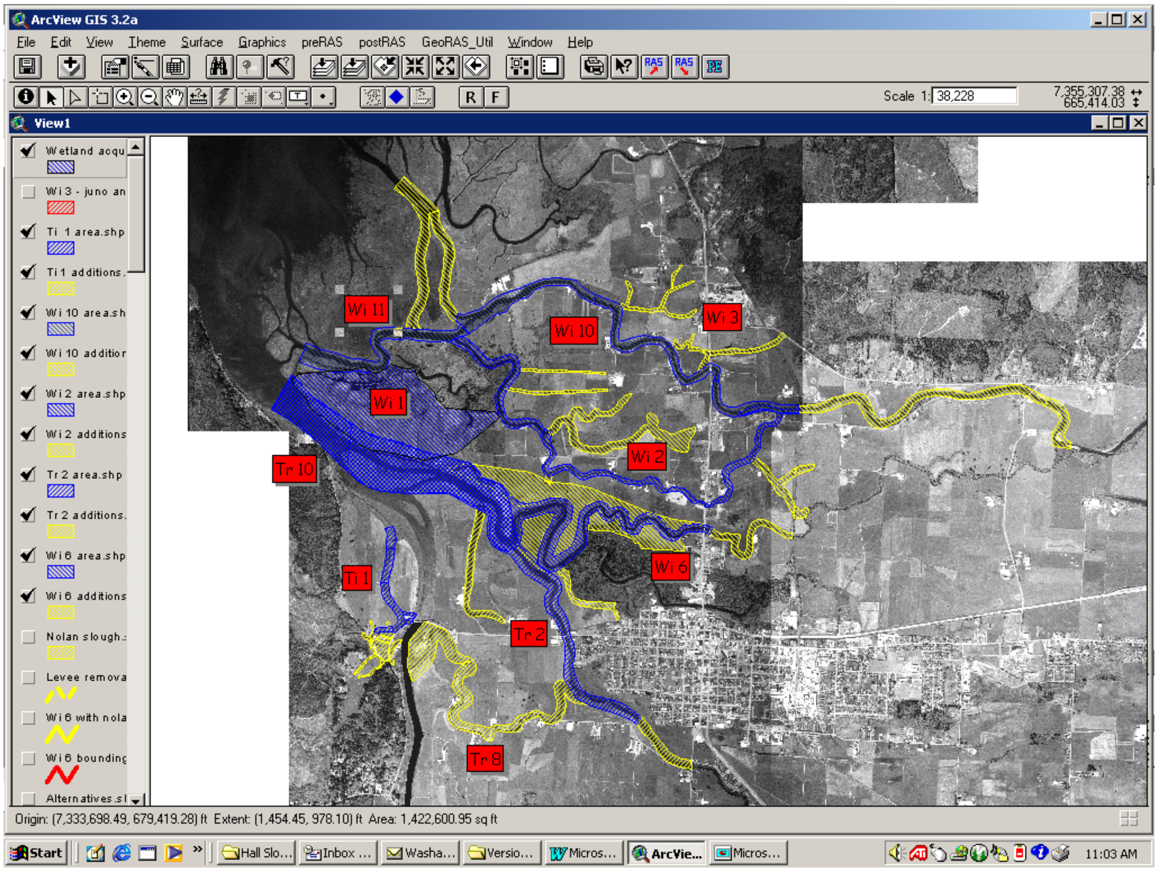

Figure 16. Lower Tillamook Area Rivers Modeled For Flood Reduction (USACE, 2003).

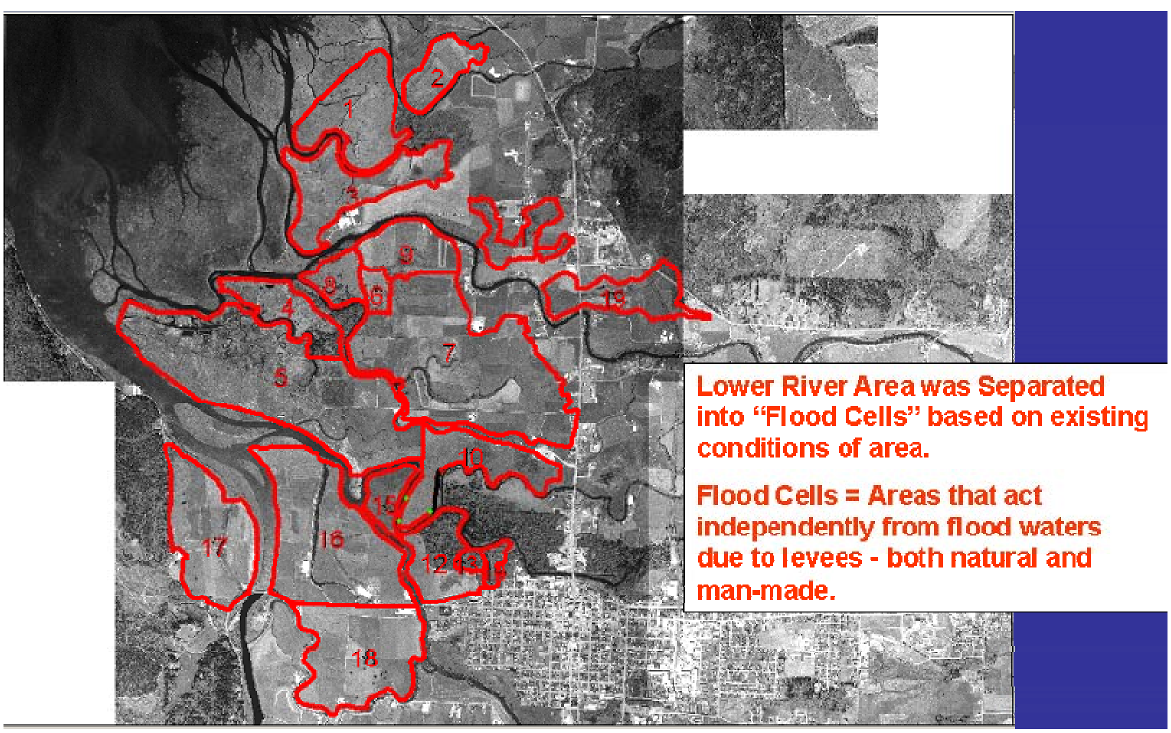

Figure 17. Flood Cells in the lower Tillamook region (USACE, 2003).

References

DHI, 2000, “MIKE 11, User Guide”, Danish Hydraulic Institute, Horsholm, Denmark

HEC, 2000, “HEC-GeoRAS, User’s Manual”, Version 3.0, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, April 2000.

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USACE, 2003, “DRAFT Tillamook Bay and Estuary General Investigation Study, Overview of Hydrologic Study including MIKE 11 Model Development”, Portland District U.S. Army Corps of Engineers, CENWP-EC-HY, August 2003.

Appendix A. Additional Tables and Figures

Appendix A-Table 1. Source of MIKE11 cross-section data.

Branch Name	Source	Date
Wilson River	FEMA restudy USACE Tillamook County	February 1999 December 2000 January 2001
Hall Slough	USACE	December 2000
Dougherty Slough	FEMA restudy USACE Tillamook County Tillamook County	February 1999 June 2000 Summer 2000 January 2002
Hoquarten Slough	FEMA restudy Tillamook County	February 1999 Summer 2000
Big Cut	Tillamook County	January 2002
Little Cut	Tillamook County	January 2002
Trask River	Tillamook County	January 2001
Tillamook River	Tillamook County	January 2001
Old Trask River	Tillamook County	Summer 2000

Appendix A-Table 2. List of gages used in the MIKE11 simulations.

Operated by	Gage ID or Number	Location	Period of Record	Parameters
USGS	14301500	Wilson River near Tillamook, Oregon	1931 - Present	Stage and flow
USGS	14302480	Trask River above Cedar Creek Near Tillamook, Oregon	1996 - Present	Stage and flow
Oregon Water Resources Department	14302700	Tillamook River	1973-1977, 1995-1998, 2000-2002	Stage and flow
U.S. Army Corps	Garibaldi	Near the north end of Tillamook Bay	2001 - Present	Stage
U.S. Army Corps	Geinger	Geinger Farm on the Wilson River	2001 - Present	Stage
U.S. Army Corps	Carnahan	Carnahan Park on the Trask River	2001 - Present	Stage
U.S. Army Corps	Kilchis Cove	Tillamook Bay	2001 - Present	Stage
U.S. Army Corps	Dick Point	Near the south end of Tillamook Bay	2001 - Present	Stage

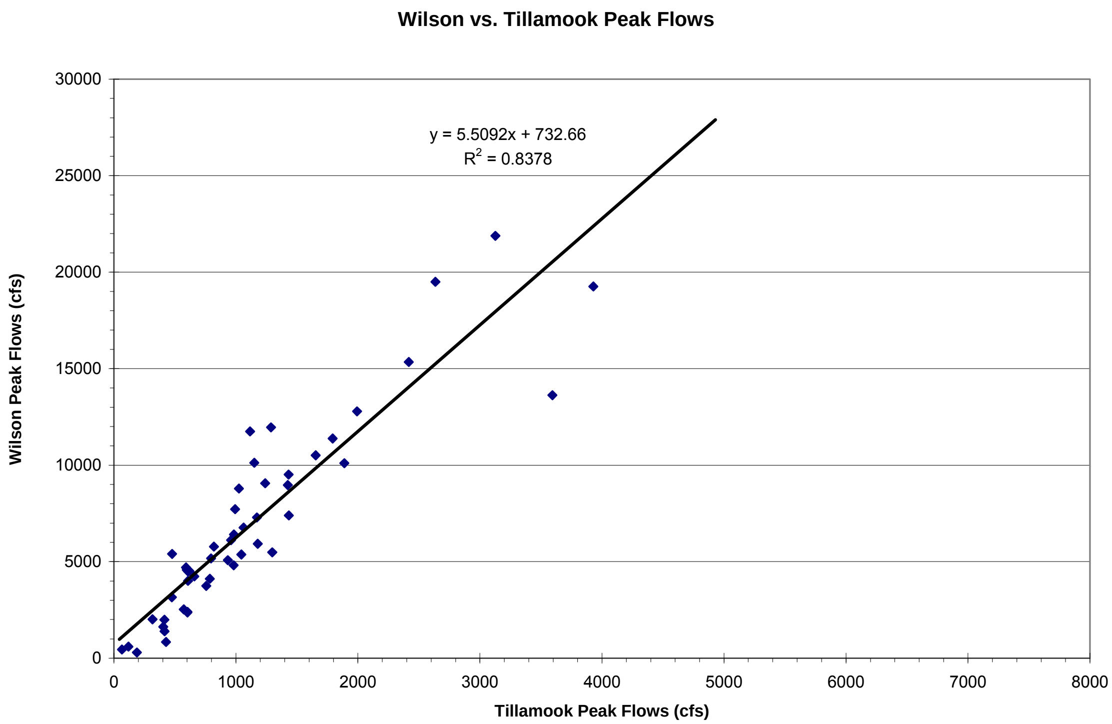
Appendix A-Table 3. Data source and location of major bridges included in the MIKE11 model.

Branch	Chainage		*Source* Survey	As-Builts	Comments
Wilson River	12454	1. US Hwy 101 RM 1.78			Data from RAS model used for the 1999 FEMA study
Wilson River	11316	2. Port of Tillamook RailRoad bridge RM 2.40			Data from RAS model used for the 1999 FEMA study
Wilson River	8926	3. Wilson River Loop Rd (Sollie-Smith) bridge	WEST	WEST	As-Builts June 1974. WEST Survey July 1998
Hall Slough	3105	1. US Highway 101 Bridge	COE		COE measured dimensions 3/22/01
Hall Slough	1291	2. County Bridge at Goodspeed Road	COE		COE measured dimensions 3/22/01
Dougherty Slough	4708	1. US Highway 101 Bridge at D1.5			Data from RAS model used for the 1999 FEMA study
Dougherty Slough	3472	2. Port of Tillamook Rail Road bridge at D2.1	Till. Co.		COE field checked curb height 2/16/01
Dougherty Slough	2182	3. Kiger Road Bridge at D4			Data from RAS model used for the 1999 FEMA study
Dougherty Slough	695.3	4. Wilson River Loop Road Bridge at D5.5			Data from RAS model used for the 1999 FEMA study
Hoquarten Slough	6258	1. US Highway 101 Bridge at H3.5			Data from RAS model used for the 1999 FEMA study
Hoquarten Slough	5145	2. Port of Tillamook Rail Road Bridge at H6			Data from RAS model used for the 1999 FEMA study
Trask River	15880.6	1. Oregon Highway 131 (Tillamook-Netarts) Highway RM 1.18	Till. Co.	COE	As-Builts March 1941. COE field checked 2/14/01
Trask River	14086.5	2. Tillamook River Loop Rd Bridge RM 2.39	Till. Co.		COE field checked 2/16/01
Trask River	10937.5	3. US Hwy 101 bridge RM 4.20	Till. Co.	COE	As-Builts October 1948. COE field checked 2/14/01
Trask River	9124.6	4. Port of Tillamook Rail Road Bridge RM 5.26	Till. Co.		COE field checked 2/16/01. COE and Larry Jones (Port of Tillamook) field checked 3/21/01 approach.
Trask River	6380.32	5. County Road 734 (Johnson) Bridge RM 6.96	Till. Co.	COE	As-BuiltsSept. 1951. COE field checked 2/14/01
Tillamook River	10188.8	1. Oregon Highway 131 (Tillamook-Netarts) Bridge RM 1.04	WEST & Till. Co.	WEST	WEST Survey Nov 1993
Tillamook River	5055.3	2. Tillamook River Loop Road (Burton) Bridge RM 3.96	WEST & Till. Co.	WEST	As-Builts Dec 1976. WEST Survey Dec 1997.
Tillamook River	2653.5	3. Tillamook River Loop Road (Blazer) Bridge RM 5.44	Till. Co.	COE	As-Builts April 1998. COE field checked some dimensions 2/14/01.
Old Trask River	722.3	1. Private Brudge at RM 1.50	Till. Co.		COE field checked dimensions 2/16/01 and 3/21/01.

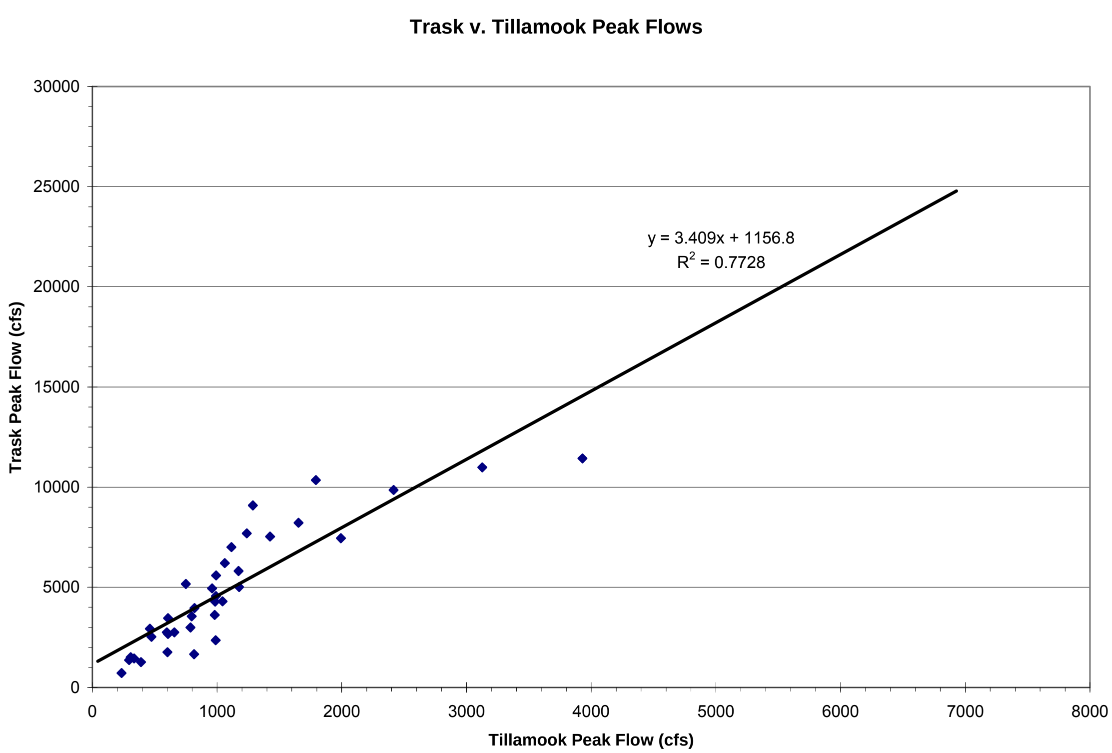
Sources: WEST = WEST Consultants, Inc.
COE = Corps of Engineer
Till. Co. = Tillamook County

Appendix A-Table 4. Data source and location of major bridges included in the MIKE11 model.

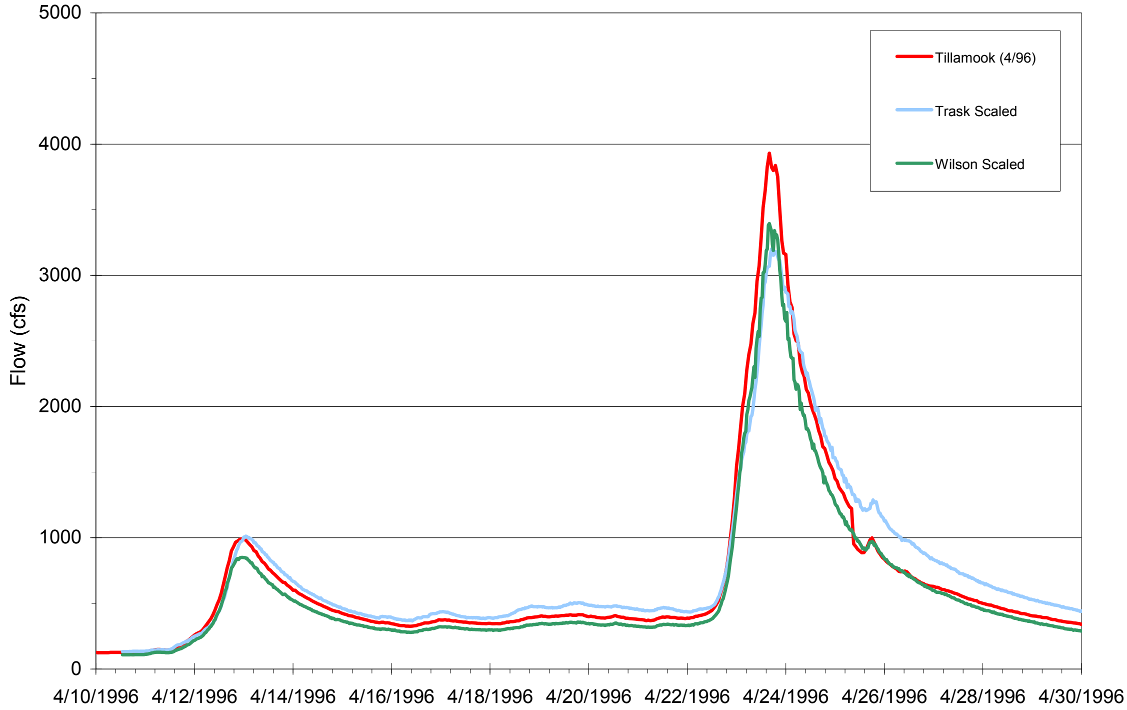
MIKE11 Link Channel Name	Chainage	Upstream Invert Elevation (m)	Downstream Invert Elevation (m)	Length (m)	Number of Culverts
LC Wils 15400 HaRB	5	1.83	1.83	9.144	1
LC Wils 15000 Wils LB	5	2.64	2.64	12.192	1
LC DS Wils RB 0.93	5	2.65	2.65	15.24	1
LC TILL 4584 TILL OLDT	10	0.83	0.46	18	4
LC TRASK 14096 TRAS RB 2.37	5	0.5	0.46	10	1
LC TRASK 14096 TRAS RB 2.37	5	0.35	0.54	10	2
LC TILL 12996 DO-TR	2.5	1.42	1.4	5.1	1
LC TILL 12996 DO-TR	2.5	1.45	1.35	5	1
LC TILL 12996 DO-TR	2.5	1.41	1.37	5	1
LC TILL 12996 DO-TR	2.5	1.5	1.38	5	1
LC TILL 12996 DO-TR	2.5	1.36	1.33	5	1
LC TILL 12996 DO-TR	2.5	1.44	1.39	5.1	1
LC TILL 12996 DO-TR	2.5	1.4	1.18	5	1
LC TILL 12996 DO-TR	2.5	1.42	1.23	5	1
LC TILL 12996 DO-TR	2.5	1.51	1.23	4.9	1
LC TILL 12996 DO-TR	2.5	1.43	1.18	5	1
LC TILL 12996 DO-TR	2.5	0.46	0.6	5	1
LC TRAS TRAS RB1.48B	5	3.72	3.72	10.5	1
LC TRAS TRAS RB1.48A	5	3.69	3.69	10.5	1
LC Till 2.00 Till lb	5	0.97	0.97	27	1
LC Till 2.44 Till lb	10	0.9	0.9	15	2
LC Till 2.95 Till lb	10	0.91	0.91	18	1
LC Till 3.09 Till lb	5	0.81	0.81	18	1
LC Till 4.00	5	1.8	1.8	9	1
LC Tras 0.32 Oldt	10	1.1	1.1	18	1
LC Till 0.10 Oldt	15	0.95	0.95	30	1
LC Till 0.37 Oldt	15	0.56	0.56	30	1
LC OldT 0.30 Oldt	10	0.94	0.94	18	1
LC OldT 0.87 Oldt	10	0.97	0.97	19.8	1
LC Till 1.54 Till oldt	10	0.85	0.85	18	1
LC Till 1.69 Ti-ot till	10	0.86	0.86	18	1
LC Till 2.00 Ti-ot till	10	0.99	0.99	18	1
LC Till 2.17 Till oldt	10	1.1	1.1	15	1
LC Till 2.35 Till oldt	10	1	1	18	1
LC Till 2.44 Till oldt	7.5	0.91	0.91	8	1
LC Till 3.55 Till oldt	10	0.7	0.7	15	1
LC Till 4.95 Till oldt	10	0.81	0.81	15	1
LC Wils 13007.4 Wils RB 1.44	5	2.82	2.82	12.192	1
Hall RB DS4	5	1.59	1.59	12.192	1
Hall RB DS4	5	1.59	1.59	12.192	1
Hall RB DS4	5	1.61	1.61	12.192	1
Hall RB DS4	5	1.61	1.61	12.192	1
Hall RB DS3	10	0.5	0.5	15.24	1
Hall RB DS2	5	1.5	1.5	10	1
LC HOQU 8137 HOQU LB 2.00	5	3	3	6.1	2
LC Hoqu LB DS	5	1	0.99	18.3	1



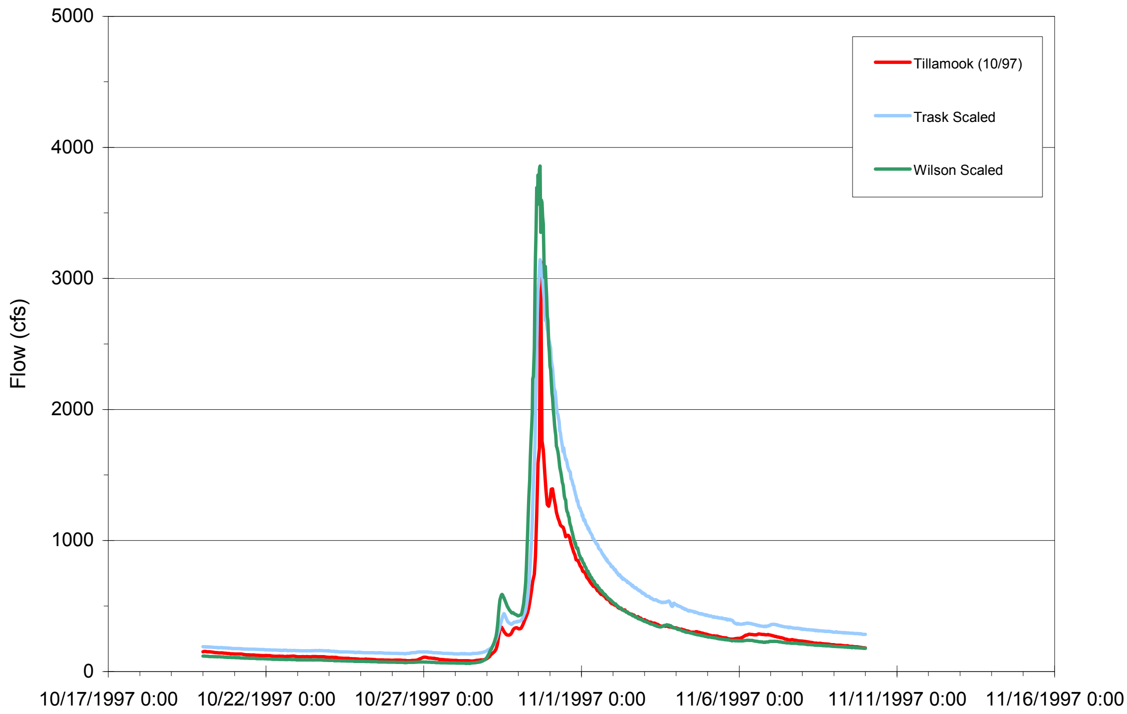
Appendix A-Figure 1. Wilson River vs. Tillamook River peak flows from November 1995 to November 1998.



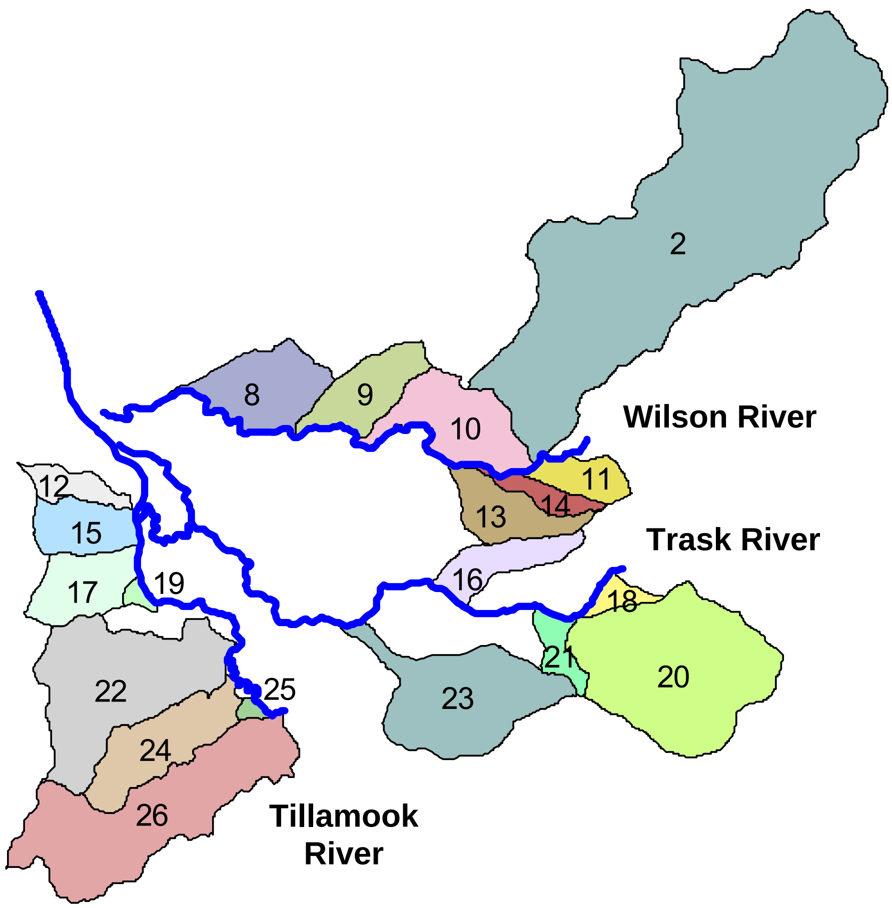
Appendix A-Figure 2. Trask River vs. Tillamook River peak flows from November 1995 to November 1998.



Appendix A-Figure 3. Observed Tillamook River flow compared to the Tillamook River flow scaled by the Trask and Wilson River regression slopes for the April 1996 event.



Appendix A-Figure 4. Observed Tillamook River flow compared to the Tillamook River flow scaled by the Trask River and Wilson River regression slope for the September/October 1997 event.



Appendix A-Figure 5. Watersheds used for computing local contributing runoff.

Appendix A-Table 5. Area of local watersheds.

Watershed Number	Area (acres)	Watershed Number	Area (acres)
2	12,657	17	1,093
8	1,492	18	274
9	1,115	19	58
10	1,673	20	4,289
11	597	21	403
12	467	22	3,449
13	988	23	2,745
14	398	24	1,653
15	904	25	98
16	835	26	3,921

Appendix A-Table 6. Calibrated Manning's 'n' values.

November 1999 Event			May 2001 Event		
MIKE11 Branch	Chainage	Manning's 'n' value specified	MIKE11 Branch	Chainage	Manning's 'n' value specified
Global Value	N/A	0.07	*Global Value*	N/A	0.05
Dougherty Slough	0	0.15	Dougherty Slough	0	0.07
Dougherty Slough	55.7	0.15	Dougherty Slough	55.7	0.07
Dougherty Slough	172	0.15	Dougherty Slough	172	0.07
Dougherty Slough	292	0.15	Dougherty Slough	292	0.07
Dougherty Slough	6368.2	0.12	Dougherty Slough	6368.2	0.07
Hall Slough	109.7	0.12	Hall Slough	109.7	0.04
Hall Slough	1460.5	0.12	Hall Slough	4924.5	0.04
Hall Slough	4924.5	0.12	Hoquarten Slough	0	0.04
Hoqu RB 2.20	0	0.15	Hoquarten Slough	5496	0.04
Hoqu RB 2.20	287.1	0.15	Hoquarten Slough	9522.2	0.04
Hoquarten Slough	2644.6	0.12	Till Bay	0	0.02
Hoquarten Slough	5496	0.12	Till Bay	2421.9	0.02
Hoquarten Slough	9522.2	0.09	Tillamook River	0.6	0.1
Old Trask River	3	0.09	Tillamook River	1745.8	0.05
Old Trask River	3212.3	0.09	Tillamook River	2706.2	0.04
Till Bay	0	0.02	Tillamook River	4239.6	0.04
Till Bay	2421.9	0.02	Tillamook River	10321.6	0.03
Till oldt 0_30	71.2	0.07	Tillamook River	14300.9	0.03
Till oldt 0_30	6793	0.07	Tras Till 0.10	0	0.04
Tillamook River	0.6	0.045	Tras Till 0.10	290	0.04
Tillamook River	1745.8	0.045	Trask River	0.3	0.13
Tillamook River	2706.2	0.045	Trask River	3952.6	0.13
Tillamook River	4239.6	0.045	Trask River	8455.8	0.05
Tillamook River	10321.6	0.04	Trask River	11699.4	0.05
Tillamook River	14300.9	0.04	Trask River	14787.8	0.04
Tras Till 0.10	0	0.035	Trask River	18930.97	0.04
Tras Till 0.10	290	0.035	Wils Kilc	34.4	0.04
Trask River	0.3	0.06	Wils Kilc	139.1	0.04
Trask River	3952.6	0.06	Wils Till	24.9	0.03
Trask River	9352.5	0.06	Wils Till	203.1	0.03
Trask River	11699.4	0.05	Wils WilsDS_B	0	0.05
Trask River	14787.8	0.04	Wils WilsDS_B	1303.76	0.05
Trask River	15337.3	0.04	Wilson River	0	0.09
Trask River	15397.2	0.04	Wilson River	1537.5	0.04
Trask River	18813.03	0.04	Wilson River	4778.2	0.04
Wils Kilc	34.4	0.04	Wilson River	9505.3	0.04
Wils Kilc	139.1	0.04	Wilson River	12543.1	0.06
Wils LB 4.92	0	0.07	Wilson River	17621.7	0.03
Wils LB 4.92	2125.72	0.07	Wilson River	17668.3	0.05
Wils Till	24.9	0.03	Wilson River	18335	0.05
Wils Till	203.1	0.03	WilsonDS_A	140.6	0.04

November 1999 Event			May 2001 Event		
MIKE11 Branch	Chainage	Manning's 'n' value specified	MIKE11 Branch	Chainage	Manning's 'n' value specified
Wils WilsDS_B	0	0.05	WilsonDS_A	394.3	0.04
Wils WilsDS_B	1303.76	0.05	WilsonDS_B	56.6	0.04
Wilson River	0	0.055	WilsonDS_B	2059	0.04
Wilson River	1537.5	0.055	WilsonDS_C	0	0.08
Wilson River	4778.2	0.05	WilsonDS_C	1365	0.08
Wilson River	9505.3	0.05			
Wilson River	11629.5	0.04			
Wilson River	12543.1	0.07			
Wilson River	15271.7	0.04			
Wilson River	17668.3	0.04			
Wilson River	18335	0.04			
WilsonDS_A	140.6	0.04			
WilsonDS_A	394.3	0.04			
WilsonDS_B	83.6	0.04			
WilsonDS_B	2059	0.04			
WilsonDS_C	0	0.04			
WilsonDS_C	1234	0.04			

Appendix A-Table 7. May 2001 high water marks supplied by CENWP.

Stream	Cross-section RM	Date	Time	Location	Elevation in feet NAVD 1988	Notes
Tillamook River	0.91	5/1/2001	8:25 AM	Paint mark on 2nd piling from the downstream side of bridge located approximately 5 ft. below a HWM mark (from 1996?), located one row of pilings toward the river from the crest gage.	6.8	placed by SF
Tillamook River	0.91	5/1/2001	8:30 AM	Paint mark on bridge along upstream face cross section of bridge	6.82	placed by SF
Tillamook River	2	5/1/2001	8:50 AM	Left bank at cross-section 2.00 marker, placed lathe and painted hub	6.51	placed by SF
Tillamook River	2.95	5/1/2001	9:00 AM	Left bank along cross-section, painted hub located in mud, 4 ft toward river from lathe	6.69	placed by SF, along narrow road
Tillamook River	3.96	5/1/2001	9:10 AM	Left bank directly toward river from crest gage under bridge, painted hub	6.51	placed by SF
Tillamook River	3.96	5/1/2001	9:15 AM	Left bank at upstream cross-section at face of bridge, painted hub placed approx. 5 ft. toward river from lathe.	6.54	placed by SF
Tillamook River	4.95	5/1/2001	9:25 AM	Left bank downstream of bridge crossing Beaver Creek, painted hub placed in mud bank approx. 3 ft. toward river from lathe, also placed a new lathe at the surveyor's control point.	6.36	placed by SF
Tillamook River	5.44	5/1/2001	9:35 AM	Right bank near downstream face of bridge, too steep to access upstream face	6.68	placed by SF
Tillamook River	6.9	5/1/2001	9:50 AM	Right bank approx. 50 ft. downstream of bridge, upstream of tide gates	15.62	placed by SF
Tillamook River	6.9	5/1/2001	9:55 AM	Right bank next to 2nd most upstream pier, paint on rock (use bottom of mark)	15.62	placed by SF
Tillamook River	6.9	5/1/2001	9:55 AM	Staff gage at bridge = 3.45	NA	read by SF
Trask River	8.75	5/1/2001	10:20 AM	Left bank approx. 10 ft. downstream of boat rails (launch), placed painted hub, lathe, flagged trees, and replaced lathe placed by surveyors at control point.	42.85	placed by SF
Trask River	6.95	5/1/2001	10:40 AM	Left bank near downstream face of bridge, placed painted hub and lathe	23.5	placed by SF
Trask River	6.95	5/1/2001	10:40 AM	Left bank under bridge: drew lower mark at current water mark, and drew upper mark at apparent high water mark (unknown time), did not place one at upstream face due to no trespassing signs	23.5	placed by SF
Trask River	5.26	5/1/2001	11:05 AM	Left bank downstream of RR bridge, painted hub and lathe placed (did not place mark u/s of bridge due to bad access), ctrl not located	14.7	placed by SF (pics taken of Mill Cr also)
Trask River	4.2	5/1/2001	11:30 AM	Right bank near upstream face of bridge	8.99	placed by SF
Trask River	4.2	5/1/2001	11:35 AM	Right bank near downstream face of bridge ***likely mismarked cross-section number on lathe**	8.94	placed by SF
Trask River	2.98	5/1/2001	12:00 PM	Right bank approx. 30 ft. downstream of surveyor's cross-section marker, painted hub in mud bank with lathe and lots of flaggin along steep blackberry slope and dump site -- fun, fun, Located across road from house #2750	6.7	placed by SF
Trask River	2.39	5/1/2001	12:20 PM	Right bank near downstream face of bridge	6.01	placed by SF
Trask River	2.39	5/1/2001	12:25 PM	Right bank near upstream face of bridge, placed painted hub in sandy bank and also painted rock	6.1	placed by SF
Trask River	1.18	5/1/2001	12:40 PM	Right bank near upstream bridge face near crest gage	4.88	placed by SF

Stream	Cross-section RM	Date	Time	Location	Elevation in feet NAVD 1988	Notes
Wilson River	0.63	5/1/2001	8:30 AM	Left bank down embankment across from first barn, approx. 50 ft. downstream from cross-section marker (no monument found), water surface marked by lathe only, no hub, located just downstream of 3 trees, cross-section mark just upstream of 3 trees.	7.7	placed by MK
Wilson River	1.08	5/1/2001	8:15 AM	Left bank down embankment and downstream from farm near "No Parking" sign, marked by hub and lathe	Unable to locate Monument	placed by MK
Wilson River	1.8	5/1/2001	8:45 AM	Left bank upstream of US Hwy. 101, near crest gage, paint line (bottom of line) on concrete steps leading to river.	9.4	placed by MK
Wilson River	2.4	5/1/2001	10:00 AM	Left bank downstream of railroad bridge near downstream cross-section and crest gage.	10.64	placed by MK, **note: replace crest gage bracket**
Wilson River	3.83	5/1/2001	10:15 AM	Left side under Sollie-Smith bridge, 2 marks: paint line on piling left side, and hub under bridge , 2nd piling from downstream end with lathe.	14.5	placed by MK
Wilson River	8.43	5/1/2001	12:30 PM	Left bank boat launch area, marked in gravel with hub and stake, surveyed 5/1/01	40.7	placed by MK
Wilson River	8.6	5/1/2001	12:00 PM	Left bank approx. 52 ft. downstream of Mills bridge, paint marks on rocks with tape	42.91	placed by MK
Wilson River	8.6	5/1/2001	12:00 PM	Left bank approx. 51 ft. upstream of Mills bridge, paint marks on rocks/moss with tape.	42.98	placed by MK
Dougherty Slough	1.5	5/1/2001	9:00 AM	Left bank upstream face Hwy 101 bridge, marked with hub and lathe, ws inside of hub	6.6	placed by MK
Dougherty Slough	2	5/1/2001	9:25 AM	Left bank approx. 25 ft. downstream of marker, marked with lathe near broken tree trunk	6.38	placed by MK
Dougherty Slough		5/1/2001	10:40 AM	Right bank downstream of logjam at Corps Sec. 4, hub and lathe	15.13	placed by MK
Dougherty Slough		5/1/2001	10:45 AM	Dougherty at Wilson confluence, hub and lathe, note: flow in Dougherty past logjam approx. 20-40 cfs.	15.85	placed by MK
Dougherty Slough	5.5	5/1/2001	11:15 AM	Under bridge on right pier at Wilson River Loop Rd. bridge, orange arrow pointing to top of beam where water was at the edge, lathe marks spot also	13.19	placed by MK
Hoquarten Slough	3.5	5/1/2001	9:10 AM	Left bank at upstream face of Hwy 101 bridge, marked with hub and lathe	6.41	placed by MK
Hall Slough		5/1/2001	9:35 AM	Right bank at upstream face of Goodspeed Rd. bridge, painted line on CMP culvert (tide gate)	6.67	placed by MK

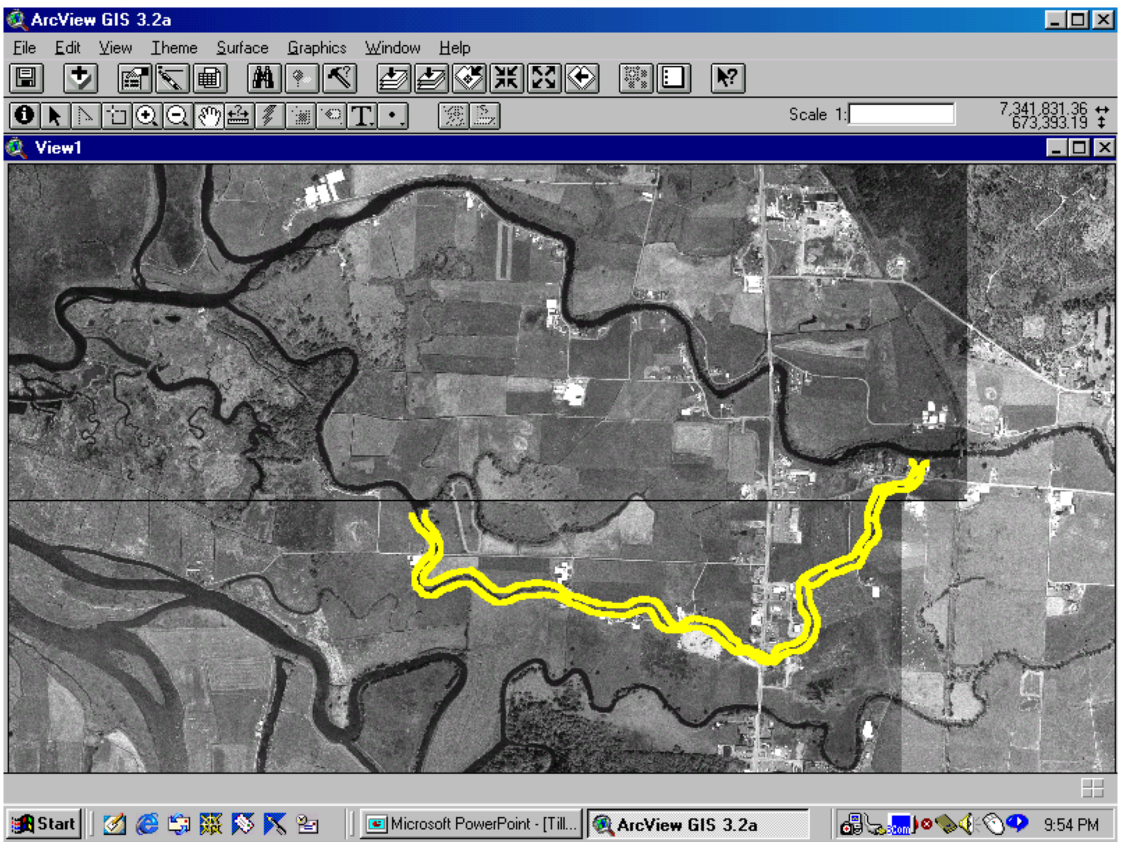
Appendix B. Flood Control Alternatives Modeled in MIKE11

PRELIMINARY RESULTS

March 2002

WI 2

"As shown in the following figure (Appendix B-Figure 6), Hall Slough is a side channel of the Wilson River. The slough's origins are upstream of highway 101 near the Wilson River Loop Road and its downstream end comes back into the Wilson River approximately 2-miles downstream near the mouth of the Wilson River. Hall Slough was connected to the Wilson River at its upstream end before 1950. At that time a bridge was in place that crossed Hall Slough on the Wilson River Loop Road. Since then the slough has been filled in at its upstream end, the bridge was removed and a small culvert was placed through the Wilson River Loop Road to drain the area behind it. This area currently represents the area of the Wilson River that overtops first during a flood event. Currently floodwaters flow over along the left bank of the river near the historic Hall Slough entrance and flow down the Wilson River Loop Road to Highway 101 where they flow south along the Highway eventually crossing and flooding the Highway. These so-called "nuisance" floods occur frequently and might be controlled by re-establishing the historic Hall Slough." (USACE, 2003).



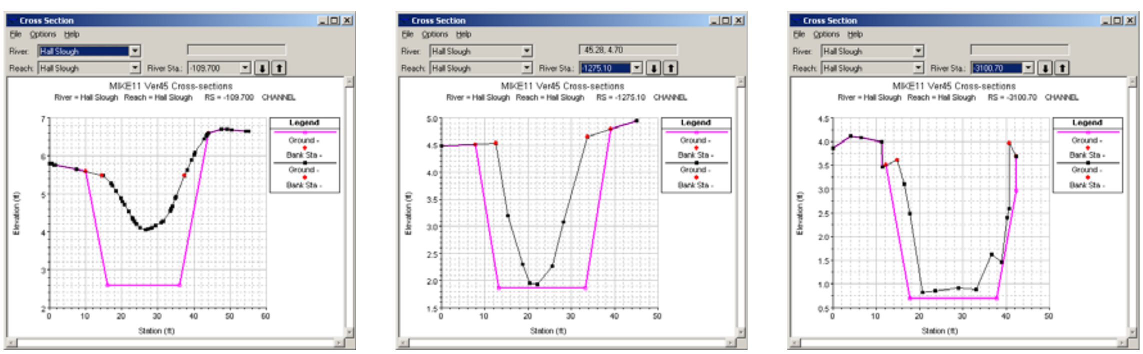
Appendix B-Figure 6. WI-2 – Hall Slough Alternative Area.

Hall Slough channel modification and levee removal. Alterations for this alternative included:

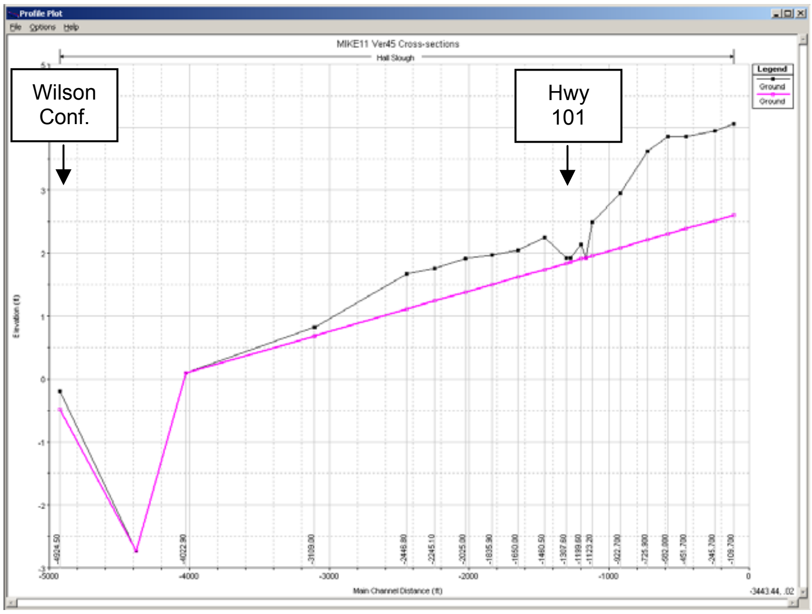
a. Modifying the channel along the entire length of Hall Slough (chainage 109.7 through 4924.5), at a slope of 0.00064, bottom width of 20m, and side slopes at 2:1 (see below).
b. Removing (lowering) the left and right bank levees of Hall Slough downstream of the Highway 101 bridge. Simulations were performed with link channel levels lowered to both 3.2 meters, an elevation just above the maximum high tide for the simulation period, and the average ground elevation on the land side of the levee.
c. Removing (lowering) the levee, as in ‘b’ above, in combination with the channel modification, ‘a’ from above.
d. Increasing the capacity though the Wilson Loop Road by altering the upstream connection of the Hall Slough with the Wilson River.

<u>a. Channel modification only</u>.

Appendix B-Figure 7 shows representative modifications for the channel relative to the base condition geometry. Note that the change to the channel transitions from both deepening and widening the Slough at the upstream end, to only widening the cross-section near the Highway 101 bridge, to having very little change at the downstream end. The thalweg change can be seen in Appendix B-Figure 7. This cut was selected to maximize the slope through the Slough without having the thalweg at the downstream end lower than the Wilson River thalweg near the confluence in the base condition. The cross-sections and culvert at the Highway 101 bridge were altered to this trapezoid shape as part of this alternative.



Appendix B-Figure 7. Typical channel modifications to the Hall Slough (channel modification shown in magenta).

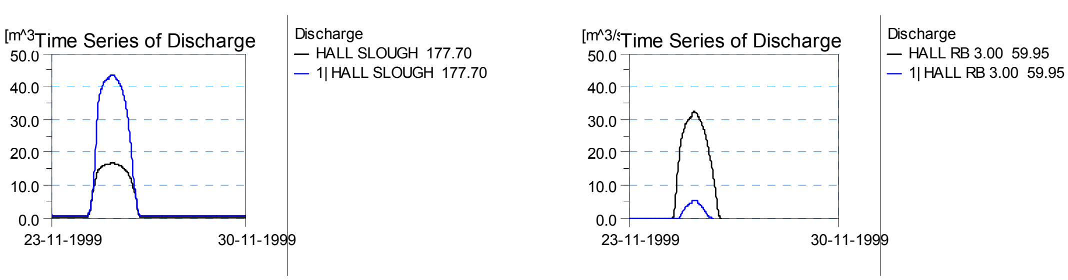


Appendix B- Figure 8. Thalweg for Alternative Wi2

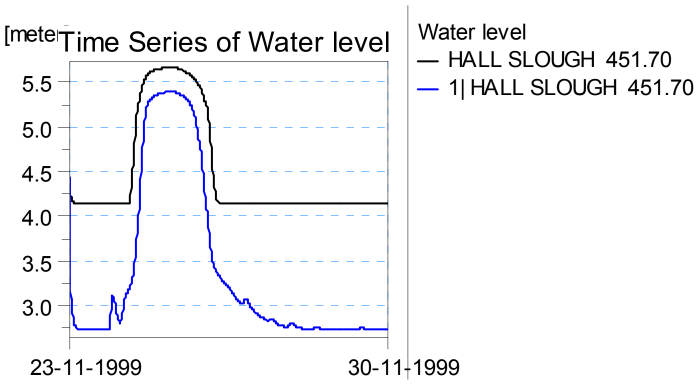
Results: Redistributing flow from the Hall right bank to the Hall Slough at the upstream end, and delaying overtopping of Highway 101, are the most significant impacts of this alternative. The channel modification re-proportions the total 49 cms from the Wilson River, to approximately 44 cms (from 32 cms) through the Hall Slough, to 5 cms (from 17 cms) in the right Hall overbank, as shown in Appendix B-Figure 9. The change to the channel geometry also decreases the maximum peak stage by about 0.4 m at the upstream end of the Hall Slough (chainage 109.7). Note that tidal effects now extend nearly to the upstream end of Hall Slough as seen in the rising and receding limb of the hydrograph in Appendix B-Figure 10.

The net effect of this alteration is to delay overtopping of Highway 101 (at a minimum elevation of approximately 3.5 m), in the Hall right overbank, by approximately 4 hours (Appendix B-Figure 11). However, this alternative does not significantly decrease the peak stage at this Highway 101 location (Hall RB 3.00, at chainage 423.69, is lowered by less than 0.1 meters).

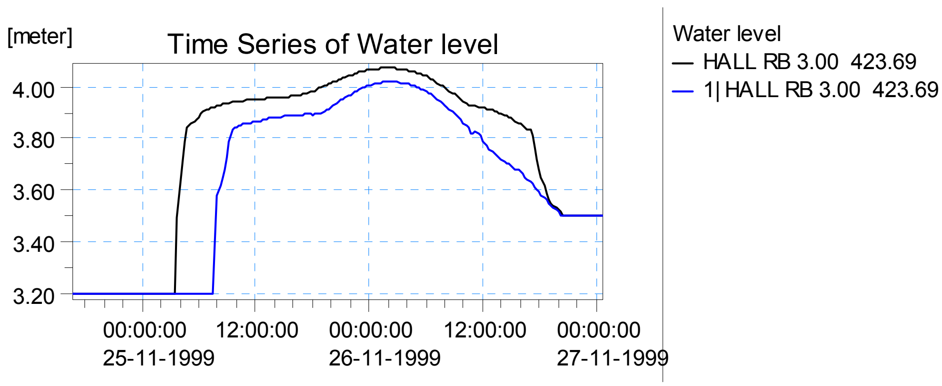
Little to no change in stage was observed at any of the flood cells due to the channel modification.



Appendix B-Figure 9. Diversion of discharge at the upstream end of Hall Slough and the right Hall overbank (Wi2 shown in blue).



Appendix B-Figure 10. Stage towards the upstream end of Hall Slough (Wi2 shown in blue).



Appendix B-Figure 11. Stage hydrograph at the upstream end of the Highway 101 in the Hall right overbank (Wi2 shown in blue).

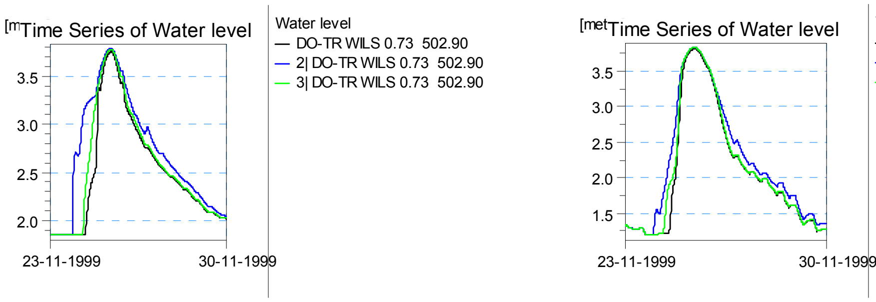
<u>b. Lowering levees</u>.

Results: Lowering levees increases duration, and likely the frequency, of flooding in the overbanks, without any significant reduction in stage. Appendix B-Figure 12 shows typical results in the overbanks from lowering the Hall Slough levees. The total duration of the flooding event increases as the levees are lowered, as evaluated by the hydrograph width. This increased duration can be up to 9 hours longer when levees are lowered to a minimum of 3.2 meters, and up to 25 hours longer for levees lowered to the ground elevation, at Flood Cells 4 and 5. In addition, peak stage is reduced by less than 0.1 meters in both cases.

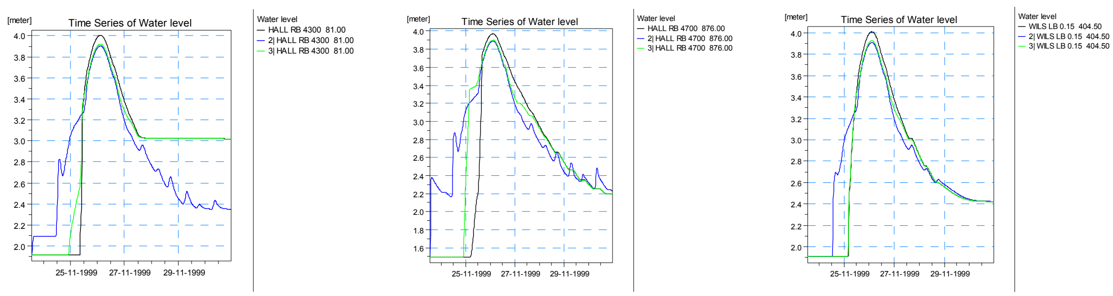
Similar effects are observed at Flood Cells 6, 7, 8, and 9 (Appendix B-Figure 13). The duration increase can be up to approximately 12 hours longer when levees are lowered to a minimum of 3.2 meters, and up to 20 hours longer when levees are lowered to the ground elevation. The stage is decreased by about 0.1 meters at most, in both cases. The exception to this is at Flood Cell #6 that does not include any kind drainage from the cell (e.g. tide gated culverts) below the levee height in the base case condition (the straight line near 3 meters of the receding limb in Appendix B-Figure 13).

Impacts to Hall Slough include <u>decreasing</u> the flood duration and the peak stage by approximately 0.1 meters for both cases (Appendix B-Figure 14).

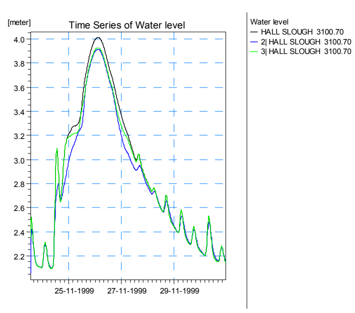
Other flood cells, or other branches in the study area, are not significantly impacted by lowering the Hall Slough levees.



Appendix B-Figure 12. Stage hydrographs for Flood Cells 4 and 5 (Wi2 with levee lowered in blue, Wi2 with levee lowered to a minimum 3.2 meters in green)



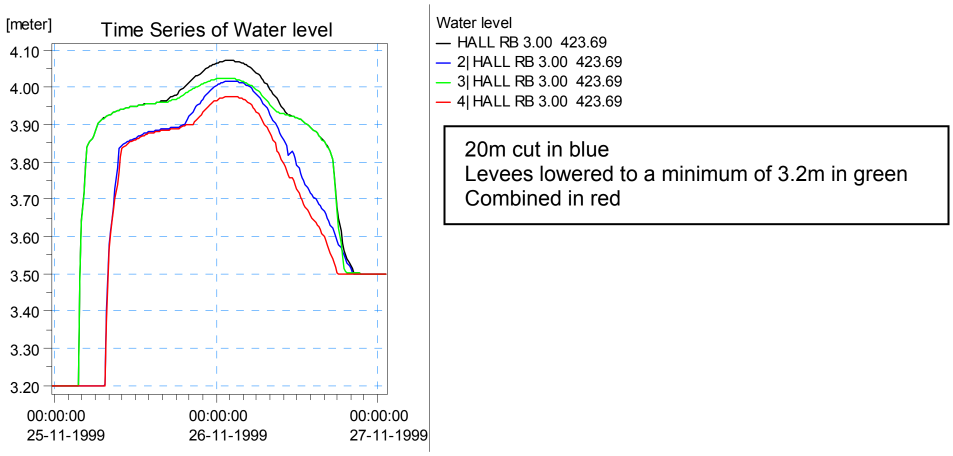
Appendix B-Figure 13. Stage hydrographs for Flood Cells 6, 8, and 9 (Wi2 with levee lowered in blue, Wi2 with levee lowered to a minimum 3.2 meters in green)



Appendix B-Figure 14. Hall Slough stage hydrographs (Wi2 with levee lowered in blue, Wi2 with levee lowered to a minimum 3.2 meters in green)

c. Lowering levees (3.2 m minimum) and channel modification.

Results: Results are similar to the alternative with just the levee lowered (3.2 m minimum) except at Highway 101 in the Hall right overbank where the duration of the roadway topping is reduced by a total of 6 hours, and the stage reduced by 0.1 meters (0.3 feet). Flood cells behave nearly identical to the levee lowered only alternative.



Appendix B-Figure 15. Highway 101 in the Hall right overbank for Alternative Wi2

d. Increasing upstream capacity.

Three culvert configurations were simulated as part of this scenario. Five 1.22 m (4 foot) diameter culverts were added below the Wilson Loop Road to the channel modification only alternative. Two simulations were performed with five 1.22 m (4 foot) diameter culverts, one with the upstream invert elevation at 4.2 m, and the other at 3.2 m. In both cases, the downstream invert elevation was set to 2.6 m, equal to the thalweg of the channel cut. Five 1.83 meter (6 foot) diameter culverts were simulated in a third alternative, with an upstream and downstream invert elevation, of 3.2m and 2.6 m, respectively.

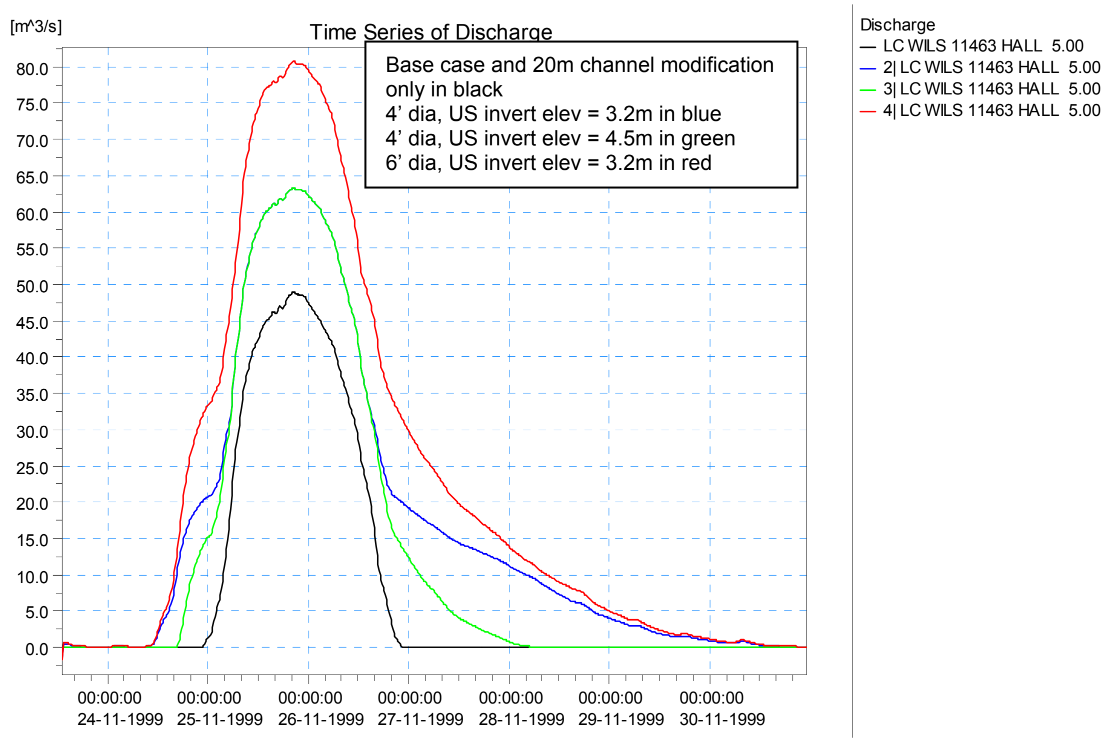
Results: Increasing the capacity through the Wilson Loop Road by adding culverts lengthens the period of flushing flows to the Hall Slough and also the duration of flooding in the Hall overbank.

The 1.22 meter (4 foot) diameter culverts (both simulation cases) increases the discharge to the Hall Slough to a total of approximately 63 cms, and the 18.3 meter (6 foot) diameter culverts to a total of approximately 81 cms. The duration of flushing flows from the Wilson River increases on the order of days for the three culvert alternatives, as shown in Appendix B-Figure 16.

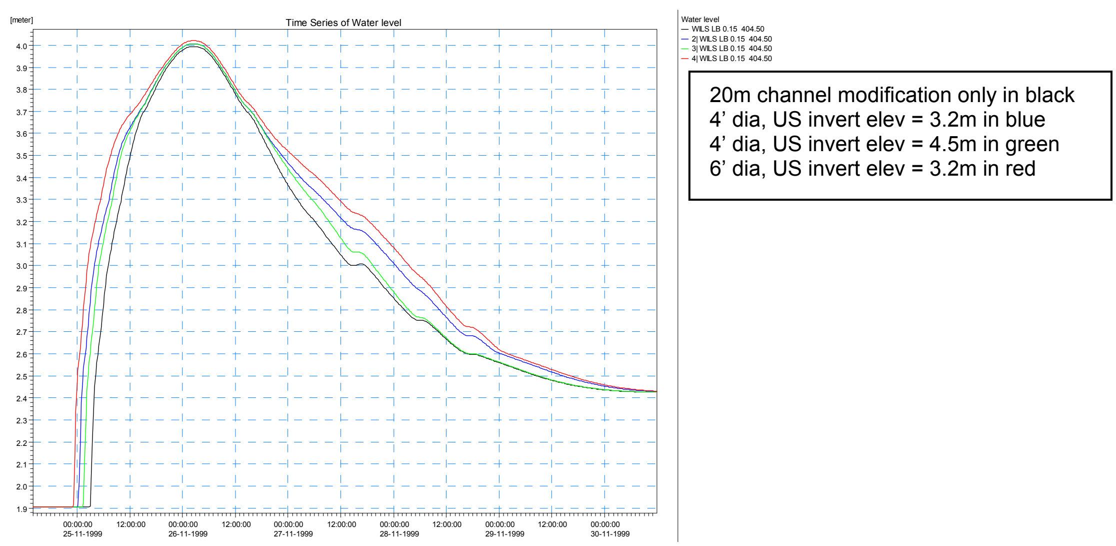
The corresponding decrease in Wilson River discharge resulted in less than a 0.1 m change in peak stage and a shortening of the receding limb of the hydrograph by up to approximately 5 hours (compared to both the base case and the channel modification only alternative).

The higher discharge to Hall Slough also increased the time the nearby overbanks are inundated, but without significantly altering the stage (a 0.1 m change or less) from either the base case or the channel modification only alternative. This increase in duration, as high as an additional 5 hours on the rising limb, and 13 hours on the receding limb, occurred most noticeably in flood cells 6, 7, 9, 11 and 19. An example of the range of flooding duration in the overbanks for the different culvert configurations can be seen in Appendix B-Figure 17. The duration of flooding in the Hall Slough left overbank is also increased, e.g., in flood cells 5 and 10, on the order of 14 total hours (Appendix B-Figure 18).

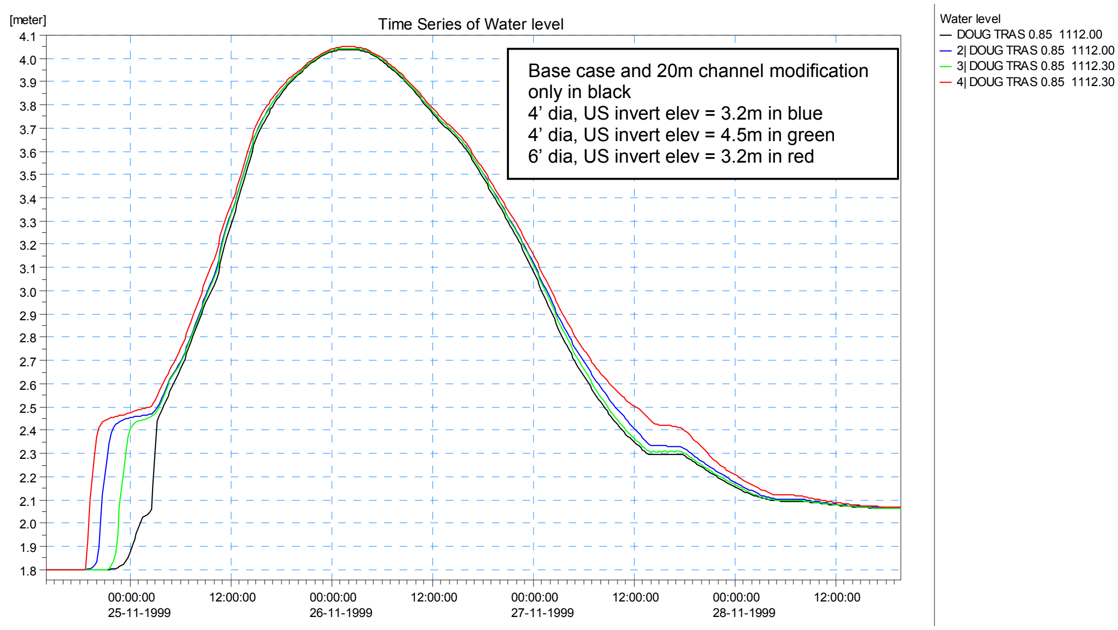
The increased discharge to Hall Slough (simulated with the channel modification in place) also negates some of the beneficial decrease in duration of Highway 101 overtopping seen in the channel modification only alternative. The duration of flooding actually increases above the base case by about 9 hours for the 1.83 meter (6 foot) diameter culverts (Appendix B-Figure 19).



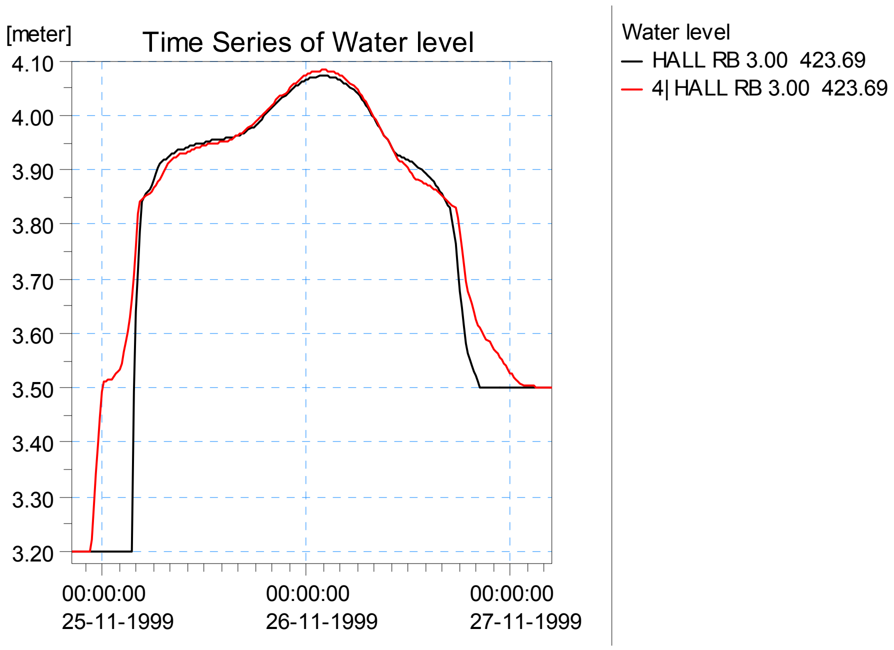
Appendix B-Figure 16. Increase in discharge from the Wilson River to the Hall Slough with the addition of culverts.



Appendix B-Figure 17. Increased duration of overbank flooding



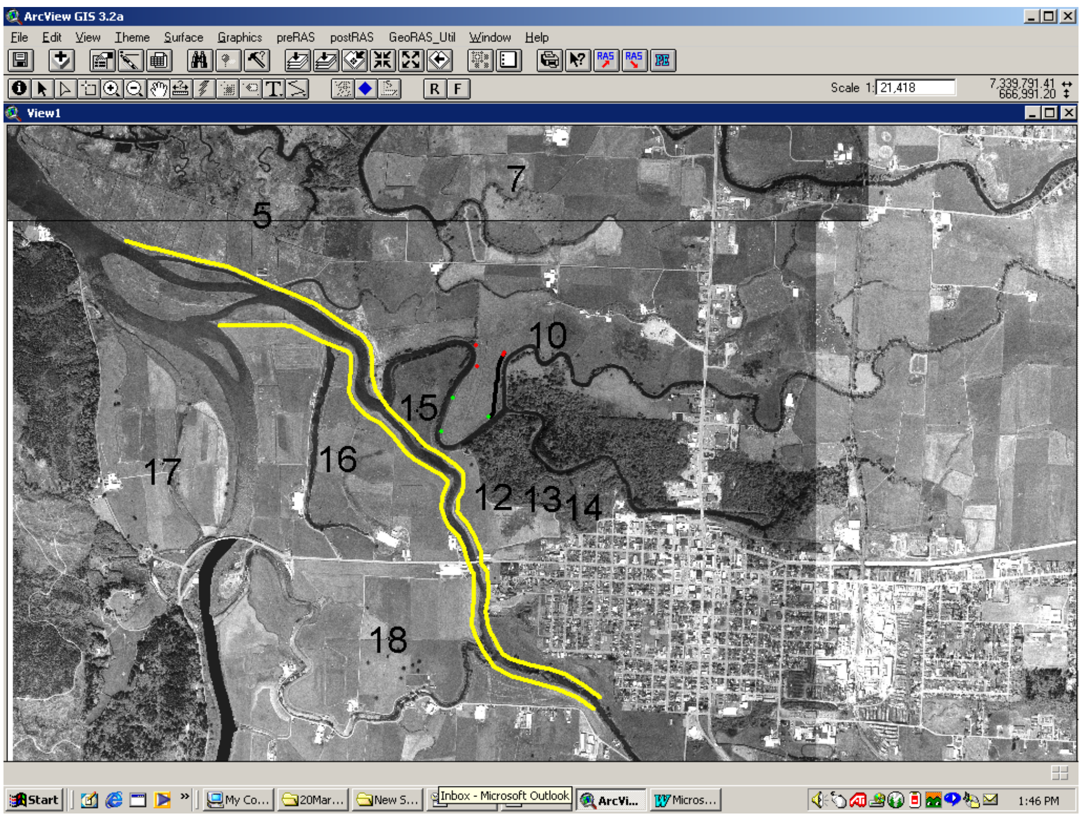
Appendix B-Figure 18. Increase in duration of flooding in flood cell 10.



Appendix B-Figure 19. Increase in duration of flooding at Highway 101 in the Hall right overbank, from 1.83 meter diameter culverts (in red) above the base case.

TR 2

"As shown in the following figure (), the Lower Trask River alternative area is located along the Trask River between river mile 2.00 and the downstream confluence with the Tillamook River. This area represents a constriction in the Trask River. The constriction appears to be man-induced as the lower river was re-routed and channelized in years past. The current river channel has a much lower capacity in this reach than both upstream and downstream reaches of this river. Furthermore, the reach represents a river lacking in riparian habitat and channel complexity. This reach of river is essentially a tidal flume devoid of riparian vegetation other than grazed trapezoidal banks. Alternatives were modeled for this reach that included setting back levees in this reach along with widening and deepening the channel in this reach" (USACE, 2003).



Appendix B-Figure 20. TR 2 – Lower Trask River Alternative

Trask River channel modification, left bank levee setback, and right bank level removal. Alterations for this alternative included:

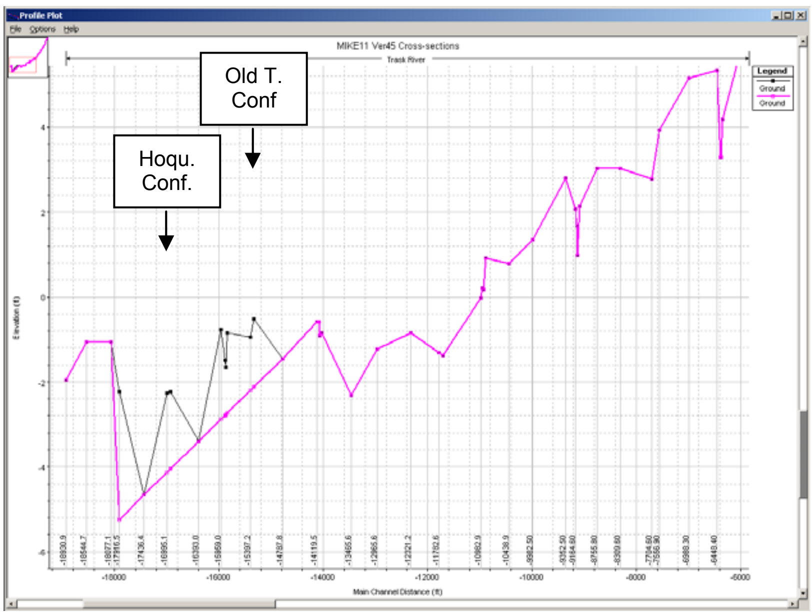
a. Modifying the channel from chainage 14787.8 (US of the junction with Old Trask) to chainage 17916.5 (just US of the junction with Tras-Till), at a slope of 0.0012082, bottom width of 40m, and side slopes at 2:1 (see below).
b. Setting back the left bank levee by approximately 60m (200 feet) in the Stillwell area. Cross-sections 15397.2 (just DS of the junction with Old Trask) to 17436.4 were altered.
c. Removing (lowering) the right bank levee from Trask 17436.4, downstream to Tillamook 12823.8. Five link channels between these cross-sections were lowered to 3.2m, an

elevation just above the maximum high tide for the simulation period. See "Alternative Wi2" for reasons for selecting this elevation.

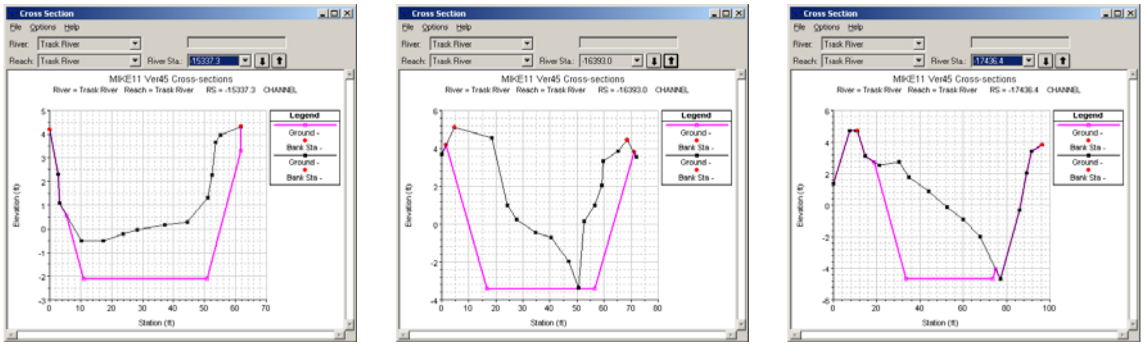
d. Combinations of the above.

<u>a. Channel modification only</u>.

A wide, deep channel, and at some cross-sections extending horizontally beyond the existing levee locations, was selected to determine if even such a large change would result in beneficial stage and flow reductions. This cut was also selected, in part, to be consistent with the lowest thalweg elevations on the downstream Doughery Slough cross-sections (as low as -4 meters), at the Dougherty Slough-Trask confluence (near Trask chainage 16995.1). Effects of a more gradual slope, closer to the natural channel slope can be seen in results for "Alternative Tr10." The thalweg before and after the channel modification is shown in Appendix B-Figure 21. The channel modification was extended as far upstream as chainage 14787.8 to create a consistent bed slope through the section. Example channel modification cuts are shown in Appendix B-Figure 22. This channel modification was made through the Netarts Highway opening.



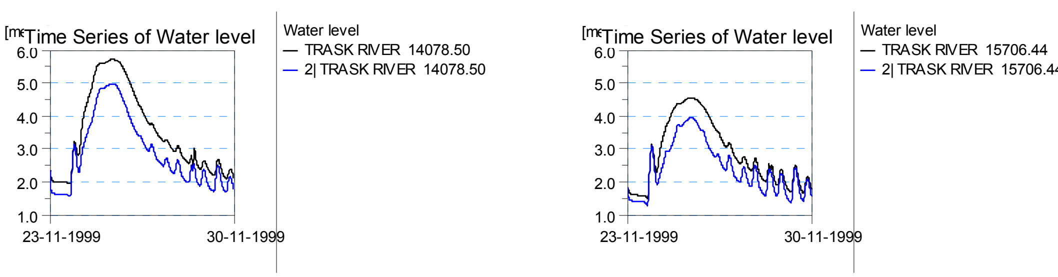
Appendix B-Figure 21. Thalweg for Tr2 channel modification (Tr2 in magenta).



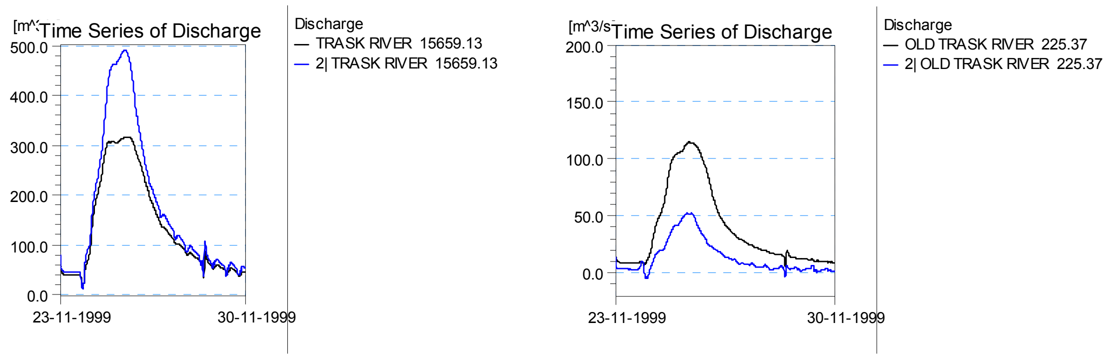
Appendix B-Figure 22. Typical channel modification cuts for Alternative Tr2 (Tr2 in magenta).

Results: Decreased stage and increased capacity in the Trask River is one of the most significant changes of this alternative. The decrease in peak stage is greatest through the cross-sections with the channel modification, and the sections upstream of these cuts (roughly 0.6 – 0.7 m, see Appendix B-Figure 23). However, the decrease in stage is greatly reduced (to approximately 0.1 m) downstream of the confluence with Hoquarten slough. This decrease in stage also reduces the overtopping flow to the overbank between the Trask and Tillamook (Branch Till OldT 0.32), resulting in a lowered peak water surface elevation stage of approximately 0.4m (at Till OldT 0.32 chainage 5700) in the overbank. In addition, the channel modification diverts a higher percentage of discharge through the Trask (by nearly 170cms, Appendix B-Figure 24), and away from the Old Trask, and consequently the Tillamook River (Tillamook River peak stage is reduced by 0.3 meters).

This channel modification has little impact with respect to the Flood Cells. There was a drop of about 0.1 m in the maximum stage in Flood Cells 4, 5, 10, 12, 13, 14, and 15. Flooding duration typically occurs roughly one hour later, and ends approximately two hours sooner (as much as 4 hours sooner in Cell 15), in these cells.



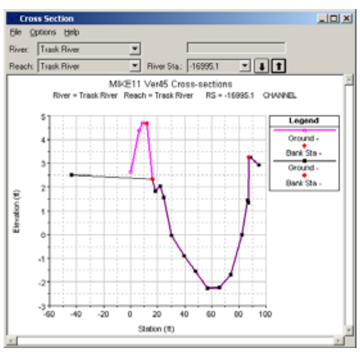
Appendix B-Figure 23. Trask River stage (Tr2 results in blue).



Appendix B-Figure 24. Trask and Old Trask discharge (Tr2 results in blue).

b. Setting back the left bank levee.

Results: Setting back the left bank levee (Appendix B-Figure 25) slightly reduces the upstream stage (by about 0.1 m at chainage 14787.8), decreasing the left bank link channel flow to the overbank between the Trask and Tillamook Rivers (i.e., to Branch: Till OldT 0.32). This difference in flow diverted back to the Trask River (approximately 25 cms at Trask River 15857.60) does not have a significant enough impact to significantly lower the water surface elevation in the overbank (less than 0.1 m at Till OldT 0.32 chainage 14787.8), or in any of the Flood Cells. In addition, both stage and discharge on the Old Trask, are essentially unaffected by setting back the left bank levee. However, the setback levee does increase the conveyance of the channel such that the additional 25 cms does not significantly alter the Trask stage downstream of the Old Trask confluence.



Appendix B-Figure 25. Typical 60m levee setback for Tr2 (original cross-section geometry in magenta).

c. Lowering right bank levee.

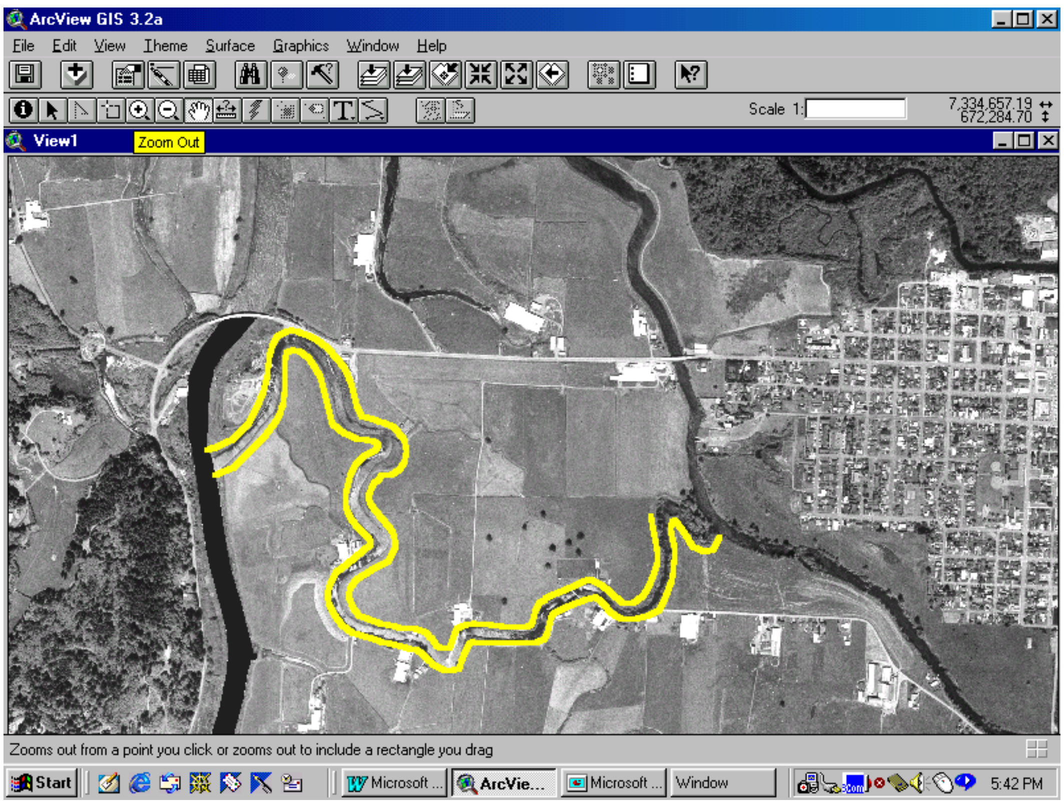
Results: Lowering the right bank of the Trask reduces the peak water surface elevation in the "peninsula" (i.e., Branch Doug Tras 0.85/Flood Cell 5) by approximately 0.2 m at the downstream end (chainage 3476.6). This effect on stage diminishes upstream (0.1 m at chainage 1112.0). There is little to no effect on stage in the Trask or to any of the other flood cells. Flood cell duration is typically decreased by less than a total of 2 hours, if at all, in any of the flood cells.

d. Combinations of channel modification, levee setback, and levee removal.

See alternative Tr10.

TR 8

"The Old Trask River is a branch of the Trask River, possibly representing the former mouth of the Trask River (Appendix B-Figure 26). This reach flows between the Trask River and the Tillamook River near Trask River Mile 1.8. This reach of river helps alleviate flooding on the Trask River. The reach is currently leveed along both sides. The Stillwell Drainage District is on the north side of the channel and the Tillamook-Trask Drainage District is on the south side. The Stillwell levee provides approximately 50-year protection while the Tillamook-Trask levee only protects for tidal flows. Therefore, the area to the south gets flooded often. This alternative included modifying the channel by widening and deepening as well as setting back the levees along the channel. Combinations of the two and on their own were modeled in MIKE 11" (USACE, 2003).



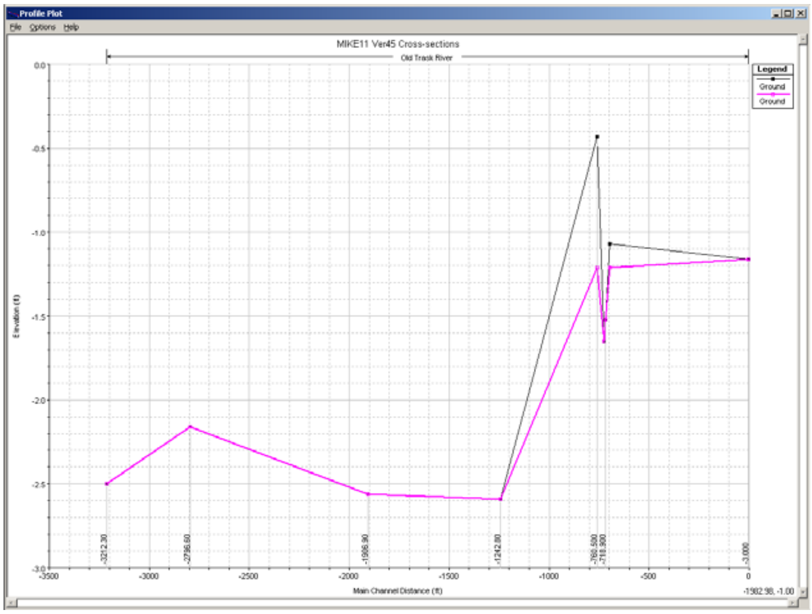
Appendix B-Figure 26. TR8 – Old Trask River Alternative

Old Trask channel modification and levee setback. Alterations for this alternative included:

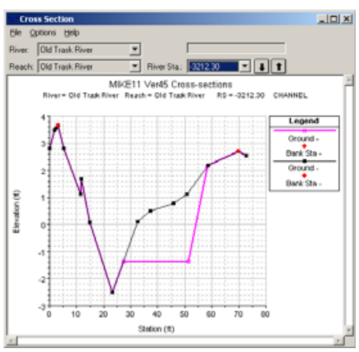
a. Modifying the channel along the entire length of Old Trask River.
b. Setting back the left and right bank by approximately 30 meters.
c. Combining 'a' and 'b' from above.

a. Modifying the channel.

The channel cut through the Old Trask River extended along the entire length of the Old Trask River, from chainage 3.0 to 3212.3, at a slope of 0.0000654, a bottom width of 30 meters, and 2:1 side slopes. This channel cut was selected to maximize the channel size and maintain a constant slope between the Trask River thalweg near the upstream end (approximately -1 meter), and the Tillamook River thalweg (approximately -2 meters) near the downstream end (Appendix B-Figure 27). This resulted in a channel modification that typically only widened the channel (Appendix B-Figure 28).



Appendix B-Figure 27. Old Trask River profile with modified channel cut (in magenta).

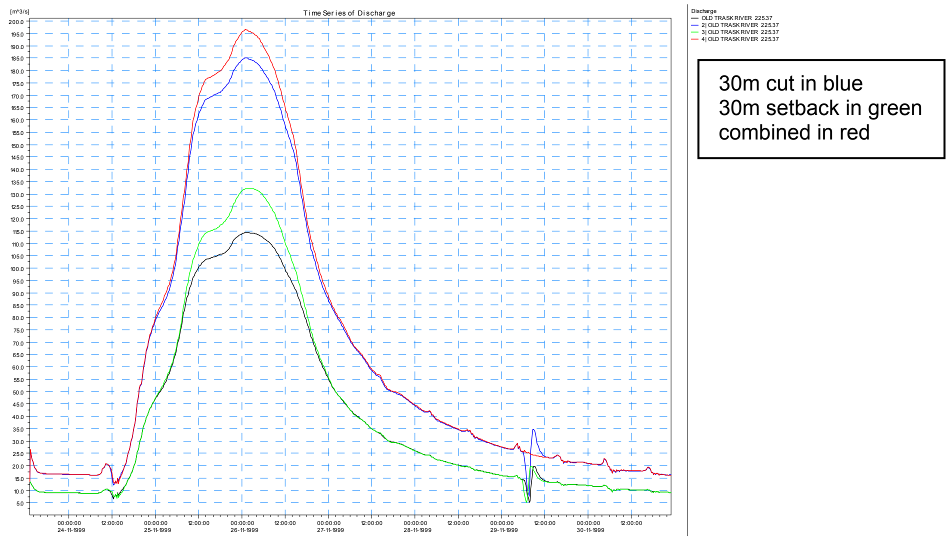


Appendix B-Figure 28. Typical Old Trask River cross-section with modified channel (in magenta).

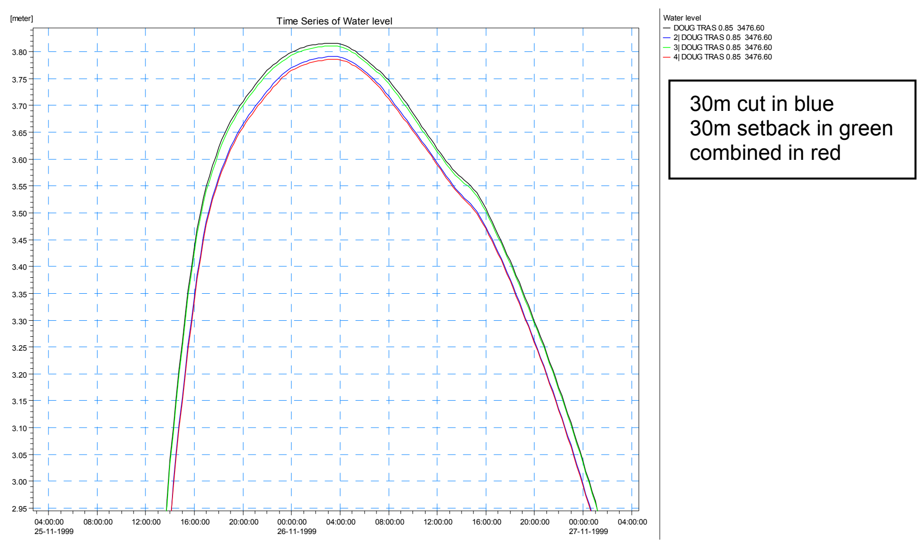
Results: The most significant change from this alternative is the redirection of approximately 70 cms from the Trask River, and link channel flow from the Trask River to the Till Oldt 0.30 branch, to the Old Trask River (Appendix B-Figure 29). However, much of this flow then overtops the left Old Trask overbanks, flowing into Till Oldt 0.30 overbank area, and resulting in a less than 0.1 m change in stage.

In addition, this alternative lowers stage 0.1 meters on the Trask and Old Trask Rivers in the area of the confluence. However, the Old Trask maximum stage is raised at the downstream end by approximately 0.1 meters.

Flood cells including 4, 5, 10, 12, 13, 14, and 15 are lowered by 0.1 meters at most and are shortened typically by about an hour on both the rising and receding limb of the hydrograph (Appendix B-Figure 30).



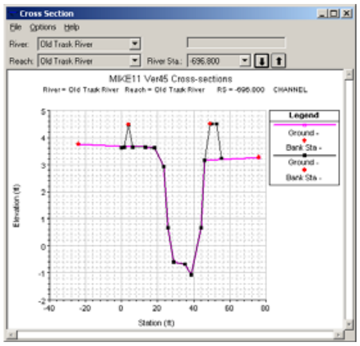
Appendix B-Figure 29. Change in Old Trask River discharge simulated in Alternative Tr8.



Appendix B-Figure 30. Typical change in stage for flood cells (Example from cell 5).

b. Setback levees

Appendix B-Figure 31 shows an example of the geometry after the levees on both banks have been setback approximately 30m (100 feet).

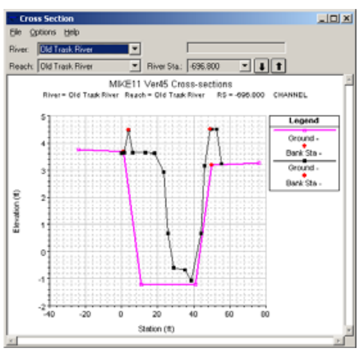


Appendix B-Figure 31. Old Trask River with modified levee setback (in magenta).

Results: Setting back the levee results in very little change from the base case, except for an additional 20 cms routed through the Old Trask River. There is very little change to stage, as seen in Appendix B-Figure 30.

c. <u>Levee setback and cut</u>

The same cut from the modified channel simulation was applied to the setback levee channel geometry as shown in Appendix B-Figure 32

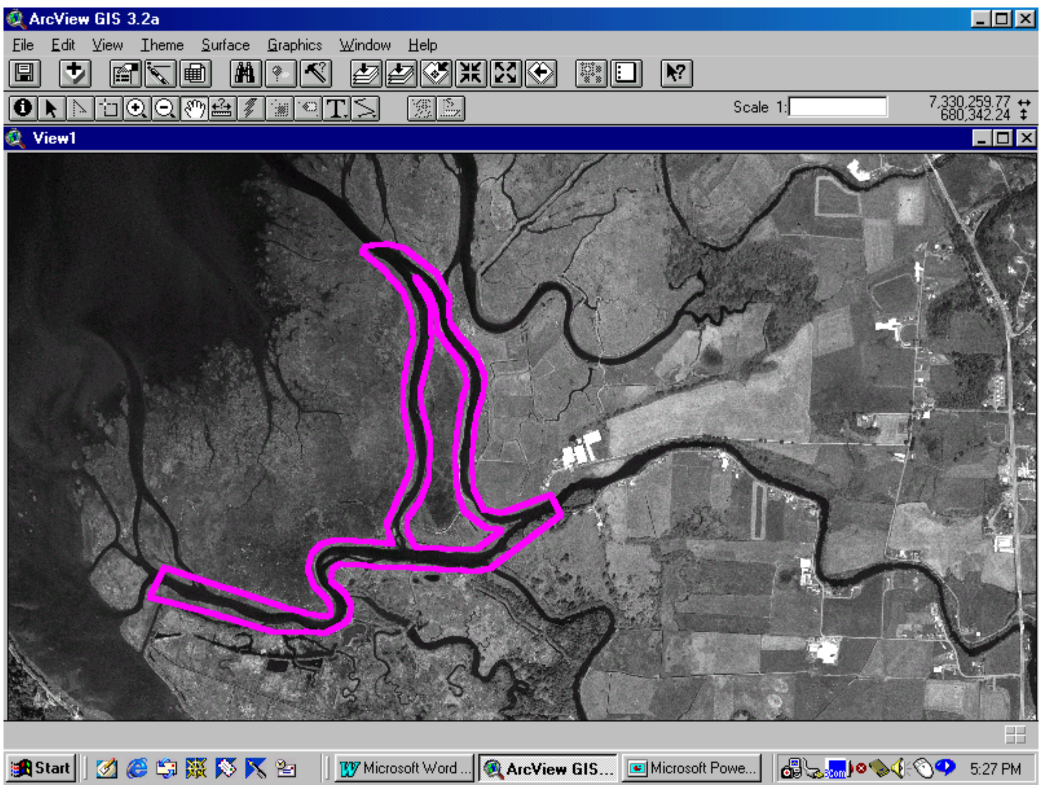


Appendix B-Figure 32. Old Trask River with modified levee setback and modified channel (in magenta).

Results: Changes in stage and discharge are on the same order as for the simulation with the channel modification only, except that an approximate additional 10 cms (a total 80 cms change from the base case) is routed though the Old Trask. See Appendix B-Figure 29 and Appendix B-Figure 30.

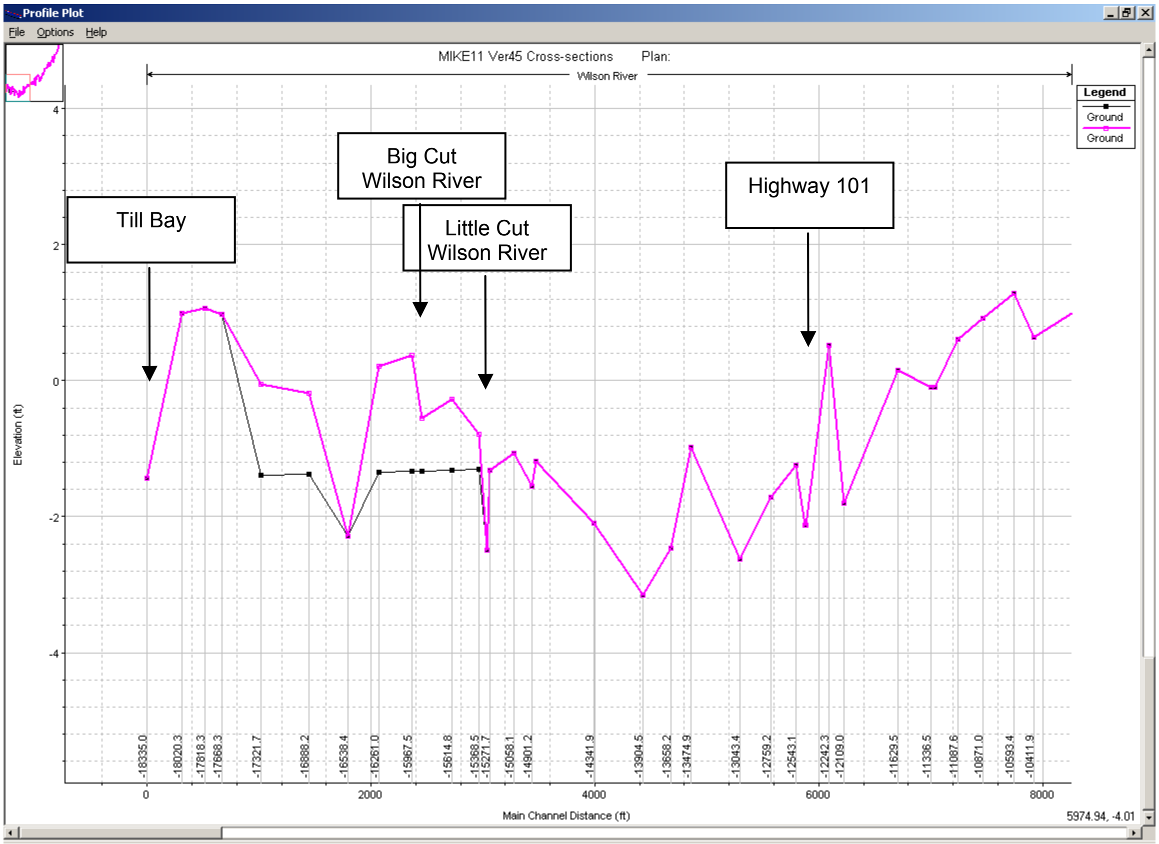
WI 11

"As seen in the following figure (Appendix B-Figure 33), the Wilson River branches into three reaches before its terminus into Tillamook Bay. It is apparent from bathymetric data and historic accounts that this area has be agrading for some time. Large sediment and woody debris deposits have been left in this area. This reach represents a very dynamic area in terms of sedimentation and planform morphology. At this tidal interface sediments are deposited as the Wilson River slows. Historically the river would have agraded and changed course as a delta was formed. However, development by humans has created a condition in which the river is not allowed to change course in this area. Therefore, sedimentation and natural tidal interface functions are viewed as a problem. To determine the extent of impact on flood conditions from recent sedimentation the MIKE 11 model was utilized. The area was dredged and the three channels were deepened in the MIKE 11 model to determine if the recent sedimentation was causing flooding problems upstream and if dredging would alleviate those problems" (USACE, 2003)

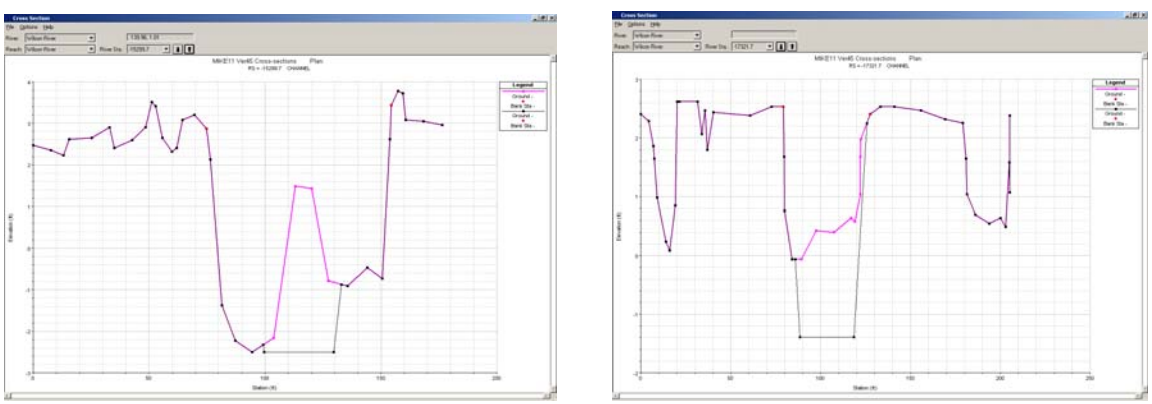


Appendix B-Figure 33. WI-11 – Lower Wilson River Dredge

The Wilson River was cut from RM 0.02 to -1.20 (chainage 15271.7 to 17321.7) with a slope of 0.000046 (Appendix B-Figure 34). The thalweg elevation at RM 0.02 was -1.3 meters. The width of the channel bottom cut was 30 meters and the sideslope was 2:1. Dredging depth varies from 0 to 1.7 meters. Appendix B-Figure 35 shows examples of cross section cuts.

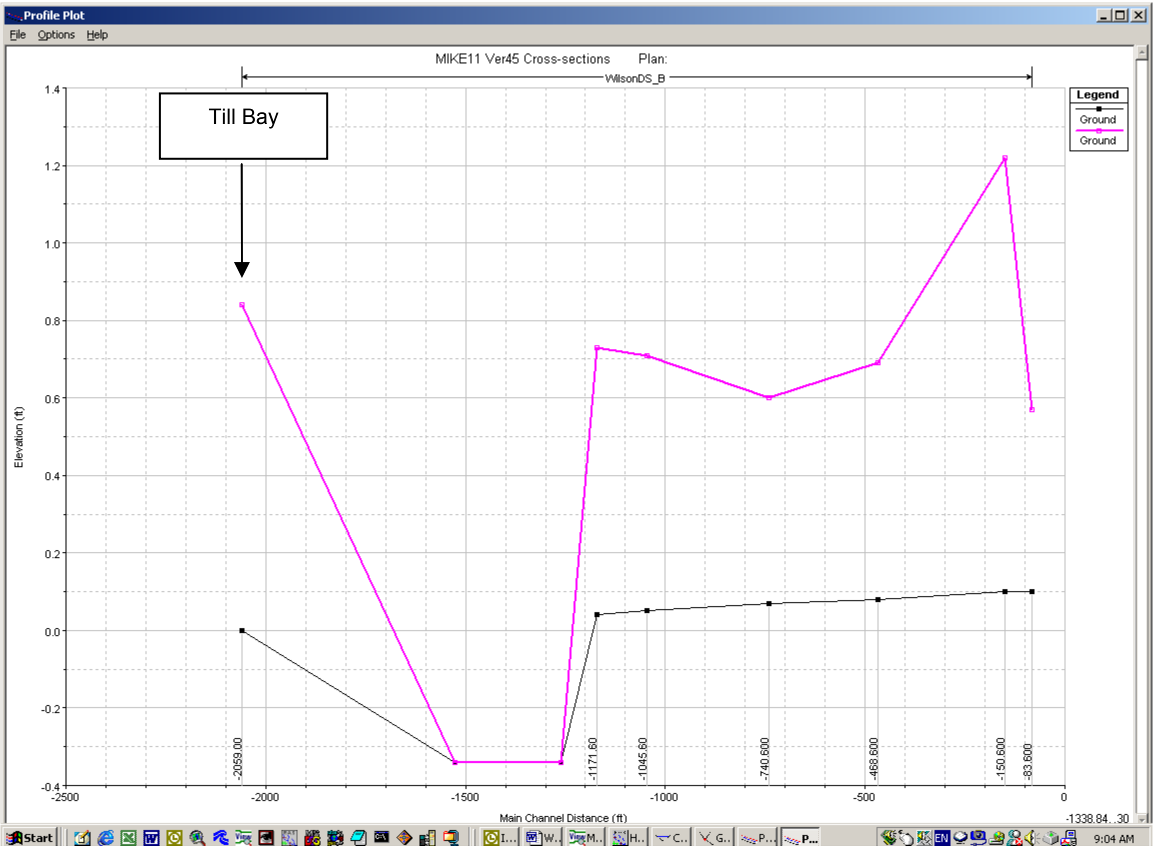


Appendix B-Figure 34. Existing vs. excavated thalweg.

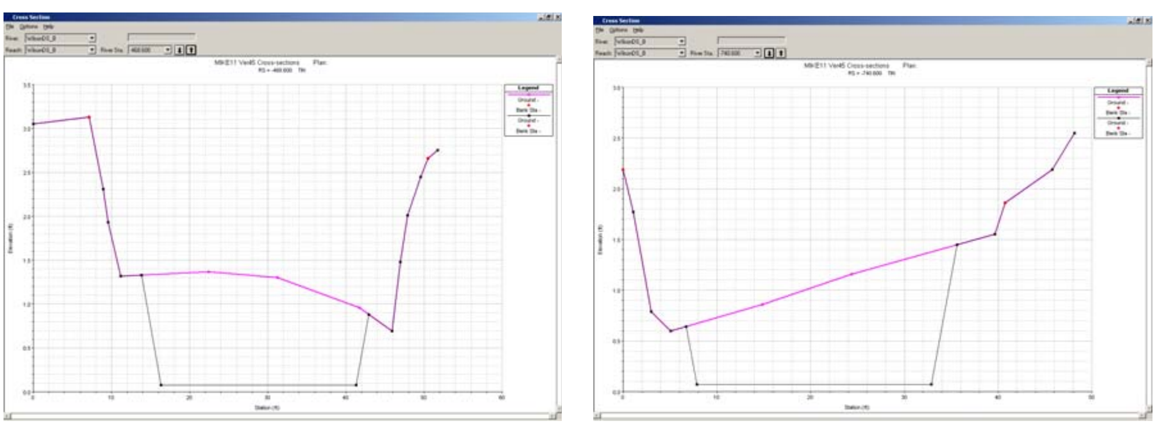


Appendix B-Figure 35. Sample cross-section cuts.

Big Cut Wilson River (WilsonDS_B) was cut with a channel bottom width of 25 meters throughout the reach with a 2:1 sideslope. A slope of 0.000051 was used to provide a downstream gradient to the bay (Appendix B-Figure 36). Sample cross section cuts are shown in Appendix B-Figure 37. Dredging depth varies from 0 to 1.5 meters.

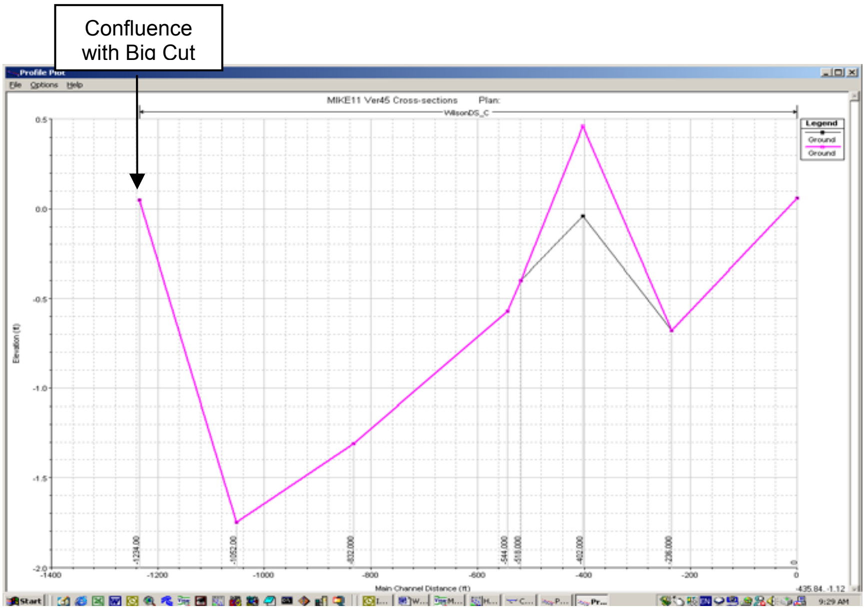


Appendix B-Figure 36. Existing vs. excavated thalweg for Big Cut Wilson River.

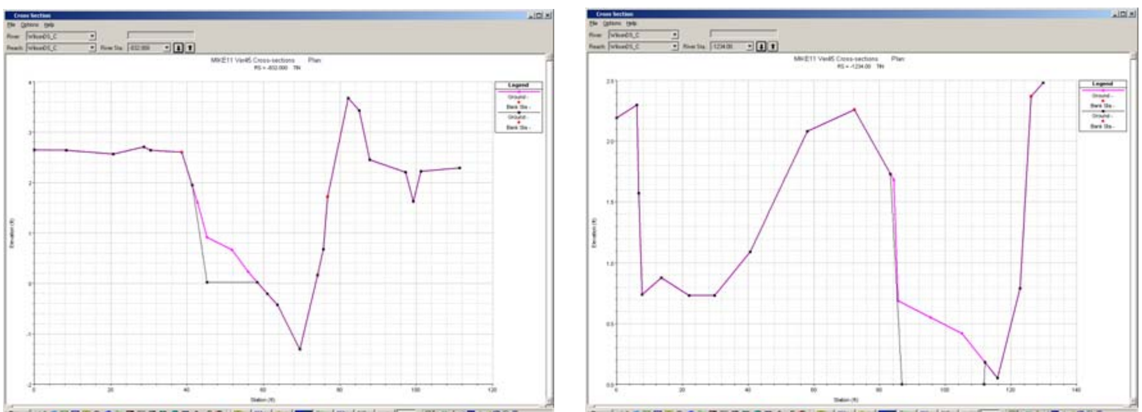


Appendix B-Figure 37. Sample cross section cuts for Big Cut Wilson River.

Little Cut Wilson River (WilsonDS_C) was cut 25 meters with a 2:1 sideslope. A slope of 0.00005 was used. Appendix B-Figure 39 shows a sample of cross sections. Dredging depth in that vicinity would be between 0 and 1 meter.



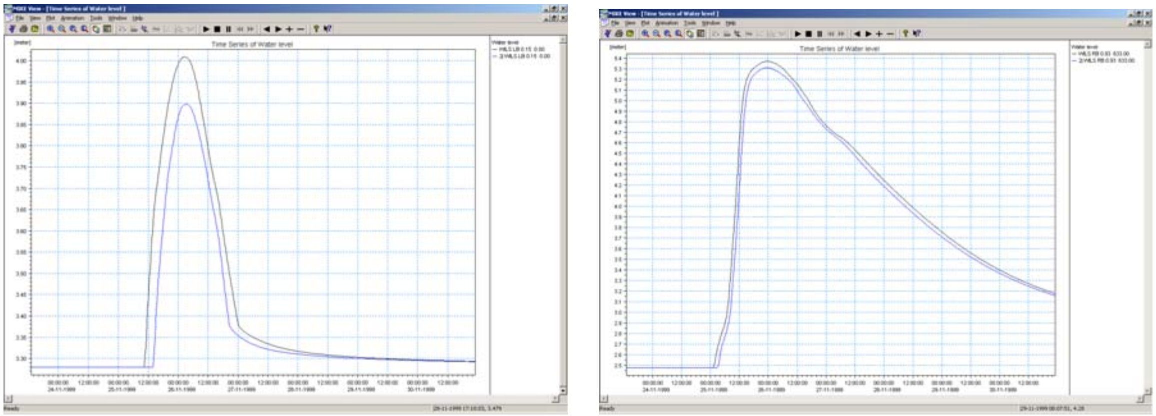
Appendix B-Figure 38. Existing vs. excavated thalweg for Little Cut Wilson River.



Appendix B-Figure 39. Little Cut Wilson River sample cross-sections

Results: Preliminary results indicate a reduction in peak water surface elevation varying from 0 to 0.35 meters on the Wilson River and Big Cut, and 0.1 to 0.3 meters on the Little Cut. The largest difference for both the Big and Little Cuts is at the upstream end, at the confluence with the Wilson River, and then tapers down to the bay. The water surface elevation in the overbanks near Highway 101 did not change by more than 0.1 m.

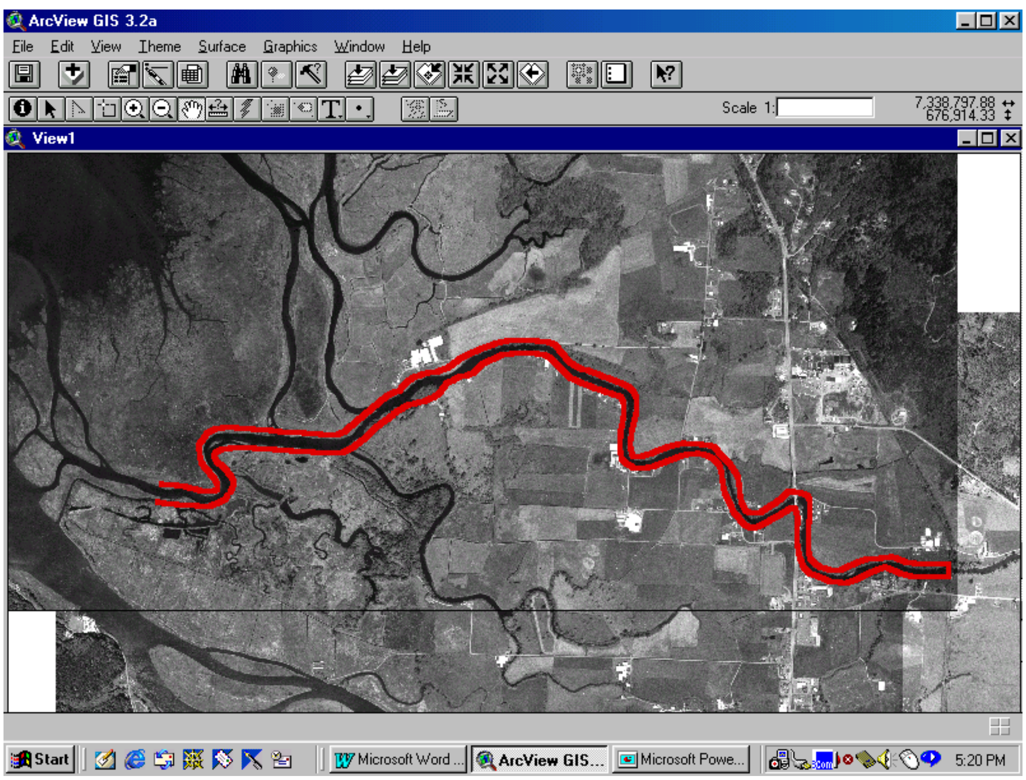
Elevations in flood cells 6, 8, 9, 11 and 19, under excavated channel conditions, showed time retardation on the rising limb of the hydrograph varying from 1 to 6 hours. The falling limb of the hydrograph shows a time decrease varying from 2.5 to 7.5 hours for the same existing condition water surface level as for existing conditions. The improvements are attributed to a reduced Wilson River water surface level, as well as increased flow capacity, which lowers the flow volume going into the overbanks. Appendix B-Figure 40 illustrates the hydrographs for pools 9 and 11, respectively.



Appendix B-Figure 40. Wilson River hydrographs, Pools 9 and 11.

WI 10

"The Lower Wilson River alternative (Appendix B-Figure 41) was similar to those mentioned previously. The main objective in this alternative was to increase flood conveyance to Tillamook Bay in this reach of River. The alternative reach is between the railroad bridge over the Lower Wilson River and Tillamook Bay on the Wilson River mainstem. The channel was modified throughout this reach to increase channel conveyance by a combination of deepening and widening" (USACE, 2003).



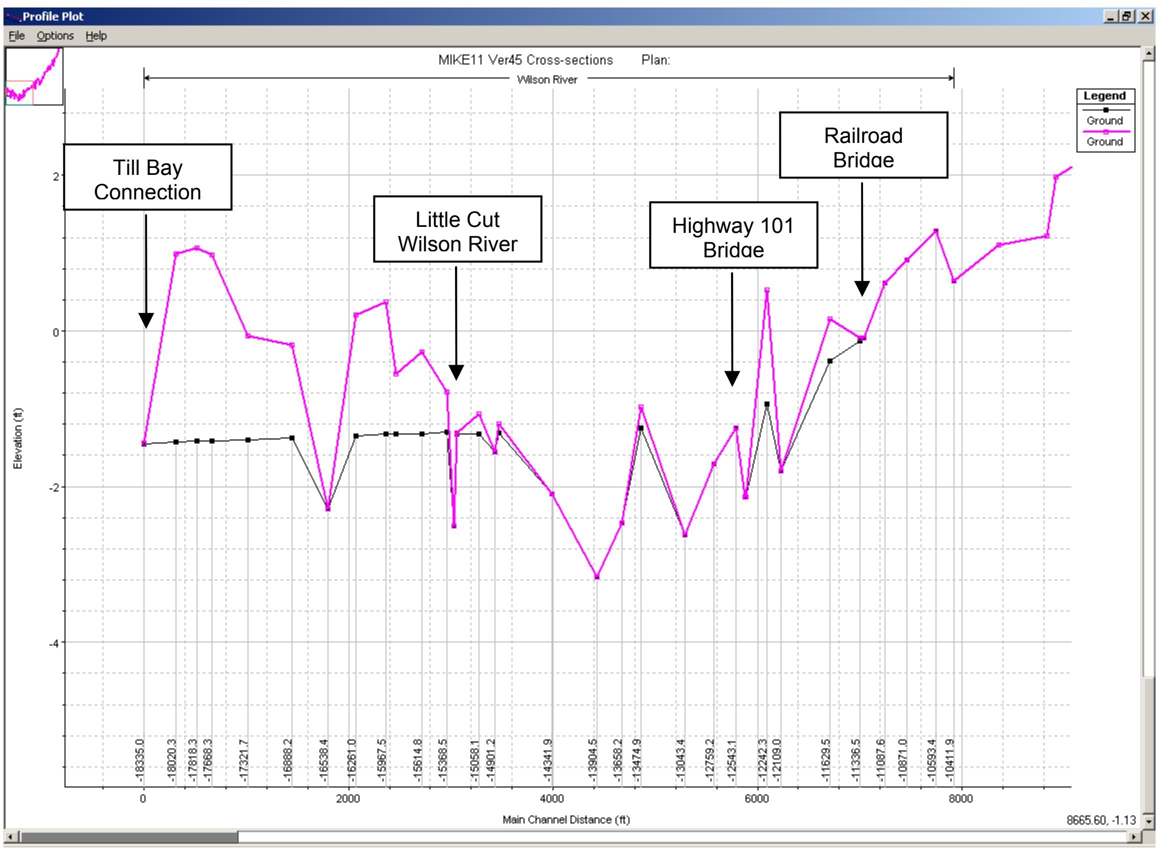
Appendix B-Figure 41. WI 10 - Lower Wilson River

Alterations for this alternative included:

a. Channel modification of the Wilson River from the RR bridge to the mouth.
b. Combining the above channel modification with alternative Wi11. Includes with and without Highway 101 bridge.

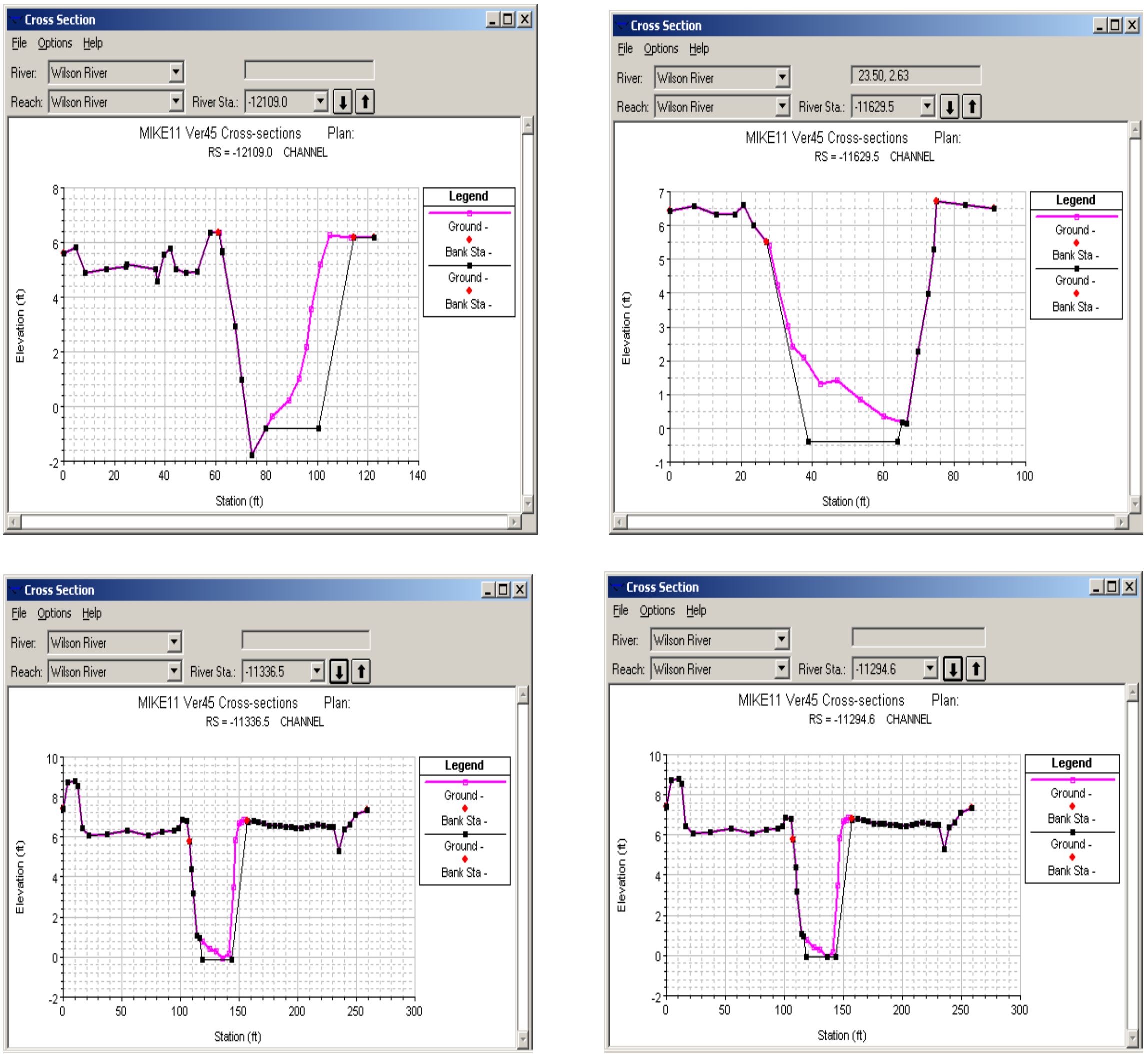
a. Modifying the channel.

The Wilson River was cut from RM 2.40 to -1.83 (chainage 11294.6 to 18335.0). The extent was expanded downstream into the bay from the originally specified downstream RM -1.20 because of the adverse slope going into the bay (see Appendix B-Figure 42). From RM 2.40 to 0.02 (chainage 11294.6 – 15058.1) the cross section bottom cut was 25 meters wide. The rest of the cross sections downstream of RM 0.02 had a bottom cut of 30 meters. The two bottom cut widths were chosen for their respective reach to improve channel capacity, but to be of a magnitude that is reasonable.



Appendix B-Figure 42. Profile of cut for Alternative W10.

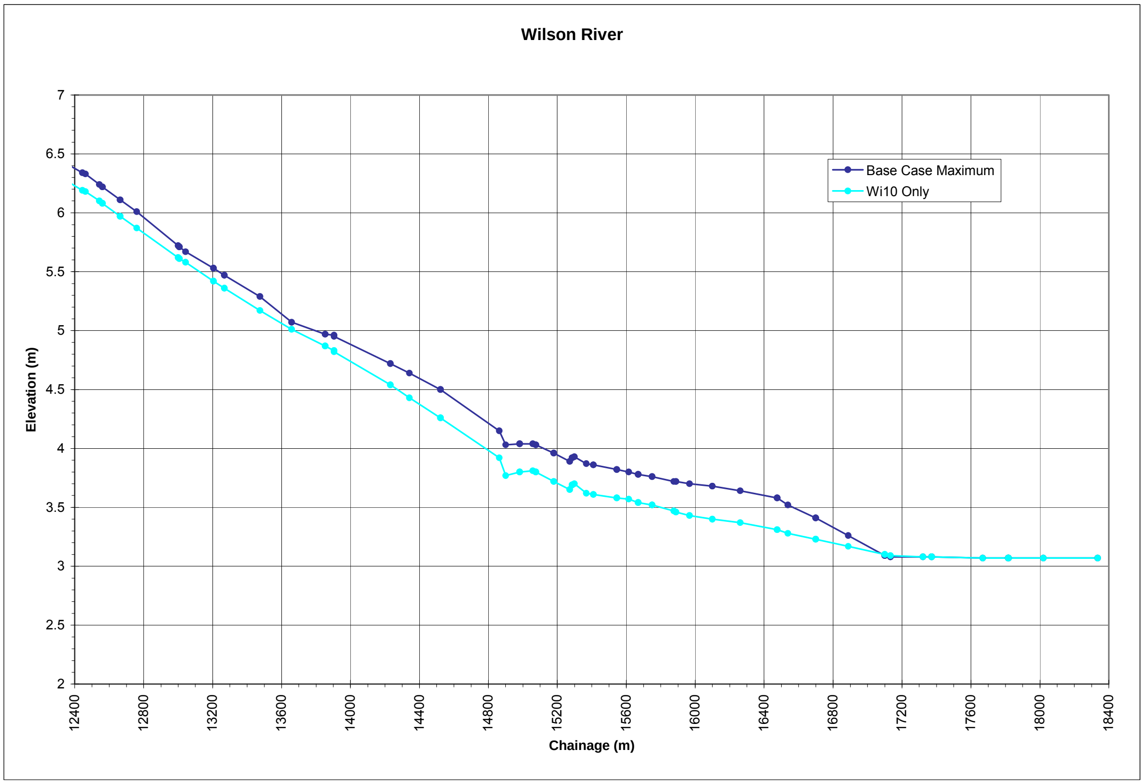
Two different slopes were used in this alternative. One to reflect the natural channel slope (RM 2.4 to 1.74), and one to reflect the slope into the bay (RM 1.74 to -1.83). A slope of 0.00093 was used from RM 2.4 to 1.74. In this reach dredging would range from 0 to 1.3 meters. From RM 1.74 to -1.83 the slope after excavation would be 0.000046, and the excavation would range from 0 to 2.3 meters. All cuts had a side slope of 2:1. Sample cross sections with a 25 meter cut are shown in Appendix B-Figure 43.



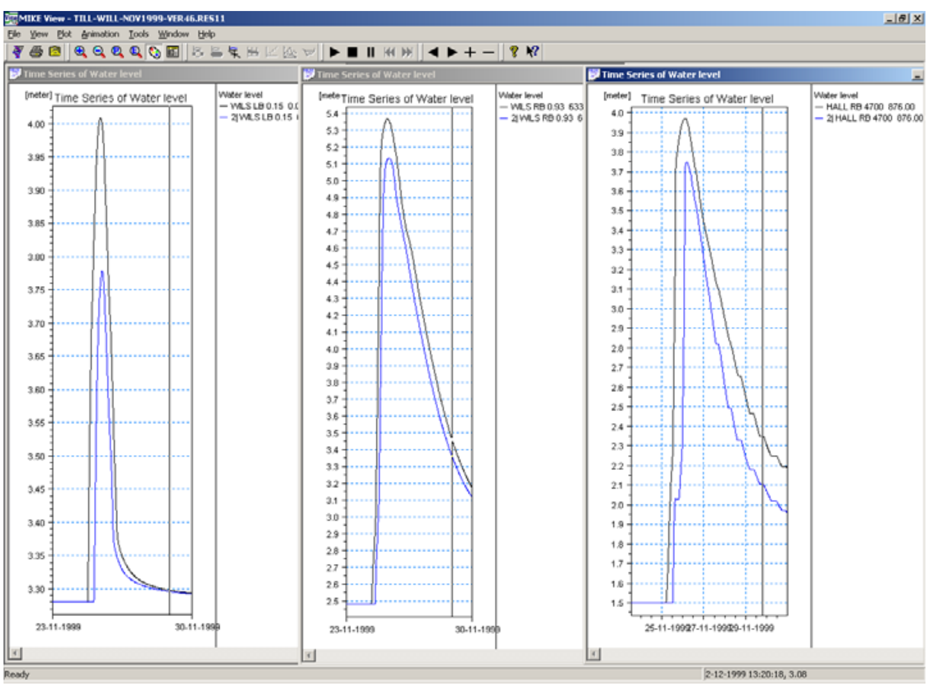
Appendix B-Figure 43. Example cross-section cuts for Alternative WI 10.

Results: Preliminary results indicate a reduction in water surface elevation varying from 0.1 to 0.4 meters throughout the modified reach of the Wilson River (Appendix B-Figure 44). Upstream of Highway 101 the water surface elevation reduction is approximately 0.15 meters.

Flood cells along the Wilson River corridor show a peak water surface reduction ranging from 0.25 to 0.30 meters. The cell drainage timeframe also shows improvement in the flood cells by 4 to 10 hours. The improvement in flow conditions is attributed to the greater flow capacity of the channel which keeps more water out of the overbanks and allows quicker overbank drainage. With the proposed channel cuts, the rising limb of the hydrograph in the flood cells was retarded between 4 to 10 hours over existing conditions in pools 6, 8, 9, 11, and 19. Appendix B-Figure 45 shows sample hydrographs from cells 9, 11, and 8 respectively.



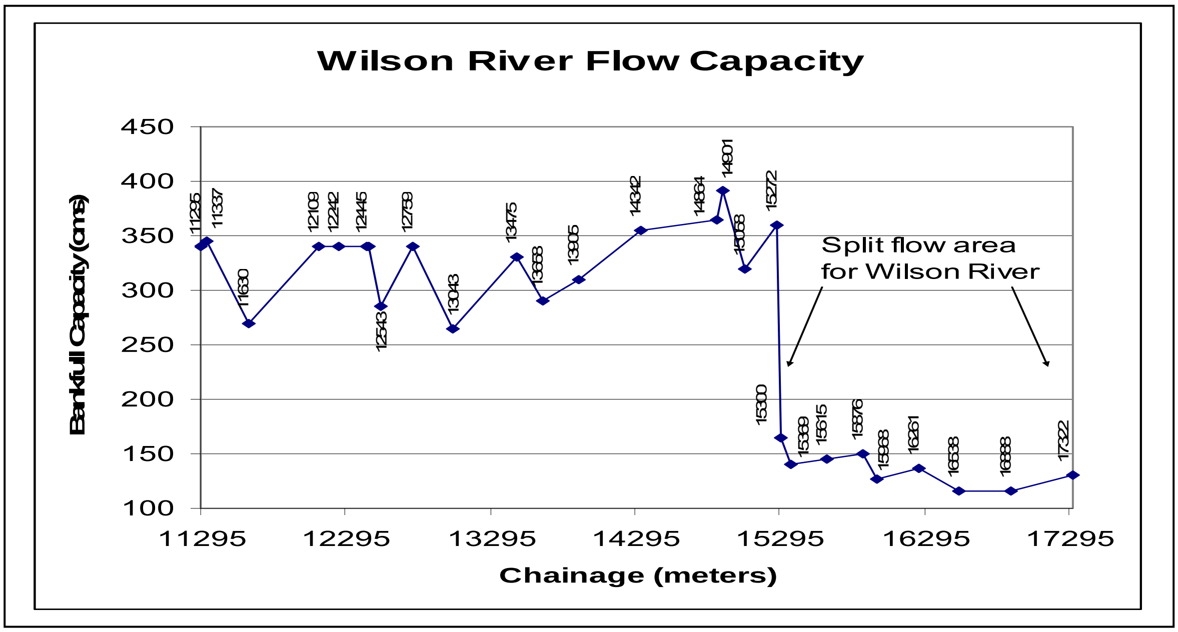
Appendix B-Figure 44. Decrease in peak stage between the base case and the Wi10 channel modification.



Appendix B-Figure 45. Pool 9, 11, 8 stage plots (alternative shown in blue).

A look at the bankfull capacity of the existing Wilson River reveals areas for channel capacity improvement (Appendix B-Figure 46). Most of the cross sections upstream of the split flow area have a channel capacity near 340 cms. Some of the cross sections, either due to a localized low bank or levee, have a bankfull capacity as low as approximately 265 cms (Appendix B-Table 8). The increased capacity at these cross-sections, from modifying the channel (i.e, dredging), are shown in red in Table 1.

Bankfull capacity for this analysis was defined by the water surface elevation just before a nearby levee or bank (i.e., link channel) was overtopped. The method was selected because a cross-section survey might not capture the lowest point on upstream or downstream banks and levees. Note that this bankfull channel analysis is based on the TIN levee and bank elevation information and not survey or more precise measurements.



Appendix B-Figure 46. Base condition Wilson River flow capacity.

Appendix B-Table 8. Bankfull capacity and elevation for the Wilson River.

Chainage	Existing channel bank full Capacity (cms) Modified channel capacity in red (cms)	Bank Overtopping Elevation (m)	Nearby Levee Overtopping Elevation (m)* *[may be on opposite side of river from bank overtopping elev.]*
11295	340	6.8	6.7
11337	345	6.8	6.7
11630	270 (355)	6.6	6.0
12109	340	6.25	6.5
12242	340	6.2	6.5
12445	340	8.2	6.0
12462	340	8.2	6.0
12543	285 (355)	5.7	5.5
12759	340	5.7	6.5
13043	265 (320)	5.3	4.8
13475	330	5.0	4.9
13658	290 (335)	4.8	4.4
13905	310 (370)	4.8	4.4
14342	355	4.6	4.4
14864	365	3.9	4.0
14901	392	3.9	4.0
15058	320 (425)	3.65	3.6
15272**	360	3.6	3.6
15300	165	3.5	3.6
15369	140	3.2	3.6
15615	145	3.2	3.6
15876	150	3.2	3.6
15968	127	3.2	3.3, est.
16261	137	3.15	3.4
16538	116	2.75	3.4
16888	116	2.5	3.6
17322	130	2.55	

*Levee elevation accuracy is dependent on the TIN data.
**Start of downstream Wilson River flow splits.

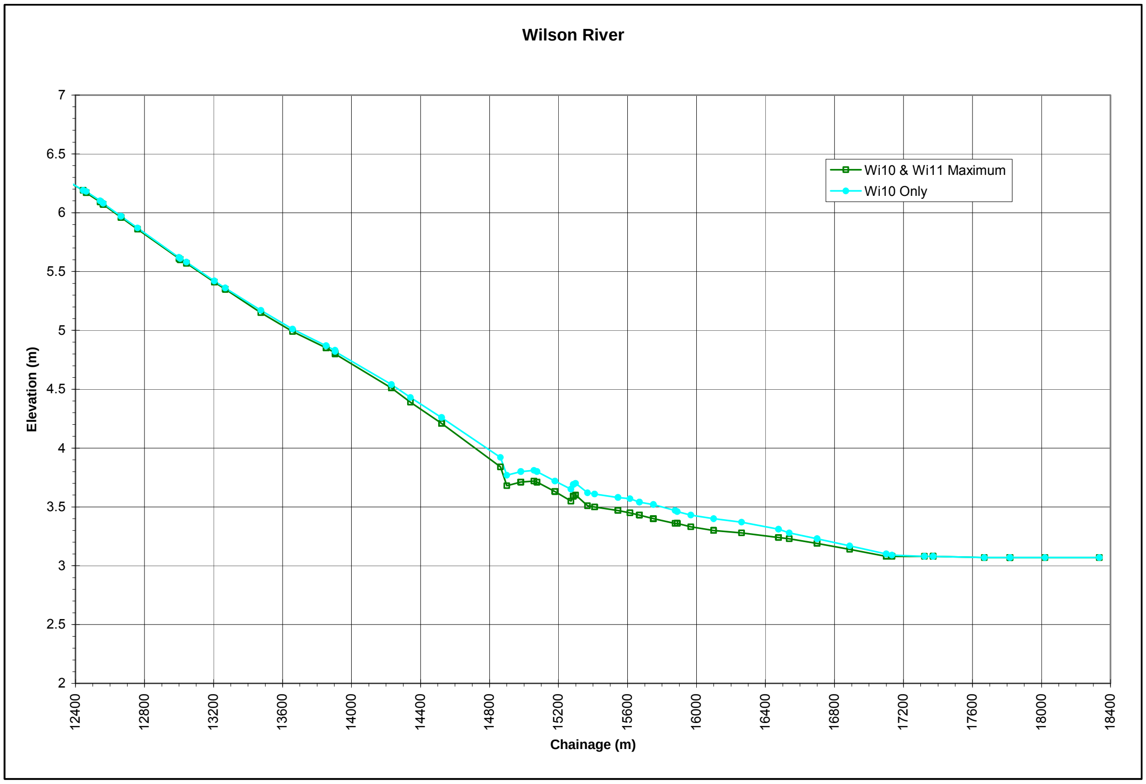
b. <u>Combining with Alternative Wi11</u>.

This alternative adds the Wi11 channel modifications for the Big and Little Cuts to the existing Wi10 Wilson River channel modification.

Results: Preliminary results indicate that the lower Wilson stage is reduced by up to an additional 0.15 meters (Appendix B-Figure 47). There is essentially no additional reduction in the upper Wilson River stage beyond that of Alternative WI10.

The addition channel modifications to the Big and Little Cuts does reduce the flooding duration in the flood cells 6, 8, 9 11 and 19, although there is less than an 0.04 meter reduction in stage. Time reduction on either side of the hydrograph was up to 1.5 hours.

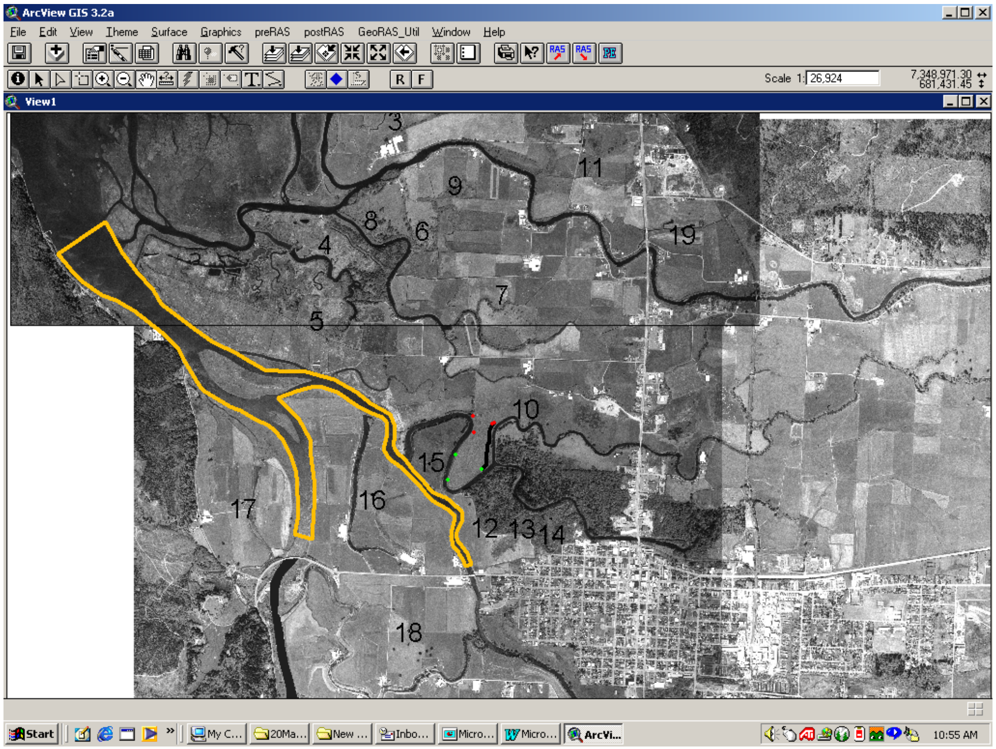
The Wi10 channel modifications were assumed to include the bridge sections. A sensitivity was performed, using the Wi10 plus Wi11 alternative, to test the effects of dredging up to, but not through, the bridge. The results were a local water surface depression as flow was squeezed through the bridge opening. The net change in water surface was less than 0.03 m immediately upstream and downstream of the bridge, and discharge though the bridge changed by approximately 0.5 cms.



Appendix B-Figure 47. Decrease in peak stage between Wi10 and combined Wi10 with Wi11.

TR 10

"Similar to the Wilson River, the Lower Trask and Tillamook Rivers have been agrading at their tidal interface with Tillamook Bay. This alternative analyzed dredging the sediments in the Lower Trask and Tillamook Rivers (Appendix B-Figure 48) to view the effects on flooding at upstream locations in the Tillamook region" (USACE, 2003).



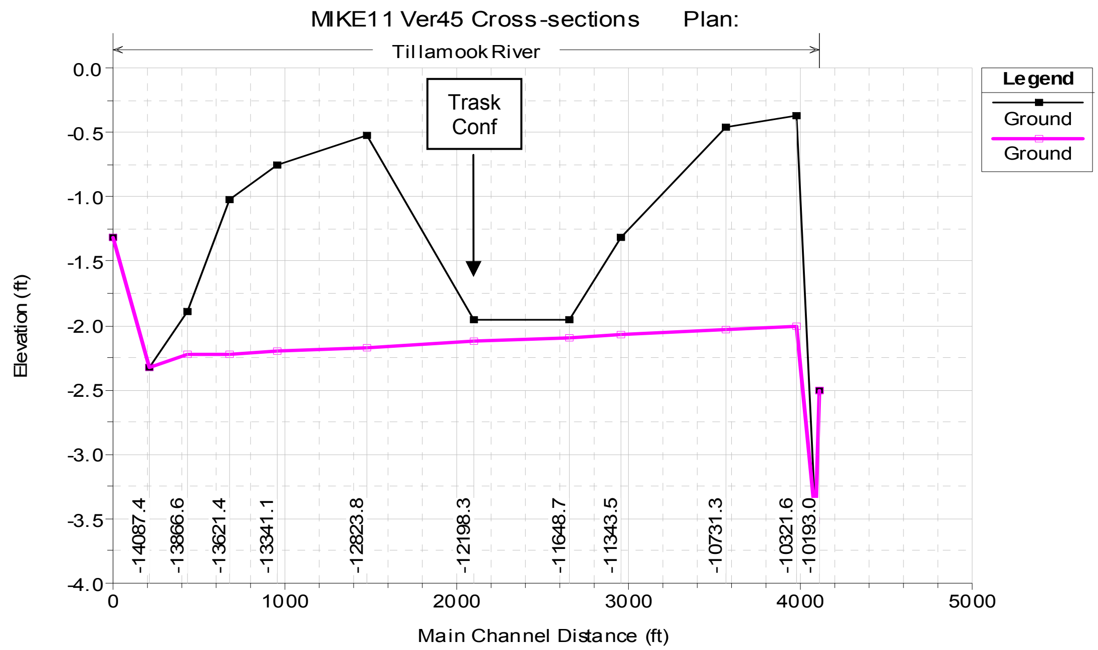
Appendix B-Figure 48. TR 10 – Lower Trask and Tillamook River Dredge

Alterations for this alternative included:

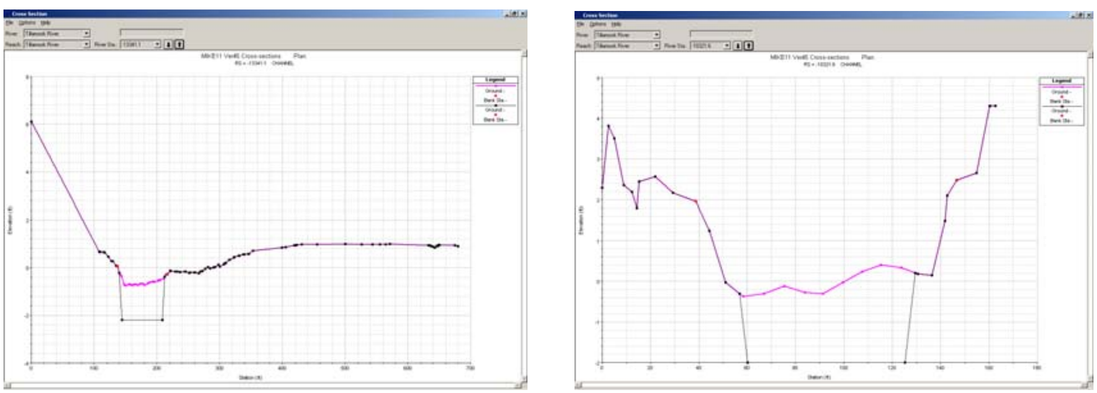
a. Modifying the channel along the downstream end of the Tillamook and Trask Rivers.
b. Combining the above channel modifications with upstream Tr2 channel modifications. Includes with and without Netarts Bridge over the Trask River.
c. Combining the above modification with the Tr2 levee setback.

a. Modifying the channel.

Tillamook River cross sections were cut from RM -1.09 (chainage 14087.4) to RM 0.86 (chainage 10321.8) at a slope of 0.000066. The range was expanded from the original task description (RM -0.85 to 0.37), to a depth of -2.25 meters at RM -1.09, in order to provide a downstream gradient (Appendix B-Figure 49). The dredging depth varies from 0.2 to 1.6 meters. The channel bottom cut was 65 meters wide with a 2:1 side slope (Appendix B-Figure 50 for sample cross sections).

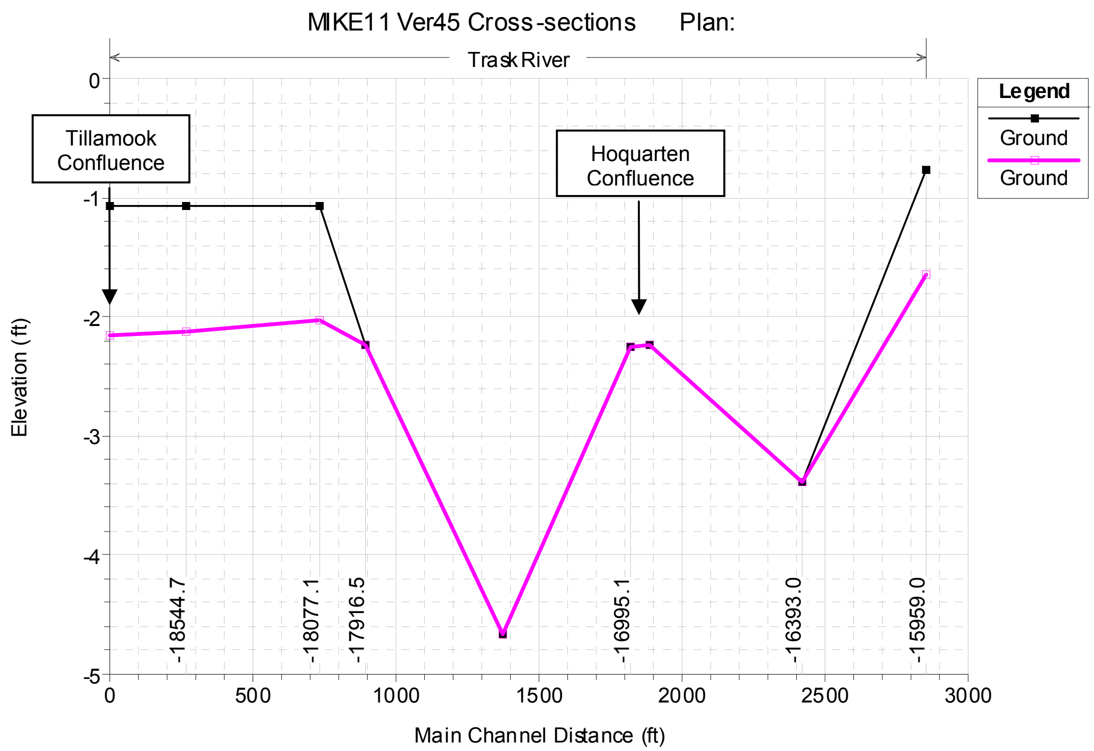


Appendix B-Figure 49. Tillamook River Existing vs. Excavated Thalweg.

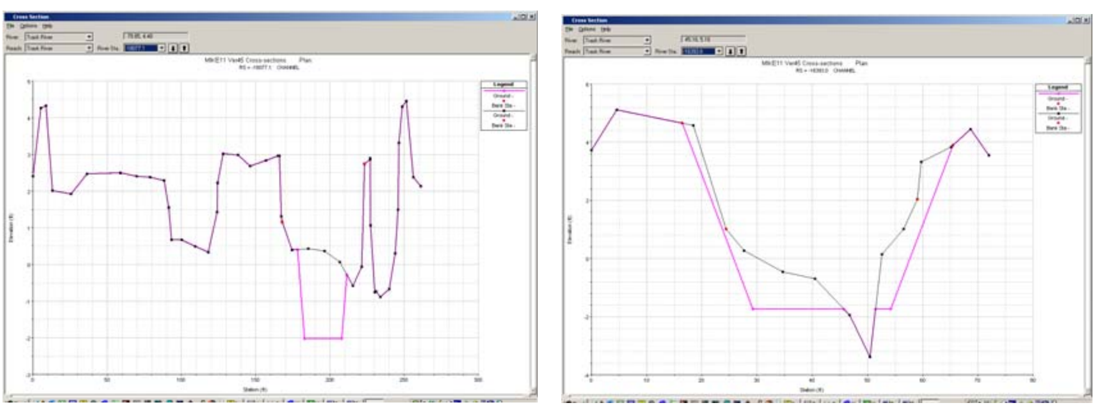


Appendix B-Figure 50. Excavated Tillamook River cross-sections.

Trask River cross sections were cut from RM 1.14 (chainage 15959.0) to RM -0.27 (chainage 18813.0) at elevation -2.15 meters to match the new thalweg on the Tillamook River (see Appendix B-Figure 51). Again the range was expanded from the original task description (RM -0.13 to 0.60) in order to provide a downstream gradient. A slope of 0.00018, channel bottom width of 25 meters, and side slope of 2:1 was used for the analysis (Appendix B-Figure 52). Dredging depth varies from 0 to 1.0 meter.

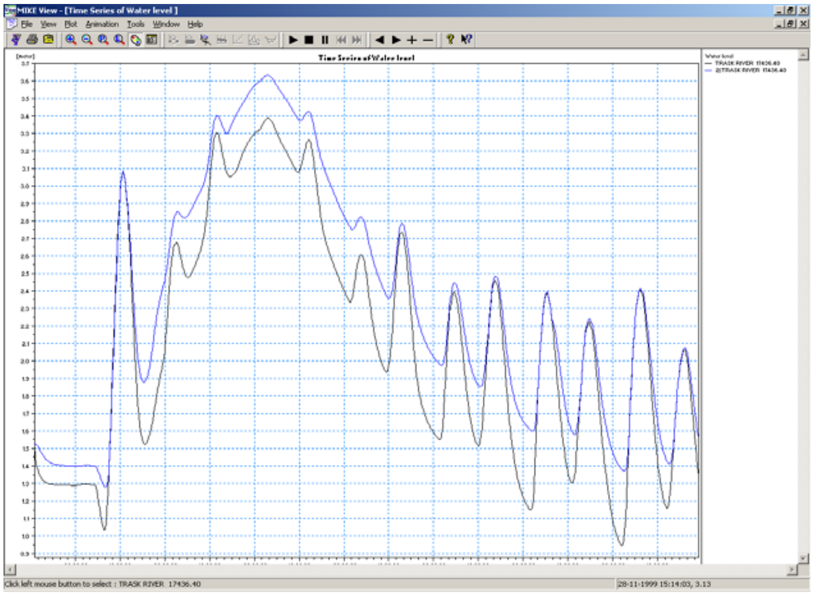


Appendix B-Figure 51. Trask River existing vs. excavated thalweg.



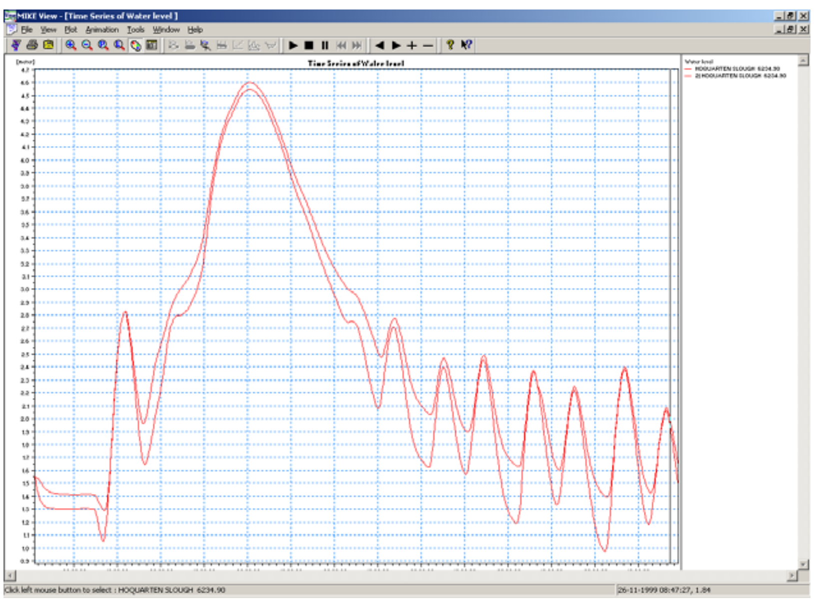
Appendix B-Figure 52. Excavated Trask River cross-sections.

Results: Preliminary results show minor reductions in water surface elevations in the modified channels (0.0 to 0.25 meters, Appendix B-Figure 53). The exception is a 0.5 meter reduction in water surface elevation for Tillamook River near RM 0.90. This is due to the increased channel capacity and lowered water surface elevations in the channel, reducing both the volume and duration of flow to the overbank areas.



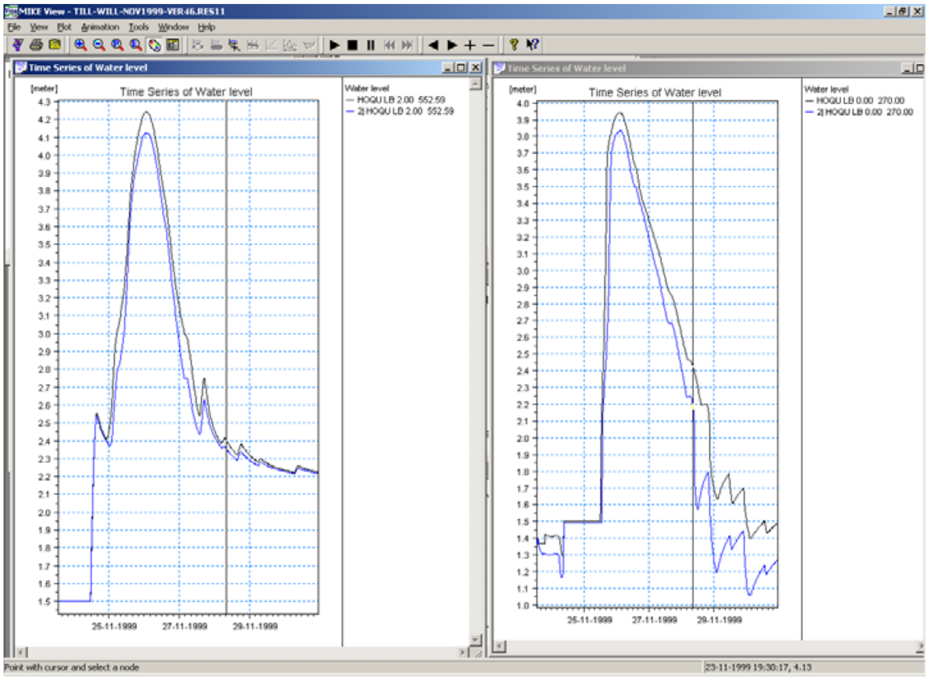
Appendix B-Figure 53. Trask River hydrograph.

Hoquarten Slough near Highway 101 shows a shortened hydrograph by approximately 2 hours on the rise and fall of the hydrograph. The change in water surface elevation is minimal (Appendix B-Figure 54).



Appendix B-Figure 54. Hydrograph of Houquarten Slough near Highway 101.

Pool elevations along the lower Tillamook/Trask corridor improve slightly in water surface elevation for excavated channels over existing conditions. Water surface elevations for revised channel conditions drop between 0.1 to 0.15 meters from existing conditions. The rising of the hydrograph occurs 1 to 2 hours later for cells 5, 12, 13, 14, and 15 when compared to the base case (Appendix B-Figure 55). Cells 12, 13, 14, and 15 drain 6-12 hours sooner than in the base case. There is little to no change in the other flood cells in the system.



Appendix B-Figure 55. Hydrograph comparison (Alternative results in blue).

Dredging Tillamook Bay may lower water surface elevations more since the bay thalweg in some locations is higher than the new excavated thalweg in the upstream branch.

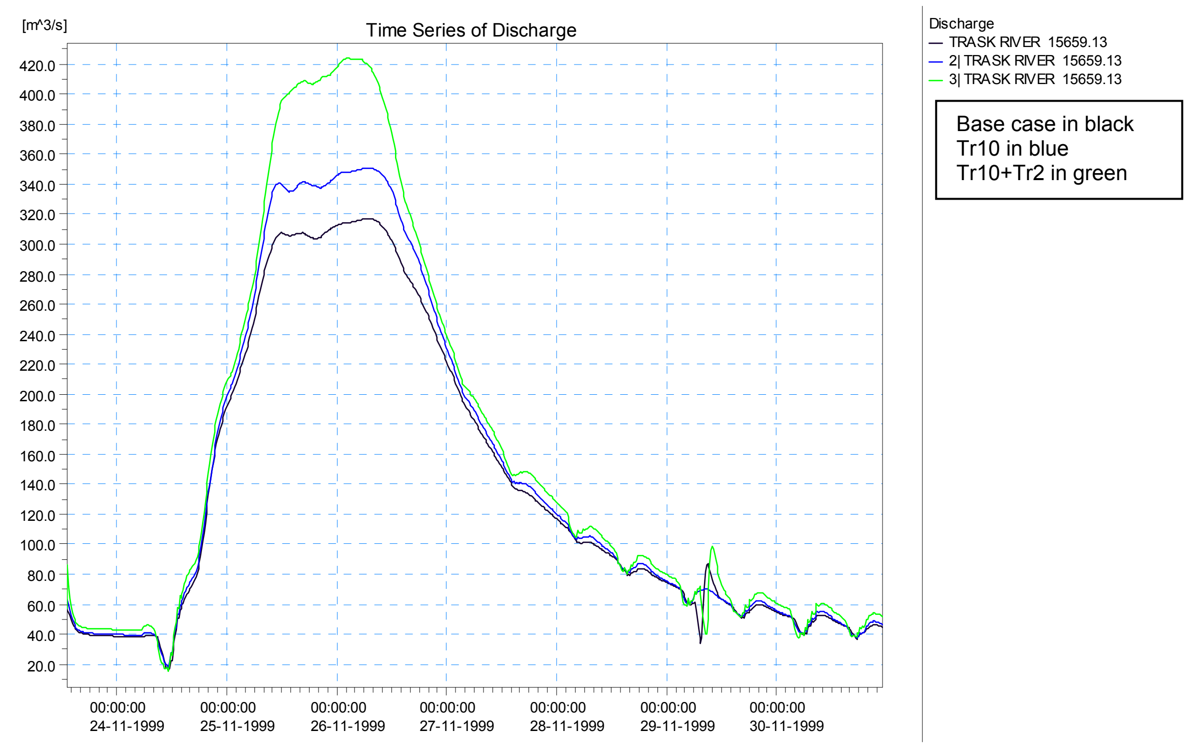
b. <u>Combining with Tr2 channel modifications</u>.

This alternative combines Alternative Tr10 with the modified channels in Alternative Tr2 upstream of Trask River 15959. Tr10 has channel excavation ranging from RM -0.13 to 0.60 (chainage 18813 to 15959) on the Trask River, and RM -1.09 to 0.86 (chainage 14087 to 10322) on the Tillamook River. That portion of Alternative Tr2 that lies upstream of RM 0.60 on the Trask River (RM 0.9 to 2.0) was added for this alternative.

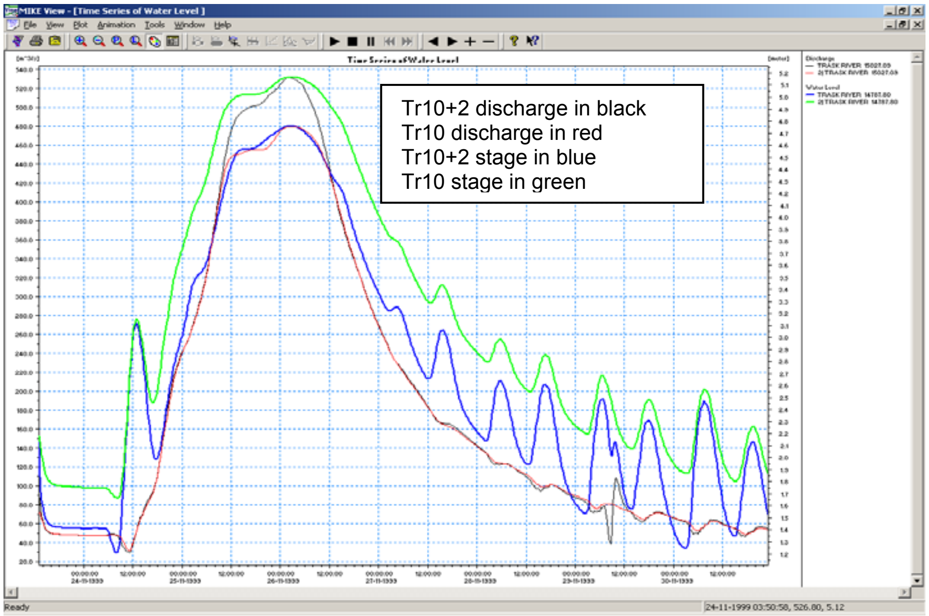
Results: Preliminary results indicate that adding the additional channel modification upstream, to Trask chainage 14787.8 (RM 2.0), lowers the Trask River stage near the Old Trask confluence and consequently an additional 70 cms flows through the Trask, instead of to the overbanks (Appendix B-Figure 56, Appendix B-Figure 57, and Appendix B-Figure 58) when compared to the Tr10 channel modification. The resulting stage is lower upstream, by as much as 0.5 meters at chainage 14787.8, but <u>higher</u> downstream by as much as 0.3 meters at chainage 15841.6, when compared to the Tr10 channel modification. Note that the combined Tr2 & Tr10 alternative still has a lower peak water surface elevation when compared to the base case.

Because of the increased channel flow and stage downstream, the pool elevations are slightly higher for the combined alternatives compared to Alternative Tr10 alone. Pool elevations are from 0.0 to 0.15 meters higher for the combined alternative than for Tr10 alone. Corresponding to that pool stage increase is a 15 minute to 2 hour expansion of the hydrograph timeframe for both the rising and falling limbs of the hydrograph. This is still an improvement over the base condition (Appendix B-Figure 59).

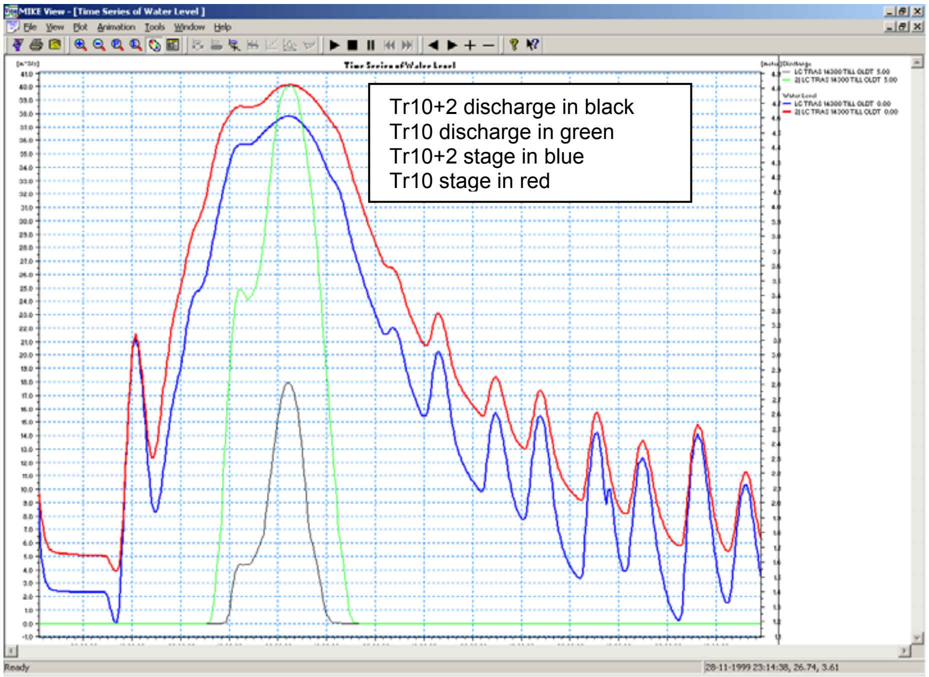
The Tr2 channel modifications were assumed to include the bridge sections. A sensitivity was performed, using the Tr10 plus Tr2 alternative, to test the effects of dredging up to, but not through, the bridge. The results were a local water surface depression as flow was squeezed through the bridge opening. The net change in water surface was less than 0.05 m immediately upstream and downstream of the bridge, and discharge though the bridge changed by approximately 2 cms.



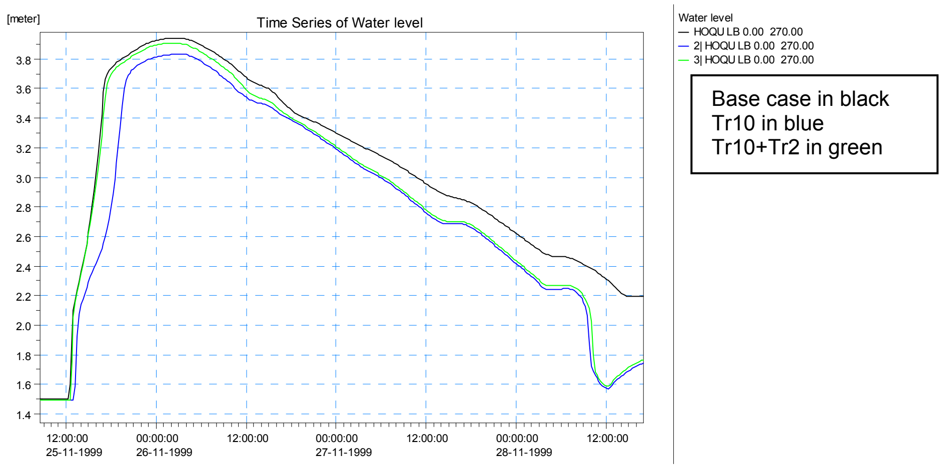
Appendix B-Figure 56. Comparison of Trask River flow downstream of the Old Trask confluence.



Appendix B-Figure 57. Hydrograph Example for the Trask River.



Appendix B-Figure 58. Hydrograph for Link Channel TRAS 14300 TILL OLDT.



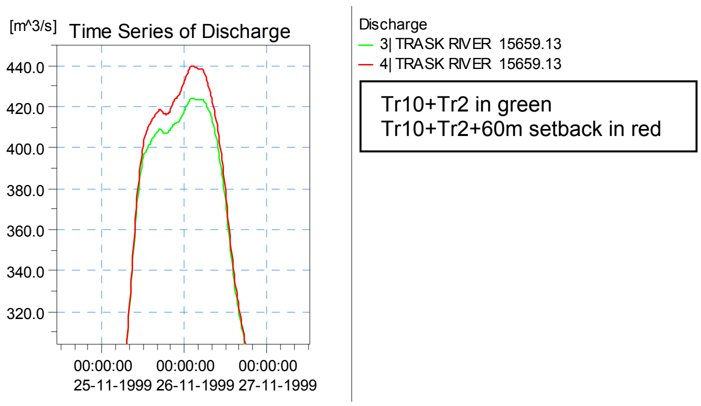
Appendix B-Figure 59. Example of increase in stage and flood duration for Tr10+2 compared to Tr2 and the base case at flood cell 15.

c. Combining with Tr2 channel modifications and left levee setback.

The left levee setback from Alternatve Tr2 was added to the Tr10 plus Tr2 alternative above.

Results: Results are similar to effect of the levee setback in Tr2. The stage upstream of the Old Trask is lowered, reducing the flow to the overbanks, and increasing the conveyance through the Trask River (Appendix B-Figure 60). Overall peak stage on the Trask is altered by less than 0.1 m for an increase of approximately 20 cms, when compared to the Tr10 plus Tr2 alternative.

Flood pools are essentially unaffected when compared to the Tr10 plus Tr2 alternative.



Appendix B-Figure 60. Increase in Trask River discharge by adding a setback levee to Tr10+Tr2.

SUMMARY OF FLOOD STAGE AND DURATION BENEFITS

Alterative	*Result Highlights*	*Significant/Major Flood Cell Changes*
Wi2 - 20m cut	Flow redirected from the Hall right bank to the Hall Slough Duration of Highway 101 overtopping reduced by ≈ 4 hours in Hall right overbank	
- levees lowered	Duration of total flood event extended Peak stage decreased by up to 0.1 m along Hall Slough	Peak stage decreased by up to ≈ 0.1 m in Cells 4, 6, 7, 8, & 9
- levees lowered & 20m cut	Nearly identical to levees lowered only alternative. Duration of Highway 101 overtopping reduced by ≈ 6 hours in Hall right overbank	Nearly identical to levees lowered only
- increased US capacity	Increased duration of Hall Slough flushing flows	Duration of flooding increased in Cells 6, 7, 9, 11, & 19
Tr2 - 40m cut	Peak water surface stage lowered in the Trask R. upstream of Netarts Hwy ≈ 0.6 - 0.7 m Peak water surface elevation lowered in the overbank between Trask & Till ≈ 0.4m	Peak stage decreased by ≈ 0.1 m in Cells 4, 5, 10, 12, 13, 14, & 15
- 60m setback (left levee)	Peak water surface elevation lowered in the overbank between Trask & Till ≈ 0.1 m	None
- levee lowered (right levee)	No significant benefits other than to Flood Cell #5	Peak stage decreased by ≈ 0.2 in Cell 5
Tr8 - 30m cut	Flow redirected to Old Trask (approximately 47 cms) and Till-OltT 0.85 overbank from Trask River Trask R. peak stage lowered ≈ 0.1 m near Old Trask confluence	None
- 30m setback	Redirects ≈ 20 cms increase in Old Trask flow No significant change in stage	None
- 30m setback & 30m cut	Flow redirected to Old Trask and Till-OltT 0.85 overbank from Trask River	None

Alterative	*Result Highlights*	*Significant/Major Flood Cell Changes*
Wi11	Wilson River, Big Cut peak stage lowered between 0 to 0.35 meters.	Flood cells 6, 8, 9, 11 and 19 are truncated 1 to 6 hours on the rising limb, and 2.5 to 7.5 hours on the falling limb.
Wi10	Wilson River peak stage lowered between 0.1 to 0.4 meters. Approximate overall channel capacity increased from 265 cms to 320 cms.	Flood cells 6, 8, 9, 11 and 19 are lowered ≈ 0.3 meters. Rising limb of the hydrograph is delayed 4 to 10 hours. Pool drainage time shortened as much as 10 hours.
- included Wi11 measures	Essentially the same results as Wi10 for the upper Wilson River. Additional stage reduction of approximately 0.1 meters for lower Wilson River.	Slight improvement in hydrograph duration, up to 1.5 hours shorter, in addition to results for Wi10 for flood cells 6, 8, 9, 11 and 19.
Tr10	Peak stage reduction from 0 to 0.2 at most cross sections altered in the channel modification.	Peak stage is decreased between 0.1 and 0.15 meters in flood cells 5, 12, 13, 14, & 15. Time to drain reduced 6 to 12 hours for pools 12, 13, 14, & 15. Rising limb of the hydrograph delayed 1 to 2 hours for pools 5, 12, 13, and 14.
- included Tr2 measures	Discharge through the Trask increased by approximately 70 cms over Tr10 results. Trask stage higher than in Tr10 but still lower than for base condition.	Up to 2 hours duration added to either end of the hydrograph when compared to Tr10, but duration still less than base condition.
- included Tr2 measures and 60m levee setback	Discharge through the Trask increased by approximately 20 cms over Tr10+Tr2 results.	None beyond Tr10+Tr2 results.

US Army Corps
of Engineers ®
Portland District

Tillamook Bay and Estuary, Oregon
General Investigation Feasibility Report

APPENDIX C

MIKE11 to HEC-RAS Model Conversion

Prepared by
WEST Consultants, Inc.
for the
U.S. Army Corps of Engineers
Portland District

March 2004

Hydraulic Modeling of the Tillamook Bay and Estuary Study

MIKE11 to HEC-RAS Conversion

Provided to:

Portland District Corps of Engineers

Provided by:

WEST Consultants, Inc.

12509 Bel-Red Road, Suite 100

Bellevue, WA 98005-2535

March 2004 Draft

Hydraulic Modeling of the Tillamook Bay and Estuary Study

MIKE11 to HEC-RAS Conversion

Table of Contents

Introduction

This report documents the conversion of the Tillamook Bay 1-D hydraulic unsteady flow model from MIKE11 Version 2001 (DHI, 2001) to HEC-RAS Version 3.1.1 (USACE, 2002b) and subsequent modeling of alternatives. This work was conducted by WEST Consultants, Inc. (WEST) for the Portland District Corps of Engineers (District) under contract DACW57-99-D-0003.

The major tasks that WEST completed included:

- Importing into HEC-RAS the MIKE11 geometry and discharges used in the prior Tillamook Bay modeling simulations, creating a “base geometry” model.
- Modification and calibration of the HEC-RAS base geometry model to successfully run the November 1999, May 2001, November 2001, January 2002, and 100-year events.

- Updating to current conditions from the base geometry model. This is referred to as “Alternative 1”.
- Modification of Alternative 1 to create a saltwater marsh in the Blind Slough area and flood control storage to the south of this area. This is “Alternative 2”.
- Modification of Alternative 2 to include ecosystem restoration in Nolan Slough. This is “Alternative 4”.

Model Conversion of Base Geometry

The first task that WEST initiated was to import the existing MIKE11 model (WEST, 2004) into HEC-RAS using existing tools in Version 3.1.1 of the HEC-RAS software. We imported the alignment and cross-section geometry for the main channels, sloughs, and overbank reaches into HEC-RAS, while attempting to keep the reach names and river stationing as close as possible to those specified in the MIKE11 model. The changes that we did make included shortening some of the reach names (due to maximum number of character limits in HEC-RAS) and setting the HEC-RAS river stationing equal to negative values of those in MIKE11 (since the direction of the cross-section ordering is reversed between the two models). We created additional cross-sections in those imported reaches that had only one cross-section in the MIKE11 model since reaches must have more than one cross-section in HEC-RAS. This was limited to the reaches near the downstream end of the model. We set junction lengths and initial Manning’s ‘n’ values equal to those specified in MIKE11 (see the Calibration section for further detail on calibration of the Manning’s ‘n’ values).

WEST created HEC-RAS boundary condition files for the November 1999, May 2002, November 2001, January 2002, and 100-year events using the data specified in MIKE11. We later modified the initial data points leading into the event in this data set to help stabilize the model (see the Model Stability section). We included in the unsteady flow files the observed highwater marks and stage hydrographs, which were identical to those specified in the MIKE11 models, that would be later used in the calibration of the Nov 1999, May 2001, Nov 2001, and January 2002 events (discussed in the Calibration section).

WEST also added bridges and culverts to the HEC-RAS model at the same locations as in the original MIKE11 model. However, when we entered the bridge information, rather than use the combination of level/width bridge geometry and culvert data that was used to define bridges in MIKE11, we created the bridges using the original data source which included survey information, other HEC-RAS models, and bridge drawings (WEST, 2003). We took culvert specifications directly from the MIKE11 data files.

WEST added “lateral structures”, i.e., levees and equivalent to MIKE11 “link channels”, in the HEC-RAS model to create hydraulic connections between various portions of the model. The lateral structure geometry were all re-cut from the TIN using GeoRAS (HEC, 2002a) rather than using the level/width information in MIKE11. We extended the length of some of the lateral structures upstream to the nearest cross-section, this being longer than they existed in the MIKE11 model, as part of this process. This simplified the process of defining the lateral structure “distance to upstream cross-section” parameter in HEC-RAS and added more definition to the model. Additional lateral structures were also added later as part of the calibration process (see the Calibration section).

We changed for clarification the lateral structure naming convention in HEC-RAS, from that used in MIKE11. We named lateral structures using four letters to identify the main reach followed by two letters indicating which bank the lateral structure is on (e.g. LB for left bank, RB for right bank) and then a letter indicating the order (ascending from upstream to down) rather then the random numbering scheme in MIKE11. As the lateral structures were later divided into smaller pieces numbers and then letters were added on to the lateral structure name. For example, “Wils_LB_ E” is a lateral structure on the left bank of the Wilson River. It is downstream of “Wils_LB_D” and upstream of “Wils_LB_F”. Wils_LB_E was later further divided into “Wils_LB_E_01” and “Wils_LB_E_02” to separate where the overtopping flow was connected downstream.

HEC-RAS does not allow lateral structures to start or end at the extents of a reach so, when necessary, we copied cross-sections 1 m away, to add the lateral structures into HEC-RAS. For those cases where the lateral structures were longer than the HEC-RAS reach length (e.g., if the structure was located in the outside of a bend), the overbank reach length was extended in HEC-RAS so as it would not overlap onto a downstream lateral structure or different reach.

We have provided in this Model Conversion of Base Geometry section of the report an overview summary of the steps taken to import the MIKE11 data. Additional detail can be found in “MIKE11 to HEC-RAS Conversion, Technical Notes” (WEST, August 2003)”.

Model Stability

We ran simulations during various stages in the process of converting from MIKE11, e.g. first with only the three major rivers, then with the sloughs added, then with bridges added, etc., identifying stability issues along the way, rather than importing the entire model at once and having less of an idea on where to look for instabilities. We ran into numerous stability problems during the development of the model, some of which we fixed by working with the Hydrologic Engineering Center to perfect the HEC-RAS code. Some of the other more wide-ranging fixes for stability including modifying the default HTAB parameters defined by RAS and adding pilot channels.

We modified each of the boundary condition files to provide a period of a constant flow or stage during the initial steps of the simulation. This was necessary since the model was typically unstable at the initial time step if the low flow on the rising limb of the hydrograph was specified. The constant stages and flows were then tapered to the observed low flow condition leading into the rising limb of the hydrograph.

One of the goals of this work was for WEST to create a geometry that could be used for numerous events, ranging from low to high flow. This added to the stability problems as the overbank channels transitioned between being “dry” (e.g., typically less than 1 cms in the pilot channel to keep it “wet” as is required by HEC-RAS) to when flow began to enter the channel, as well as transitions from narrow channel flow to the wider overbank flow. Additional complexity was also added as lateral structures (levees) were overtopped in the model. In all the simulations we increased the weir stability coefficients to help stabilize the model. We also converted some of the shorter overbank reaches, which appeared to have a level pool during most of the simulation, to storage areas. This helped to stabilize the simulations. Other changes to help stabilize the model included fitting a line to the upstream flow hydrographs, while maintaining the peak flow as best possible, where there were unrealistic jumps in the observed data. In the end, computation time steps of 5 or 15 sections were required to keep the model stable.

Some of the more significant and consistently troublesome spots include the Hall Do-RB 2090 reach, a small channel branching off from the upstream end of Hall Slough, the Hoqu RB 2.20 overbank reach, complicated by many overtopping lateral structures in a relatively short reach length, and the Tras RB 2.37 overbank reach, where the reach transitions from a well defined channel to no channel downstream of Highway 101. The Hall overbank area, downstream of Highway 101, originally modeled as a grouping of reaches, also caused significant stability issues as the lateral structures were overtopped. Preliminary results indicated that these reaches typically had a relatively uniform stage along the reach. Therefore, these reaches were converted to storage areas which especially improved the instability issues.

A numerical increase in the stage was created at the downstream end of the DoTr 0.85 reach in the simulation of the alternatives (alternatives are discussed in the Modeling Alternatives section) where it was connected to the Wetlands Acquisition storage area. An example is shown in Figure 1. This was due to the computation of the water surface being made during the transition from channel to overbank flow at the downstream end of the reach and the fact that the reach was connected at the downstream end to the Wetlands Acquisition storage area, which controlled the stage at this location. We modified the channel to make s smooth transition from channel to overbank flow which corrected for this phenomenon. Figure 1 shows that although the stage during the initial period of the simulation, when the model is transitioning from initial boundary conditions set for stability to the observed hydrograph, is different but that during the main event the results are identical except that the peak has been removed.

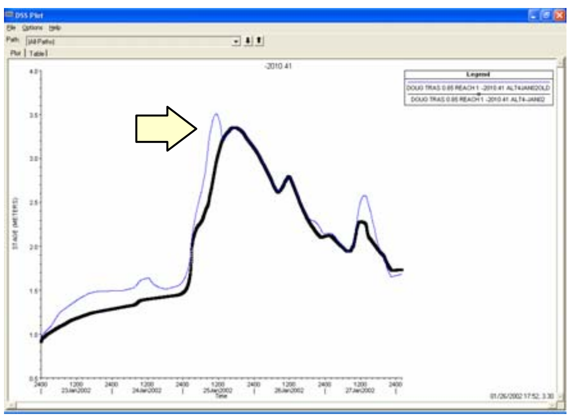


Figure 1. Example of the stage hydrograph rise calculated due to the calculation being made at the DoTr 0.85/Wetlands Acquisition storage area, with (heavy black line) and without (thin blue line) the correction for this phenomenon.

Of interest is a small oscillation in the flow that can be observed in numerous cross-sections in the lower portions of the model. The effect is typically only observed in the flow hydrograph when results are written at relatively small time steps (e.g., 2 minutes) since writing data at larger steps tends to mask these oscillations. This appears to be a numerical wave that is occurring based on the reflection of the tidal wave against the land boundary and the fixed downstream boundary condition, as best we could identify. We created a test case to help determine the root of this oscillation. An example of the oscillation from the test case is shown in Figure 2. We simplified the model to help eliminate potential causes, with the resulting test case being a single reach in HEC-RAS which including the Tillamook reaches and the Tillamook Bay reach form the base geometry. All bridges, lateral structures, culverts, storage areas, and storage area connections were removed. We set the upstream flow to a constant 60 cms and created a sinusoidal curve at the downstream boundary oscillating between 0 and 2 meters (Figure 3). We ran this test at 5 second time steps. The resulting simulation after this change still showed the oscillating flow (Figure 2) indicating that the oscillating downstream stage boundary was the cause. We could not dampen this effect during simulation of the events, however this change in flow is relatively small compared to the observed flows at the upstream boundary conditions.

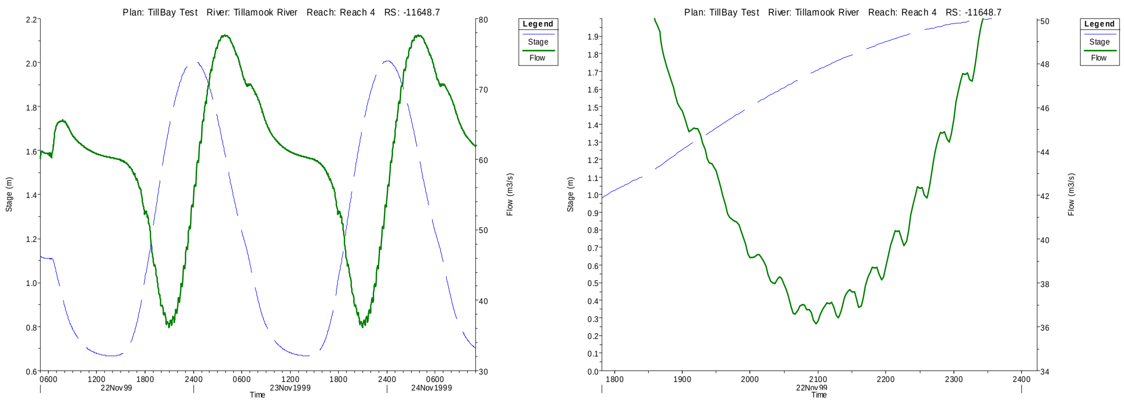


Figure 2. Example of small flow oscillations from the test case.

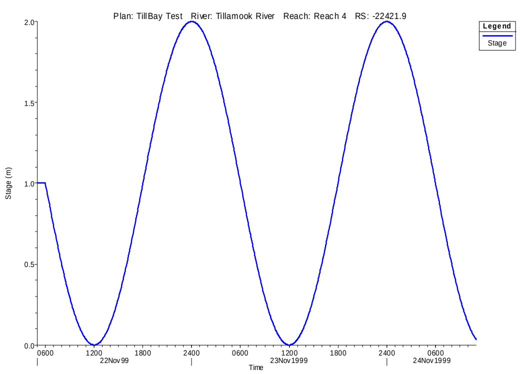


Figure 3. Downstream boundary for testing the cause of small flow oscillations.

Calibration

WEST began the calibration once we had created a stable model for each of the four calibration events (November 1999, May 2001, November 2001, and January 2002). We initially used the Manning's 'n' values specified in the MIKE11 simulation and then modified them to match the simulated stages to highwater marks and observed stage hydrographs. We first calibrated the Manning's 'n' values in the rivers and sloughs for the in-channel events and then, while keeping these values fixed, calibrated the overbank Manning's 'n' values for the larger events. However, we found it difficult to select one set of parameters to adequately model all events, and ended up modifying the Manning's 'n' value in the rivers and sloughs for the out-of-bank events. We observed that during the calibration of the out-of-bank events that the amount of flow over the lateral structures had a considerable effect on the results. The amount of flow over the lateral structures was most affected by 1) the Manning's 'n' value in the channel, which would changes the stage and therefore the head driving flow over the lateral structures, 2) the weir coefficient (Cd), 3) the amount of lateral structure submergence, and 4) the geometry defining the lateral structure geometry. WEST found that during calibration of the out-of-bank events that initially too much flow was overtopping the lateral structures as there was not enough flow in the main channels to match the high watermarks. The weir coefficient was typically lowered to 0.55 (1.0 in English units) to reduce the amount of flow leaving main channels. In addition, throughout the study area the TIN had significant deficiencies in definition of the levee elevation frequently showing "gaps" in locations were levees are known to exist (Figure 4). The "filling" of these gaps reduced the amount of flow leaving the main channels and improved the calibrated results.

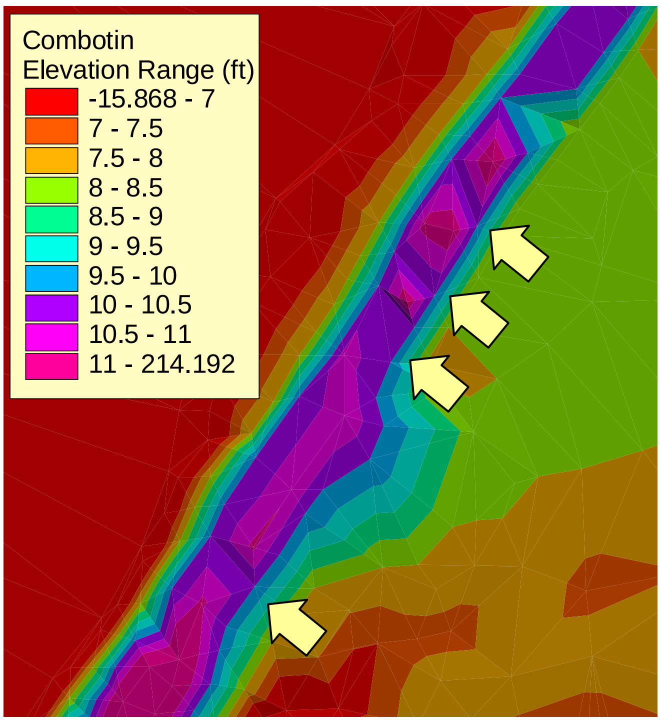


Figure 4. Example of "gaps" (indicated by arrows) in the TIN definition of the levee geometry.

The final calibrated Manning's 'n' values and comparison of simulated results to both high water marks and observed stage hydrographs are shown in Table 1, Table 2, and Figure 5 through Figure 9. Overall the results are good, with highwater marks typically being within ±0.4 meters and the timing and the shape of the hydrographs matching well. However, there are some high excursions during specific events, but improvement could not be made without drastically affecting other events. For example, the simulated stage is high (0.97 meters) for the November 2001 event at river station -10193 on the Tillamook River, yet much better for the May 2001 and November 1999 events upstream and downstream of this location. This may be due to an error in the November 2001 highwater mark as this stage is lower than the observed stage at the downstream boundary condition. Another example is Hall RB 3.00, which is 1.26 meters too low for the November 2001 event, yet the difference between observed and simulated at the same location is 0.03 meters for the November 1999 event. Dougherty Slough which is high at the upstream end for the May 2001 event yet low, and much closer, for the other three events. Looking across all events typically shows some events being high and others low for the same location. Another example is the Hall at RS -3100.7 being high for the May 2001 event (0.13 meters) and low for the November 1999 event (-0.21).

The upstream end of the Wilson River (reach 8a) is consistently high for all four calibration events, however downstream (reach 7) the values are equal or below the observed high water marks. The Manning's 'n' value is consistent through these reaches and no rational could be determined for decreasing the Manning's 'n' value in an upstream direction (the system typically shows an increase in Manning's 'n' value moving in an upstream direction). Modifying the lateral structure coefficients, downstream connections, adding additional lateral structures, etc. to try to adjust the flow distribution in the left bank of the Wilson River, near the Wils-Doug 690 reach area, helped to improve the calibration in this area. Additional refinement might further improve the calibration.

The upstream end of the Till OldT 0_30 at river station -258 is too low (-1.1 meters), but nearly perfect, 0.03 meters, downstream. This is likely due to not enough division in the lateral structures as there are no lateral structures connected to the reach in this area or upstream of this location.

On last general note is that the May 2001 event has times associated with the highwater marks (i.e., they may not be the maximum stage for the event). If the simulated timing is off slightly for this event it can obviously affect the comparison to simulated results.

Table 1. Range of Manning's 'n' values used in the HEC-RAS simualations.

River	Manning's 'n' value
Tillamook Bay	0.02
Wilson River	0.04 - 0.07
Hall	0.07
Dougherty Slough	0.09 - 0.15
Hoquarten Slough	0.07
Trask River	0.034 -0.07
Tillamook River	0.04 - 0.07
Old Trask River	0.04
Overbank reaches	0.07 - 0.09

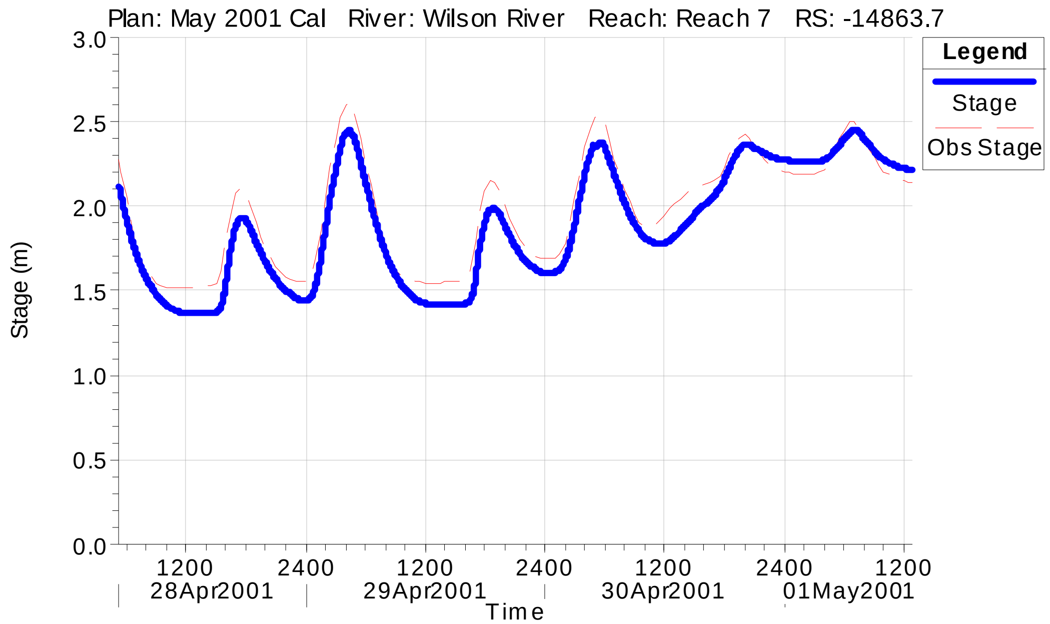


Figure 5. Simulated (solid blue) and observed (dashed red) at Geinger Farm during May 2001.

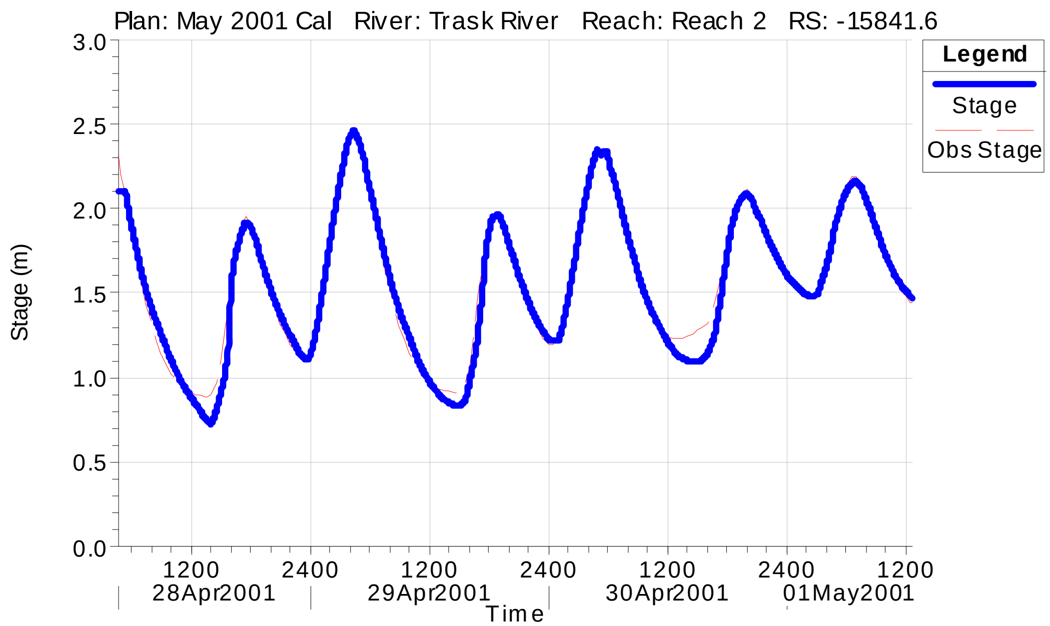


Figure 6. Simulated (solid blue) and observed (dashed red) at Carnahan tide gage during May 2001.

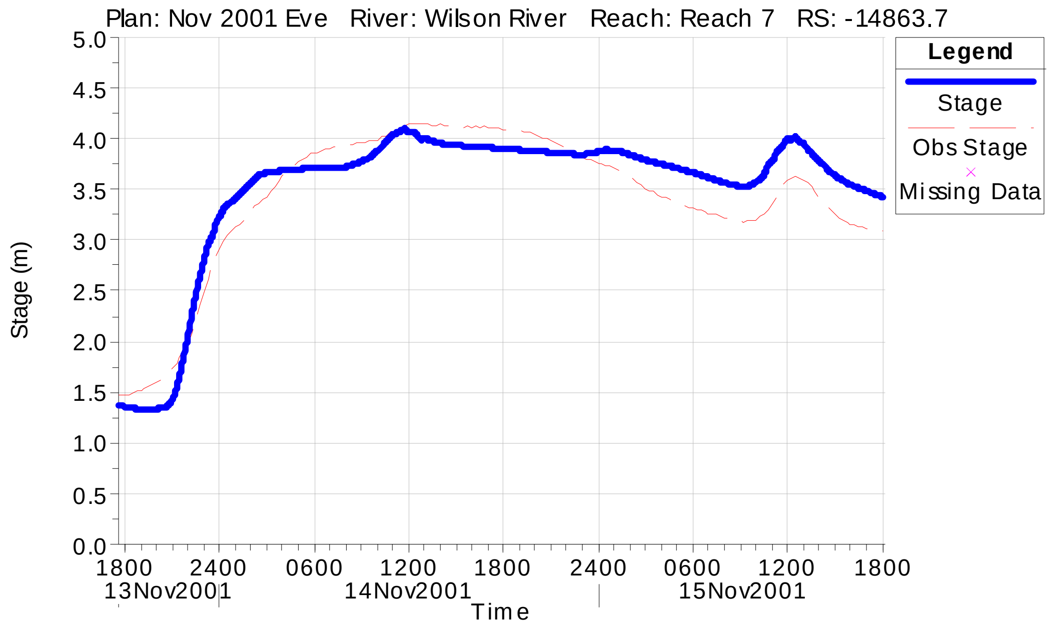


Figure 7. Simulated (solid blue) and observed (dashed red) at Geinger Farm during November 2001.

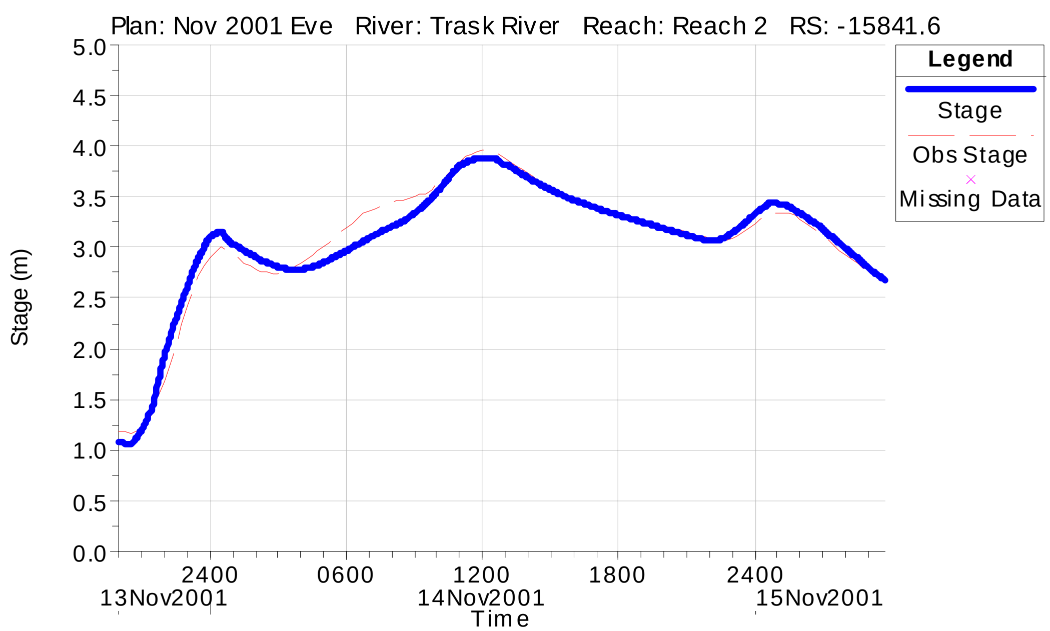


Figure 8. Simulated (solid blue) and observed (dashed red) at Carnahan during November 2001.

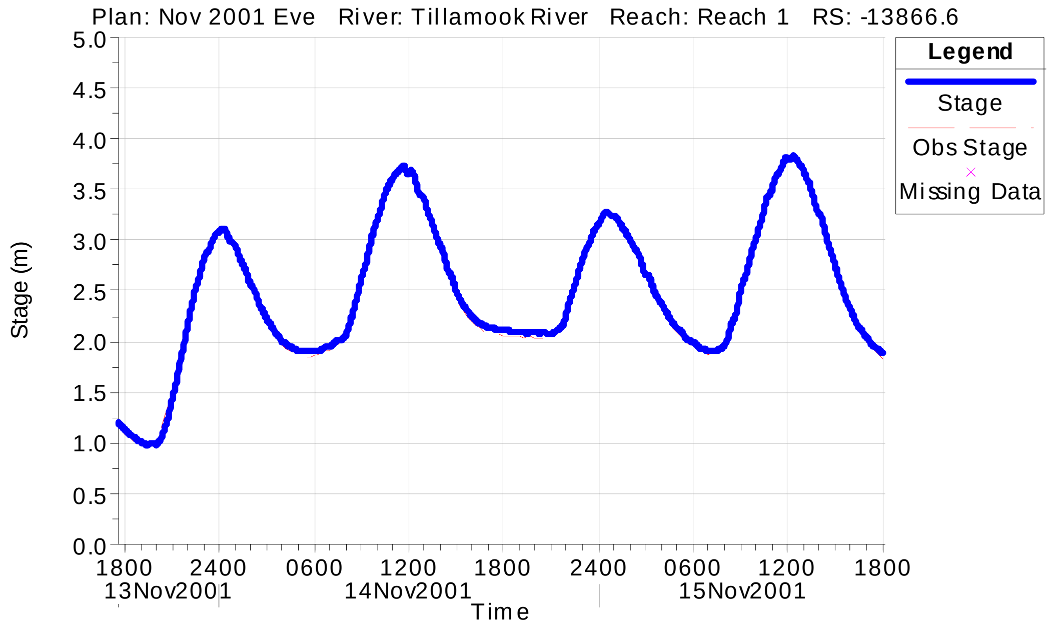


Figure 9. Simulated (solid blue) and observed (dashed red) at Dick Point during November 2001.

Table 2. Observed vs. Simulated Highwater Marks

				May-01				Nov-01				Nov-99				Jan-02		
River	Reach	River Sta	Obs WS (m)	Simulated (m)	Diff (m)	Diff (ft)	Obs WS (m)	Simulated (m)	Diff (m)	Diff (ft)	Obs WS (m)	Simulated (m)	Diff (m)	Diff (ft)	Obs WS (m)	Simulated (m)	Diff (m)	Diff (ft)
Wilson River	Reach 8a	-1299.9	13.1	13.28	0.18	0.59	16.06	16.46	0.40	1.31	17.53	17.75	0.22	0.72	16.09	16.49	0.40	1.31
Wilson River	Reach 8a	-1650.7	12.41	12.67	0.25	0.84	15.51	15.82	0.31	1.02								
Wilson River	Reach 8a	-5010.1					11.26	11.58	0.32	1.05								
Wilson River	Reach 7	-8908.9					8.82	8.82	0.00	0.00	8.99	9.15	0.16	0.52	8.87	8.83	-0.04	-0.13
Wilson River	Reach 7	-8942.9	4.42	4.77	0.35	1.15												
Wilson River	Reach 7	-11294.6					7.08	6.71	-0.37	-1.21	7.14	6.84	-0.30	-0.98	7.09	6.72	-0.37	-1.21
Wilson River	Reach 7	-11336.5	3.24	3.43	0.19	0.62												
Wilson River	Reach 7	-12445.1	2.87	3.12	0.25	0.82	6.42	6.16	-0.26	-0.85	6.45	6.24	-0.21	-0.69	6.36	6.16	-0.20	-0.66
Wilson River	Reach 7	-12759.2					5.69	5.84	0.15	0.49								
Wilson River	Reach 7	-14341.9	2.35	2.56	0.21	0.69												
Hall	Reach 1	-1275.1					4.5	4.49	-0.01	-0.03								
Hall	Reach 1	-2245.1									4.2	4.15	-0.05	-0.16				
Hall	Reach 1	-3100.7	2.03	2.16	0.13	0.43					4.27	4.06	-0.21	-0.69				
Hall RB 3.00	Reach 1	-345.2					5.04	3.78	-1.26	-4.13	4.1	4.11	0.01	0.03				
Dougherty Slough	Reach 1a	0	4.83	5.29	0.46	1.51												
Dougherty Slough	Reach 1a	-172	4.61	4.94	0.33	1.08												
Dougherty Slough	Reach 3	-690.6	4.02	4.33	0.31	1.02	7.96	7.92	-0.04	-0.13	8.42	8.38	-0.04	-0.13	8.1	7.95	-0.15	-0.49
Dougherty Slough	Reach 3	-2157.0					6.03	6.03	0.00	0.00								
Dougherty Slough	Reach 3	-2184.3									6.52	6.3	-0.22	-0.72	6.26	5.97	-0.29	-0.95
Dougherty Slough	Reach 1	-4170.2	1.94	1.96	0.02	0.07												
Dougherty Slough	Reach 1	-4684.9	2.01	2.00	-0.01	-0.03	3.76	4.01	0.25	0.82								
Dougherty Slough	Reach 1	-4730.6					3.86	3.97	0.11	0.36								
Hoquarten Slough	Reach 3	-6234.9	1.95	1.88	-0.07	-0.23					4.78	4.78	0.00	0.00				
Wetlands	Storage																	
Trask River	Reach 3	-3231	13.06	13.08	0.02	0.07												
Trask River	Reach 3	-6374									11.86	11.8	-0.06	-0.20	10.61	10.48	-0.13	-0.43
Trask River	Reach 3	-6385.95	7.16	7.26	0.09	0.31												
Trask River	Reach 3	-9164.6	4.48	4.59	0.11	0.36					9.6	9.33	-0.27	-0.89				
Trask River	Reach 3	-10930.5	2.74	2.63	-0.12	-0.38												
Trask River	Reach 3	-10954.3									8.14	8.07	-0.07	-0.23				
Trask River	Reach 3	-12965.6	2.04	2.00	-0.04	-0.13												
Trask River	Reach 3	-14070.4	1.83	1.78	-0.05	-0.16												
Trask River	Reach 3	-14078.5									5.78	5.6	-0.18	-0.59				
Trask River	Reach 2	-15841.6									4.51	4.43	-0.08	-0.26	4.5	3.91	-0.59	-1.94
Trask River	Reach 2	-15873.6	1.49	1.48	-0.01	-0.03	3.96	3.89	-0.07	-0.23								
Old Trask River	Reach 1	-2796.6					3.14	3.68	0.54	1.77								
Tillamook River	Reach 4	-28.2	4.76	4.68	-0.08	-0.26												
Tillamook River	Reach 4	-2605.7									4.3	4.22	-0.08	-0.26				
Tillamook River	Reach 4	-2658.5	2.04	2.08	0.04	0.13												
Tillamook River	Reach 4	-3532.8	1.94	1.92	-0.02	-0.07												
Tillamook River	Reach 4	-5060.3	1.99	1.95	-0.04	-0.13					4.25	4.18	-0.07	-0.23				
Tillamook River	Reach 4	-6775.5	2.04	1.91	-0.13	-0.43												
Tillamook River	Reach 4	-8402.1	1.98	1.88	-0.10	-0.33												
Tillamook River	Reach 3a	-10193					2.75	3.72	0.97	3.18	3.75	3.87	0.12	0.39				
Tillamook River	Reach 2	-12823.8									2.96	3.08	0.12	0.39				
Till oldt 0_30	Reach 2	-258									5.5	4.4	-1.10	-3.61				
Till oldt 0_30	Reach 2	-1045									4.3	4.33	0.03	0.10				
Tras rb 2.37	Reach 1	-2919.4									6.1	6.11	0.01	0.03				

Modeling Alternatives

WEST modeled three alternatives, which included:

- Alternative 1: Updating to existing conditions from the base geometry model.

- Alternative 2: Modification of Alternative 1 to create a saltwater marsh in the Blind Slough area and flood control storage to the south of this area (Figure 10).

- Alternative 4: Modification of Alternative 2 to include ecosystem restoration in Nolan Slough (Figure 10).

We modeled two flows, the January 2002 and 100-year events as selected by the District, for these alternatives. The modifications WEST made to for Alternatives 2 and 4 were to achieve no-rise, defined as a water surface increase above 0.0015 meters (0.005 feet), in areas with existing structures, especially near Highway 101, for the two events. Any changes that WEST made during modeling of any of these alternatives, e.g. copying additional cross-sections, further division of lateral structures, etc. were made to all geometry files in the HEC-RAS model to ensure equivalent comparisons could be made between results.

Base geometry to Alternative 1

A number of modifications were made to the base geometry to update it to existing conditions under direction from the District. This included raising the Wilson River lateral structures at river stations -10412 and -11088 so that they were not overtopped (raised an arbitrary 1 meter), removing the Jones cross-levee (at river station -1817.81 on the Doug Tras 0.85 reach) and replacing it with data provided by the District, and updating Dougherty Slough geometry with new cross-section data (at river stations -3467, -3468, and -3477.1).

Alternative 1 Conversion to Alternative 2

Alternative 2 modified Alternative 1, under guidance from the District, to create a saltwater marsh in the Blind Slough area and flood control storage to the south of this (Figure 10). We breached lateral structures to reconnect the main channel to blocked off sloughs in the overbanks. We set the width of the breaches to approximately match the slough widths, and the side slopes of the breaches were set at 2:1 slopes. Table 3 lists a summary of the levee breaches added for Alternative 2.

Table 3. Breaches in the lateral structures made for Alternative 1.

River	River Station	Breach Width (m)	Breach Station (m)
Wilson River	-15616	4	262
Wilson River	-16541	4.5	400
Wilson River	-16541	16	522
Hall Slough	-3855	10	872
Blind Slough (DO TR Wils 0.73)	-504	15	433.5
Blind Slough (DO TR Wils 0.73)	-504	10	866

We removed the inline structure (at river station -1225) on the Blind Slough reach (DO TR Wils 0.73) for Alternative 2 and added three 1.5 meter diameter culverts (with flap gates) to the lateral structure that connects the upstream end of Blind Slough (at river station -383) to the Wetlands Acquisition Storage Area. We divided the Wetlands Acquisition Storage Area in Alternative 1 into two storage areas with a 1,551 meter long levee that linearly varied in elevation from 3.8 to 3.82 meters and contained three 1.83 meter diameter culverts (with flap gates). The northernmost of these two new storage areas was hydraulically connected to the main river channel by the previously mentioned laterals structure breaches.

We also included tide gates in the lateral structure that connects the Wetlands Acquisition area to the Tillamook River (at river station -12200 3). This is the same lateral structure that contains the eleven existing flood control culverts. We assigned arbitrary dimensions to these three gates of 6.5 meter width, 1.83 meter height, and invert elevation of 1.3 meters. We specified that these gates be closed throughout the Alternative 2 simulations, since an endless number of time series gate opening could be defined in an attempt to cause no rise in the 100-year and January 2002 events and the culverts, with tide gates, left in place. In addition, tidal flaps cannot be added to gates in HEC-RAS which would have complicated even further setting an appropriate time series. The final gate design and operations could be defined to mimic the flow through the culverts for the Alternative 2 simulations.

Finally, a swale was added in the Doug Tras 0.85 overbank reach from river stations -1240 to -2529.71. We made two “cuts” for this swale at elevations directed by the District; one that was 21 meters wide at a bottom elevation of 1.8 meters, and one that was 1.8 meters wide at a bottom elevation of 1.5 meters.

The January Alternative 2 results initially showed an undesirable rise in the downstream portion of the DoTr 0.85 overbank reach. Two additional culverts with the tidal flaps (which the gate time series would also need to replicate for this simulation) were added to the lateral structure to help alleviate this increase.

The resulting Alternative 2 water surface elevation shows no-rise in the January 2002 water surface elevation (Table 4). The 100-year event, with identical geometry to the January 2002 event except that these additional two culverts were not added, showed a rise only in areas that met the approval of the District; at the Blind Slough/Wilson River confluence, in the southernmost of the two new Wetlands Acquisition storage areas, and at the downstream end of the Doug Tras 0.85 overbank reach where is connects with southern storage area.

Alternative 2 Conversion to Alternative 4

WEST modified Alternative 2 to include ecosystem restoration in Nolan Slough for Alternative 4 (Figure 10). We created a new Nolan Slough reach for this alternative, and reduced the volume of the southern Wetlands Acquisition area accordingly. New levees were added to separate Nolan Slough from the Wetlands Acquisition storage area and the Doug Tras 0.85 reach so that it would not be overtopped during typical tidal flows. A 1.83 meter culvert with a tidal flap was placed in each of the two new levees. We breached the lateral structure connecting the upstream end of Nolan Slough with the Houquarten Slough (at river station -9017) with two 10 meter wide breaches starting at bottom elevations of 1.83 meters and having 2:1 side slopes. We also breached the lateral structures connecting to the Trask River near the downstream end of Nolan Slough (at river station -16998 [station 130] and at river station -17437 [station 500]). We used the same dimensions as at the upstream breaches except that the bottom elevation was set to 0 meters for the most downstream breach.

WEST also lowered, by 0.3 meters for a distance of 288 meters, a lateral structure connecting Dougherty Slough (river station -4731 from station 1365 to 1653) to the DoTr 0.85 reach to assist in reducing peak stages. Other differences between the Alternative 2 geometry to ensure that no rise in undesirable location included setting the lateral structure height between the two Wetlands Acquisition storage areas at 3.81 meters and using a 1.5m diameter culvert, not including the additional two culverts that were added in the Tillamook lateral structure for the January 2002 Alternative 2 simulation, and increasing the breach width to 20m from 16m in the Wilson River lateral structure at river mile -16541 (station 400).

Table 4 shows that Alternative 4 creates a rise only at the Blind Slough/Wilson River confluence for the January 2002 event, which met with approval by the District, and no rise for the 100-year event.

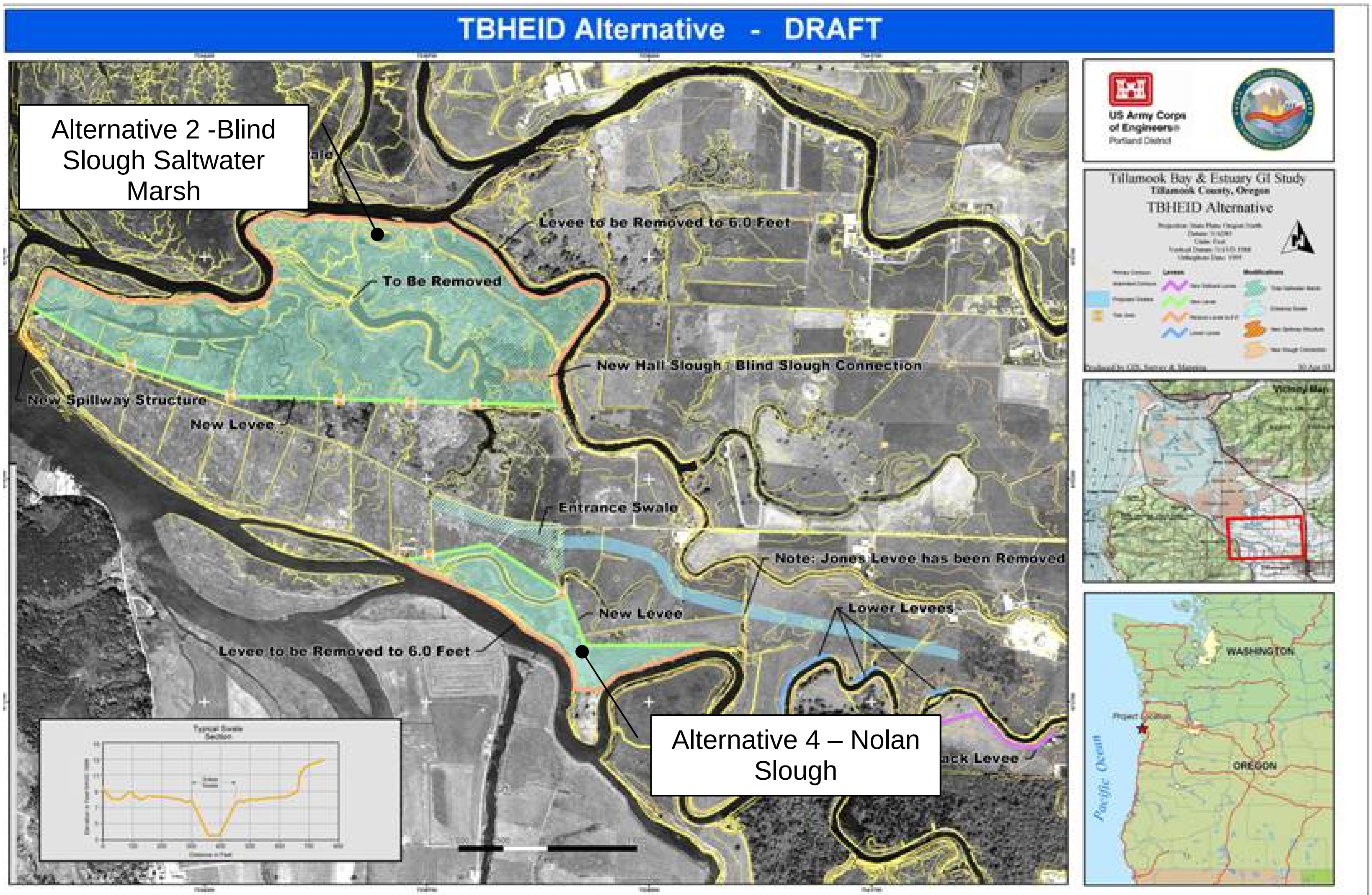


Figure 10. Schematic of Alternative 2 and Alternative 4.

Table 4. Increase in January 2002 and 100-year simulations for Alternative 2 and Alternative 4.

Simulation	Location: Reach	Location: River	Location: Station	Stage (m)	Increase greater than 0.0015 (m)	Notes
Alt2 Jan02	*N/A*	*N/A*	*N/A*	*N/A*	0.0000	No rise greater than 0.0015m
Alt2 100yr	Wilson River	Reach 4a	-16260	3.6122	0.0085	Blind Slough/Wilson R. Confluence
	Wilson River	Reach 4a	-16261	3.6119	0.0085	Blind Slough/Wilson R. Confluence
	Wilson River	Reach 4b	-16538.4	3.6119	0.0085	Blind Slough/Wilson R. Confluence
	Wilson River	Reach 4b	-16539.4	3.6104	0.0089	Blind Slough/Wilson R. Confluence
	Hall RB 3.00	Reach 1	-39.9	4.6622	0.0094	Water surface elevation is in pilot channel
	Doug tras 0.85	Reach 1	-2529	4.0139	0.0088	Junction with wetlands acquisition storage area
	Doug tras 0.85	Reach 1	-2529.71	4.0136	0.0091	Junction with wetlands acquisition storage area
	Do-Tr Wils 0.73	Reach 1	-1556.62	3.6119	0.0085	Blind Slough/Wilson R. Confluence
	Wetland Aqu SA S	*N/A*	*N/A*	4.013	0.0091	Storage Area
Alt4 Jan02	Wilson River	Reach 4a	-16260	3.2662	0.0024	Blind Slough/Wilson R. Confluence
	Wilson River	Reach 4a	-16261	3.2659	0.0024	Blind Slough/Wilson R. Confluence
	Wilson River	Reach 4b	-16538.4	3.2659	0.0024	Blind Slough/Wilson R. Confluence
	Wilson River	Reach 4b	-16539.4	3.2656	0.0027	Blind Slough/Wilson R. Confluence
	Do-Tr Wils 0.73	Reach 1	-1556.62	3.2659	0.0024	Blind Slough/Wilson R. Confluence
Alt4 100yr	Hall RB 3.00	Reach 1	-39.9	4.6634	0.0106	Water surface elevation is in pilot channel

Note: This data presents the results where HEC-RAS shows a rise above 0.0015 meters in the maximum water surface elevation. The stage shown for the upstream end of the Hall RB 3.00 overbank reach for the two 100-year simulation is within the pilot channel, and not above the ground geometry. Therefore, it would not result in an observed rise at the surface and is not included as a rise in the discussion of this report.

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US Army Corps
of Engineers ®
Portland District

Tillamook Bay and Estuary, Oregon General Investigation Feasibility Report

APPENDIX D

Fluvial Geomorphic Analysis of the Tillamook Bay Basin Rivers

Prepared by
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for the
U.S. Army Corps of Engineers, Portland District
and Tillamook County, Oregon

March 2002

Fluvial Geomorphic Analysis of the Tillamook Bay Basin Rivers

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Fluvial Geomorphic Analysis of the Tillamook Bay Basin Rivers

1. INTRODUCTION

The catastrophic flood events of February 1996 renewed interest in improving flood protection in the Tillamook Bay Basin (Plate 1). This was not the first major flood event; major flooding dates back to the initial settlement of humans on the Tillamook alluvial floodplain. Post-flood reports from the Portland District, U.S. Army Corps of Engineers (Corps) date back to the early 1960s. Report data provides positive information that flood events have had major impacts on the basin. Although the results are visible, the processes and historic, present, and future conditions require additional understanding. Research conducted under the Tillamook Bay National Estuary Project (TBNEP) provides a plethora of information from the early to middle 1990s. The U.S. Environmental Protection Agency (USEPA) coordinated these cooperative research agreements.

Intent and Scope of the Present Study

The purpose of this Tillamook Bay assessment is to inventory and characterize the five river basins (the Miami, Kilchis, Wilson, Trask and Tillamook Rivers) within the study area of Tillamook County, and to provide a foundation in order to undertake a geomorphic assessment. Reviewing and synthesizing existing data, as well as collecting new data during site visits to the study area, were conducted for this assessment.

It is important to understand that there are a number of documents that provide assessment of the individual watersheds. These reports also contain sections dedicated to river basins or subdrainage basins. Summarizing the existing basin conditions will provide a foundation for the geomorphic model and the hydrologic model, which will be developed in the Corps' General Investigation Study of the Tillamook Bay Basin.

The TBNEP recently characterized many of the resources in the Tillamook Basin. These documents provide a fundamental collection of reference material for the existing basin conditions and site references to earlier investigations. The historic and baseline setting is provided in the 1978 report, *Tillamook Bay Drainage Basin Erosion and Sediment Study Oregon,* prepared by the Tillamook Bay Task Force, the Oregon Water Resources Department (OWRD), and the U.S. Department of Agriculture, Soil Conservation Service (SCS). These documents provide a wealth of baseline information, and data for this assessment was taken from some of these reports. Nevertheless, data was logically presented with little geomorphic analysis conducted.

Setting

Tillamook Bay is a small, shallow estuary located on the northern Oregon Coast about 80 miles south of Astoria and 60 miles west of Portland. The bay's current geographic dimension is 6 miles in length and up to 3 miles in width; it averages about 6 feet in depth over its 13 square mile area. The settlement and therefore, the human impact on the Tillamook Bay Basin, started in the 1850s. Small rural/agricultural settlements were established and petitioned the State of Oregon to create Tillamook County.

On December 13, 1853, the State Legislature established Tillamook County, as well as several of the surrounding counties. Shipment of all products was by sea until 1871, when the first road access was completed; however, it was not until some 30 years later that rail service was established. From this early date, humans started to modify the environment to enhance their living conditions.

Today, it appears that the bay and channel network are being loaded with sediment. This reduces boat and access from the bay to the river systems that drain into the bay. There is an apparent perception that at the river-bay interface, channel sedimentation rates have or are increasing; sediments are now plugging channels, reducing in-flow capacity, and increasing flood levels and duration.

This apparent erosion-sediment problem has been combined in part with the devastating forest fires that burned over extensive areas in the basin between 1933 and 1945. The fire history is complex, burning and laying bare over 228,000 acres of highly erodible volcanic material to winter storms. These intense precipitation events saturated the soil, and coupled with steep slopes and highly weathered rock material, increased the sediment loading of basin channel systems for many years after the last fire.

Geomorphic processes from these events have formed larger channel systems. Sediment transport also was accelerated downslope by numerous mass movement types of processes. During storm events, high discharges can transport higher volumes of sediment out of the mountain reaches and to the alluvial/delta complex and the bay/river interface zones. This process causes sediment loading of the complete channel system, which increases temporary sediment storage from the mountain reaches to the lower channel/bay reach.

A summary of the erosion-sediment problem in the Tillamook Basin is provided below.

- Channels in the bay are impassable to most shipping because of sediment.
- Sediment carried down the rivers and into the bay has built up at rapid rates, filling former channels south of Garibaldi.
- The drastic erosion-sediment problem has been traced in part to the devastating forest fires between 1933 and 1945. These fires have exposed over 228,000 acres of highly erodible material to severe winter storms.
- As these channels became larger, more soil particles and debris were carried down the slope and accelerated erosion problems.

- The lower river channels were choked with sediment; as a result of reduced channel capacity, flooding was often aggravated during storms.
- Commercial activities such as farming, logging, road construction, and uncontrolled cattle movement across streambanks increased the erosion-sediment problem.
- The general problem is obvious: too much sediment.
- The problems are complicated and oversimplification is a hazard.

Previous Geologic and Geomorphic Work

The study area was relatively far from population centers (Willamette Valley) and lacking in significant mineral wealth; as such, it has been the focus of very few geologic investigations. The area was covered in general terms in regional reconnaissance studies by Warren and others (1945) and Wells and Peak (1961). Early geologic investigations were conducted by Layfield (1936) and Baldwin (1952), and were related to the study of volcanic rocks.

The majority of geologic studies are related to flood data along the five major rivers within the Tillamook Bay Basin (post-flood reports by the Corps in 1966, 1972, 1978, and 1999). The flood events of the early 1960s energized an expansion of general investigations, which included the impacts of logging and agricultural activities in the basin. Waananen and others (1971) also generated documentation of the 1964 and 1965 flood events. The Oregon Department of Geology and Mineral Industries (DOGAMI) published two reports that considered environmental geology and flood events in Tillamook and Clatsop Counties (DOGAMI 1972, 1973). These reports provide the foundation and the bulk of the geologic investigations in the study area.

The erosion and sediment study prepared by the Tillamook Bay Task Force and others (1978) appears to present the view that a serious sediment problem exists in the Tillamook Bay Basin. In addition, it appears that all impressions and actions related to the sediment-erosion problem in the basin are linked to this document. Some information about the study and its conclusions are provided below.

- The study used 1975 as a baseline date.
- Sampling sites and suspended sediment samples were collected from the five rivers.
- Sediment samples from the bay floor were collected.
- The five river basins were subdivided into agriculture or forestlands.
- Erosion on agricultural lands was divided into two major groups (29,490 acres): streambank erosion or sheet and rill erosion on croplands.
- Forestland erosion was divided into seven major groups (323,050 acres): roads, trails, landslides, streams, clearcuts, forested areas, and burns.
- The study found that sediment enters the bay at the rate of 61,000 tons annually.
- The study found that forestlands in the upper watershed comprise over 90% of the area and contribute about 85% of the sediment.

Tables 1 and 2 provide data from the study on the erosion and sediment production from agricultural and forestland, respectively. Tables 3 and 4 provide data from the study on the sediment delivery from agricultural and forestland, respectively. The data in the tables show that 61% of the mean annual erosion and 86% of the mean annual sediment is on agricultural land, and that 17% of the mean annual erosion and 52% of the mean annual sediment is on forestland (Plate 1).

In 1992, the USEPA established a National Estuary Project; the Tillamook Bay/Estuary was added into the program, which allowed funding for the TBNEP.

Table 1. Stream System Erosion and Sediment Production for Agricultural Land

Subbasin	Stream System Mean Erosion (tons per year)	Stream System Mean Sediment (tons per year)	Percent
Miami	1,211	1,114	16
Kilchis	1,414	1,300	17
Wilson	1,973	1,874	24
Trask	2,479	2,355	30
Tillamook	1,152	1,071	16
TOTAL	8,229	7,714	---

Source: Tillamook Bay Task Force et al., 1978.

Table 2. Stream System Erosion and Sediment Production for Forest Land

Subbasin	Stream System Mean Erosion (tons per year)	Stream System Mean Sediment (tons per year)	Percent
Miami	3,026	760	2
Kilchis	1,760	1,378	5
Wilson	15,198	7,720	29
Trask	25,295	13,846	50
Tillamook	3,500	2,929	11
TOTAL	48,799	26,633	---

Source: Tillamook Bay Task Force et al., 1978.

Table 3. Sediment Delivery from Agricultural Lands in the Tillamook Bay Basin

Total Acres	Mean Annual Gross Erosion - Acres	Percent and Tons of Sediment Reaching the Stream
Miami Subbasin 1,260 acres	220.2 tons from 1,205.6 acres	27% or 59.0 tons/year
Kilchis Subbasin 3,600 acres	1,211.2 tons from 10.9 acres	92% or 1,114.3 tons/year
Wilson Subbasin 4,430 acres	634 tons from 4,090.2 acres	25% or 144 tons/year
Trask Subbasin 11,900 acres	1,896.4 tons from 10,651.7 acres	95% or 2,355 tons/year
Tillamook Subbasin 9,570 acres	1,868 tons from 9,340 acres	20% or 370 tons/year

Source: Tillamook Bay Task Force et al., 1978.

Table 4. Sediment Delivery from Forest Lands in the Tillamook Bay Basin

Total Acres	Mean Annual Gross Erosion - Acres	Mean Annual Gross Fluvial Sediment	Bedload	Sediment Delivery to Fluvial Sediment
Miami Subbasin 24,290 acres	20,492.0 tons or 540.0 tons/sq. mile	2,041.4 tons or 53.7 tons/sq. mile	47.0%	10.0%
Kilchis Subbasin				
Upper Kilchis 21,400 acres	12,040.0 tons or 360.05 tons/sq. mile	1,070.0 tons or 32.0 tons/sq. mile	47.0%	8.8%
Lower Kilchis 15,010 acres	11,704.7 tons or 578.5 tons/sq. mile	2,310.7 tons or 98.5 tons/sq. mile	64.0%	19.7%
South Fork Kilchis 6,910 acres	10,466.1 tons or 967.2 tons/sq. mile	1,001.1 tons or 92.6 tons/sq. mile	17.0%	9.5%
Wilson Subbasin				
Lower Wilson 47,720 acres	41,535.4 tons or 557.0 tons/sq. mile	8,514.8 tons or 114.2 tons/sq. mile	20.5%	20.5%
Upper Wilson 56,960 acres	28,833.3 tons or 324.0 tons/sq. mile	4,325.4 tons or 46.8 tons/sq. mile	41.0%	15.0%
North Fork Wilson 16,430 acres	7,103.44 tons or 276.72 tons/sq. mile	416.1 tons or 16.2 tons/sq. mile	41.0%	16.0%
Trask Subbasin				
Main Trask 69,920 acres	78,504 tons or 718.6 tons/sq. mile	16,485.8 tons or 150.9 tons/sq. mile	19.0%	21.0%
East Fork Trask 18,830 acres	29,002 tons or 985.8 tons/sq. mile	7,250.5 tons or 246.5 tons/sq. mile	11.0%	25.0%
South Fork Trask 13,190 acres	4,995.7 tons or 240.45 tons/sq. mile	1,090.27 tons or 52.9 tons/sq. mile	48.0%	22.0%
Tillamook Subbasin 33,570 acres	41,628.7 tons or 703.7 tons/sq. mile	7,097.6 tons or 135.3 tons/sq. mile	7.6%	17.0%

Source: Tillamook Bay Task Force et al., 1978.

Sediment Problem

Brown and others (1958), Terich and Komar (1974), Percy and others (1974), Komar and Terich (1976), and Schubek and Meade (1977) indicate that the extensive farming and logging that followed settlement of estuarine drainage basins, as well as construction of jetties to facilitate navigation at estuary mouths, contributed to shoreline erosion and/or deposition.

Tillamook Bay Sediment

Analysis by Glenn (1978) found a mixture of sediment from various sources in some parts of Tillamook Bay. The tidal rivers of Tillamook and Tillamook-South Trask have sediments from both river and shoreline sources, as in parts of the southwestern and eastern margins. The almost total dominance of sediments from the river source in the combined Tillamook-Trask tidal rivers and in the eastern margin south of Kilchis Point, indicates that the rate of sediment supply from the shoreline source far exceeds the river source in much of Tillamook Bay. Komar and others (1997) found that currently, 60% of the total bay sediment has a shoreline source. This could indicate that the rate of supply and/or transport has undergone modifications over the last 50 years.

According to Glenn (1978), sedimentation in Tillamook Bay during the Holocene shows two rates of infilling: the period between 9,000 to about 7,000 years ago was the most rapid, and the period from 5,000 to 3,000 years ago was at a slower rate. During this earlier period, a structural ridge between northern and southern Tillamook Bay appears to have developed. The structural ridge divides the bay along a south to north axis. Sedimentation patterns and bathymetric surveys date back to 1867. The 1957, 1995, and 2001 data sets are of major significance. Depositional patterns and trends indicate bay aggradation east and limited erosion west of the structural high (Corps of Engineers, Portland District, internal working documents, 2001). Tillamook Bay has a complex sedimentary history, which is outside the scope of this analysis. The governing investigative factor for this assessment is the aggradation of the eastern bay/river zones.

Methods and Limitations

There are extensive data gaps in the knowledge of the geomorphology and geology of the Tillamook Bay Basin. However, it was beyond the scope of this effort to undertake any geologic field investigations or to develop additional geomorphic data sets. New interpretations are offered, and geomorphic processes are combined with resolving inconsistencies in existing data sets and problems normally encountered when data from multiple sources are synthesized into a single fluvial geomorphology format.

It is acknowledged that perceptions and factual data sometime initially conflict. This report presents material that combines these factors to present the current geomorphic conditions leading to possible predictions of future geomorphic conditions. The geomorphic analysis involved identifying the physical processes actively reshaping the alluvial deposits and determining the importance of each one to long-term sediment production. Aerial photographs taken of the alluvial plain deposits in 1939, 1965, and 2000 were studied to identify historic and current geomorphic processes. The processes identified were depositional and erosional in nature. Geology, geomorphology, hydrology and forest events were combined with aerial photography and analyzed to provide a processes driven explanation of current and future landscape developments of the Tillamook Bay Basin.

Map and Aerial Photo Interpretation

Maps of the Tillamook Basin by the Tillamook Bay Task Force and others (1978) provide a wealth of geologic, hydrologic, erosion and sediment, and slope data to serve as baseline data sets. Basic geologic quadrangle-scale mapping by the U.S. Geological Survey (USGS) and other researchers provides the geology of the area. Bostrom and Komar (1997) documented the rock types in the Tillamook Bay Basin for the TBNEP.

Due to the large area and scale of the alluvial sediment plain, aerial photographs constitute an indispensable tool for initial landform and drainage identification and delineation. Subsequently, photo interpretation is typically refined using subsurface data, topographic and hydrologic information, soils maps, land use patterns, and field reconnaissance. Multiple aerial photo coverage flown at different dates has become essential. It provides opportunities to observe geomorphic basin modifications over time. Some limitations were encountered, however, due to the vast quantity of photos and the lack of total basin coverage.

The most used coverage has been individual frames and index mosaics of vertical, black and white photography at a scale of 1:20,000 obtained from the Corps. Coverage from this source is available at various intervals and area coverage; however, study area coverage of the Kilchis, Wilson, and Trask Rivers from 1939, 1965, and 2000 mosaics were compiled and reproduced digitally and geographically rectified. These photos are of exceptional quality and allowed interpretation of geomorphic and cultural condition modification over time. Discharge variations occur between the photos based on gauge data from the Wilson and Trask Rivers (Table 5). These data sets aided in mapping river pattern changes, and processes such as gravel bar development, erosion, and basic fluvial changes. Topographic and basin delineation analyses were undertaken based on USGS topographic maps.

Table 5. Wilson and Trask Rivers Discharge Data During Aerial Photograph Flights

Flight Date	Wilson River Discharge	Trask River Discharge
May 12, 1939	183 cfs	184 cfs
April 26, 1965	625 cfs	470 cfs
Sept. 29, 1999	54 cfs	76 cfs
March 24, 2000	1,270 cfs	1,080 cfs

Field visits were made to each river basin to verify the processes, conclusions, and to define smaller scale features. Both visual methods and geo-positioning systems were used to locate major sites. Spot measurements were made of active channels, channel slopes, terrace formations, and on the alluvial plain. During the field visit, specific investigations included channel descriptions, comparative differences in surface and channel conditions based on data analysis of the historic photographs and current conditions. Upper basin terrain, geologic rock type, and slope were analyzed in order to understand sediment yield.

Subsurface Investigations

The lack of outcrops on the alluvial plain complex or massive bank exposures of more than a few feet led to an interest in obtaining water well log information. It was hoped that well log data would provide clues to alluvial plain deposits, development, and deltaic formation, as well as answers to the thickness and geographic distribution of the alluvial plain deposits. However, although well log information was abundant, it provided limited data.

In the alluvial plain area, less than 10% of all borings are more than 200 feet deep and do penetrate through or into the major of the alluvial sequence. Holocene alluvial deposits are reached. The effect of these sections created with the well log data in depth and geographical subsurface variations are discussed in later sections. By combining these items and analyzing the well log data, a basic geomorphic model was developed. The model was used to couple historic geomorphic activity to predict future processes and impact along the alluvial plain and deltaic area.

Sediment Transport and Sediment Forecast

The overall objective of the sediment transport analysis was to develop a sufficient understanding of the processes in order to identify historic conditions and to be able to forecast future trends. Standard methods of analysis, such as streamflow, sediment transport measurements and computer modeling were generally not used in the study. The lack of detailed sediment transport models and limited scope of this study did not allow for data collection. However, the magnitude and mechanics of the sedimentation processes allowed for a more generalized approach based on field investigation and aerial photography.

The significant transport processes in gravel and steep-sloped terrain have been described by a number of researchers. Sediment transport assessments were made for some basins to estimate long-term potential erosion/deposition conditions in the study area. After an understanding of the historic and current geomorphic processes were developed, the next step was to prepare a geomorphic forecast. The key element in the future forecast or trends is the sediment available for erosion, transport and deposition.

The geomorphic analysis determined that the extremely high historic sediment supply was the result of rapid sediment delivery to the channel network, and that the constant hydrology to transport those high loads would continue until the sediment load would reach a “stable” longitudinal profile and cross-sectional geometry. Judgments were made about the main channel systems crossing the alluvial plain as to the idea of “stable” conditions. The idea of “stable” conditions is based on geomorphic analysis, pre-fire conditions, hydrology, and local geologic conditions.

Longitudinal Profile Comparison

Longitudinal profiles for the study reaches of the Miami, Kilchis, Wilson and Trask Rivers were constructed using data from 1978 and 2000. A Tillamook River profile was not constructed because the study reach is only 2 river miles, and is at or below the sea level datum plain. The 1978 elevation data is based on NAVD 1929 (FEMA 1978) and was compared with 2000 elevation data from the Corps (2001), with a datum of NGVD 1988. Mathematical corrections were completed to superimpose the profile elevation data from each river. Survey information indicates that there is an elevation correction between these two base elevation data sets.

Constructing longitudinal profiles with differing datum plains could induce a degree of elevation error. Using the standard geodetic correction factor of 3.1 feet, the numerical error should be minimal. Regardless, it was decided that a 1 foot plus or minus allowance would be used. Based on these allowances, the longitudinal profile data provided important information linking geomorphic processes and current fluvial conditions. The plotted profiles use raw elevation points for ease of comparison. Data analyses of the constructed longitudinal profiles indicate an increase in bed elevations for the majority of the rivers plotted. Each river has both degrading and aggrading reaches. There appear to be limited reaches that are in a state of pseudo-equilibrium.

2. REGIONAL GEOLOGIC SETTING

Geologic Units

Bostrom and Komar (1997) provide an update, review, and summary of the geologic rock formations found within the Tillamook Bay Basin. The Siletz River Volcanics (Tsr) are the oldest rock unit identified in the basin about 50-62 Ma (mega-annum or millions of years), making them early Eocene. The typical suite of volcanics consists of aphanitic to porphyritic flows, tuff breccias, and some massive lava flows. Tectonic activity created sills of thoeleiitic alkolic basalt. The upper units are interbeds of basltic siltstone, sandstone, tuff, and conglomerate. The origin for most of the unit is marine with seafloor deposits interbedded (Walker and MacLeod 1991).

There are six additional formations found within the basin ranging in age from Eocene to Miocene. Rock type consists of massive- to thin-bedded marine sedimentary units with volcanic material interbedded. These rock types are eroded by the drainage system of the basin. The weathering effect on the geologic column (volcanic and marine units) provides a constant sediment supply. Additional impacts generate fluctuations in the sediment supply but not the transport capacity. Bostrom and Komar (1997) base their detailed descriptions of the rock types in each river system (Miami, Kilchis, Tillamook, Wilson, and Trask) on the basic geologic map of Walker and MacLeod (1991).

Tectonics

The eastern uplands of the Tillamook Bay Basin are a broad northeast-plunging structural arch in Tertiary volcanic and sedimentary strata. Eocene basalt and interbedded marine strata constitute the core of this structural feature. The major fault zones are northwest trending, and locally truncate the southwest-striking Siletz River Volcanics. The major river systems flow westward cutting across the northwest-trending fault systems.

Engineering Characteristics of Geologic Units

The engineering characteristics of the geologic units in the Tillamook Bay Basin are discussed by DOGAMI (1972, 1973) and only a cursory review is presented here. Six quadrangle maps in a section of the DOGAMI reports delineate the geologic units. Plate 2 provides the fundamental basin geology.

The volcanic material in the basin is constantly undergoing attack by both chemical and physical weathering agents, and by the interrelated processes of mass wasting and erosion. The chemical and physical weathering breaks down the unstable volcanic bedrock material and a variety of gravel-induced mass wasting processes transport the sediment downslope to the fluvial system, which is ultimately transported to the bay.

The basin geology creates areas of steep slopes, landslide or mass movement topography, weak or no-cohesive strength sediment, and sedimentary rocks that result in a landscape that favors slope failure, which is inherently unstable and especially sensitive to modification and slope loading during storm events. Slope failures under the influence of gravity and water weight have occurred throughout the geologic history of the Tillamook Bay Basin. Shallow slumps, rapid earthflows, rockfalls, and debris flows characterize the upper basin sediment delivery processes.

The factors of mass movement or slope failure of regional scope include climate and rock type. The climate of the basin is moist marine and is typified by heavy winter storm events that produce high amounts of precipitation. This water increases the weathering processes of these non-cohesive rocks, increases pore pressure, decreases shear strength within the basin rock types, and initiates slope failure in the upper basin area. The weathering of the volcanic rocks the marine sediments, which are composed of high clay, are prone to failure under the basin's climatic conditions.

Engineering and Habitat Restoration Sites

Projecting geomorphic response to predict the impact of engineering actions is a predictive tool based on historic geomorphic patterns and processes combined with current events. Due to the risk and uncertainty of predicting channel processes from engineering actions, only three general types of actions are modeled in this assessment: (1) realign, deepen, and/or widen the channel, (2) remove revetments/levee systems, and (3) take no action.

3. GEOGRAPHIC AND PHYSIOGRAPHIC SETTING

Tillamook Bay Basin

Some general information about Tillamook Bay is provided below.

- The bay is about 6 miles long, up to 3 miles wide, and covers about 12 square miles at high tide.
- In 1978, average depth in the bay was about 6 feet.
- The watershed that drains into Tillamook Bay measures 550 square miles and consists mostly of steep forested terrain.
- Climate is dominated by strong marine storms off the Pacific Ocean, with wet winters and moderately dry summers; temperature ranges are narrow. Frequent southwest storms between November and March bring heavy rainfall over short periods of time.
- Average annual precipitation for the basin is 115 inches, ranging from 90 inches at Tillamook to 150 inches at higher elevations.

Sediment and Landscape

Geomorphic evolution of the Tillamook Bay Basin has changed or moved the dynamic equilibrium conditions resulting in a landscape in flux. Noticeable modifications have occurred in the upper watershed, along the rivers and floodplains, and to the river/bay/estuary environments.

Flooding and sedimentation patterns have impacted the Tillamook Bay Basin watershed from its minor tributary streams to its five major river systems. High sedimentation volume is acknowledged in a Corps' internal document from the early 1900s. The quantities were not defined, but it was stated that, "considerable quantities of gravel, sand, and mud is annually deposited in the bay and channels."

The DOGAMI (1973) documented the sediment sources in the basin as stream bank erosion, landslides and debris flows. The report of the Tillamook Bay Task Force and others (1978) analyzed the five watersheds and concluded that landslides (natural or man-induced) are numerous in all basins. The Wilson and Trask watersheds produced a significant occurrence of landslides; the steep and highly weathered volcanic bedrock combined with ample hydrology produced slope failures in all basins within the watershed.

Subsurface Geologic Analysis of the Tillamook Bay Alluvial Plain

The Tillamook alluvial plain is underlain by fine-grained marine sedimentary rocks and associated volcanic rocks. The DOGAMI (1972) concluded the material is of low porosity and permeability, and that water yield in the study area is low. The groundwater movement is oriented down gradient (west to northwest). Discharged groundwater provides much of the fluvial network base flow during the summer dry season.

The majority of subsurface data was extracted from water well logs. In 1972, DOGAMI analyzed 61 well logs for water yield, but little subsurface geology analysis had been completed. From published well log sections (DOGAMI 1972), a geologic fence diagram was constructed, and illustrates the complex nature of riverine and deltaic sedimentation patterns and/or processes (Plate X). Well number 81, Trask River Bridge at Highway 101, and well number 65 (at Tillamook County fairgrounds) illustrate transgression and regression sedimentation patterns. Data indicates that the marine sediments are progressively transgressed by terrestrial (alluvial plain) sediments. Coupling current sea level elevation and sediment delivery patterns shows that bay infilling will continue. Deltaic zone growth and riverine transgression sedimentation will fill the eastern bay area. Initially the eastern section (east of the tectonic ridge) will fill and low volumes sediment will pass the ridge and deposit in the bay proper.

Flooding

Preliminary investigations by DOGAMI (1972) revealed that clogging of the lower streams and bay by silting was not the primary cause of flooding in the floodplain areas. The effect of high ocean tides driven farther ashore by gale force winds was a far greater cause of flooding. The report concluded that any advantage in getting floodwaters to the ocean as quickly as possible by dredging would depend on the simultaneous occurrence of flooding conditions and the ebb and slack tide. Such an occurrence would be purely coincidental and not dependable. Commonly, the high ocean tides would combine with stream flooding to overflow the deepened channel ways regardless of the dredging effort.

Basin Forest Fire History

Fire history in the Tillamook Bay Basin can be traced to the late 1800s. The earliest identified fire affecting the watershed was in 1845 (Johannessen 1961; PWA 1996); this fire was an intentional fire started in the Willamette Valley (Marion County), which crossed over the Coast Range Mountains and burned large sections of the upper watershed.

Minor fires occurred in the lower mountain area between 1845 and 1880. The Soil Conservation Service (1978) provides a conceptual diagram of historic major fires in 1918, 1933, 1939, 1945, and 1951 (Figure 1). Based on documented fire events, sediment delivery rates and volume are qualitatively produced. Understanding the complex fire history of the Tillamook Bay Basin provides vast knowledge about the history of the sediment problem in the basin. The timing and fire patterns provide an understanding of sediment supply and the delivery of sediment to the basin channel network.

A fire map produced by the Tillamook Bay Task Force and others (1978) illustrates the complex fire sequence in the basin. Mapping by the Oregon Department of Forestry (1990) and imagery analysis of the 1933 fire called the “Tillamook Burn” shows that this fire burned a total of 239,695 acres. As shown in Table 6, the total acreage burned by subsequent fire events decreased to about 32,700 acres in 1951.

Figure 1. Estimated Sediment Rates from Major Fires, 1875 to 1975

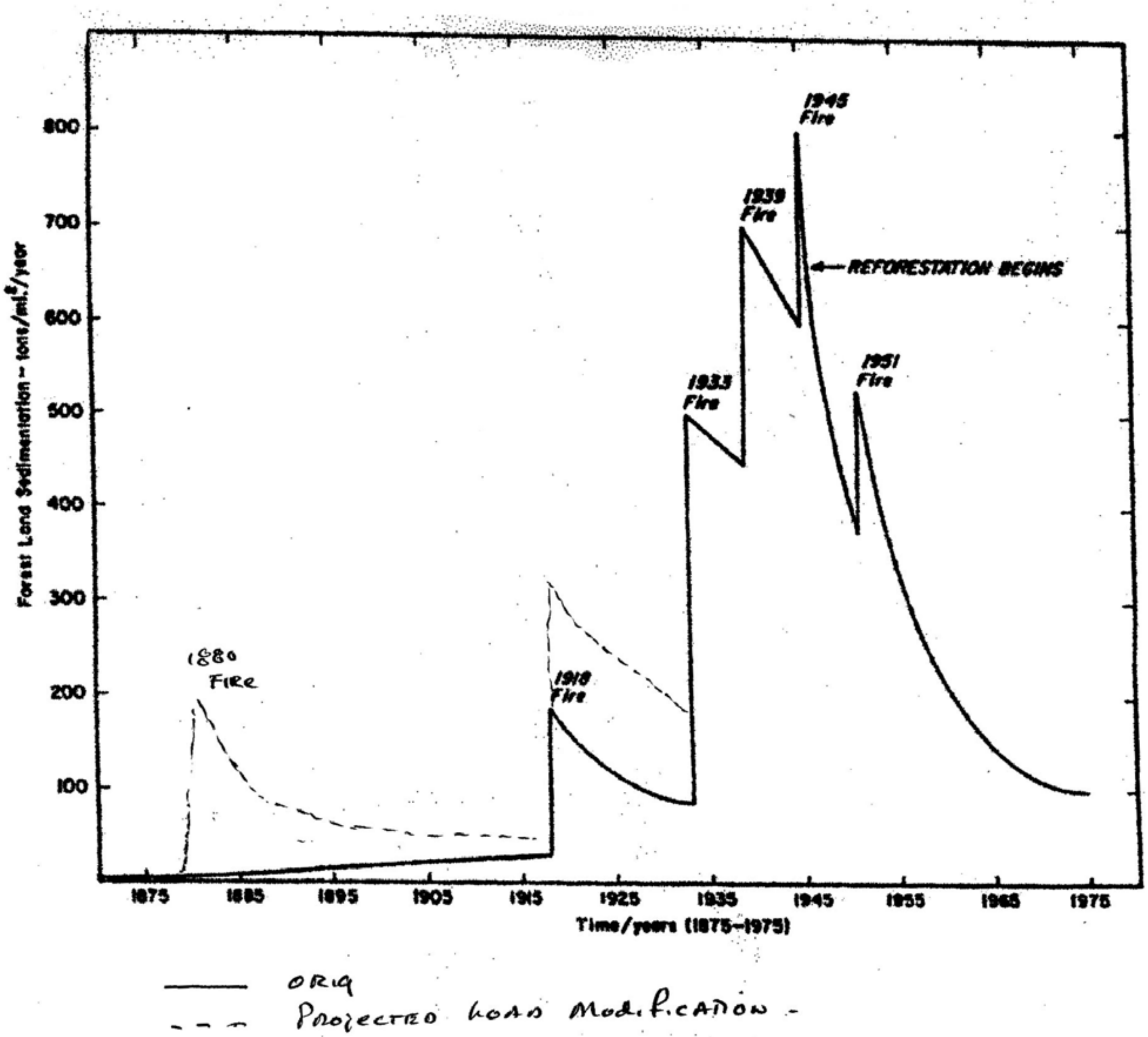

Table 6. Burn Acreage for the Tillamook Fires in 1933, 1939, 1945, and 1951

Year	Perimeter Area of Fire (acres)	Unburned Area in Perimeter (acres)	Previously Burned (acres)	Burned Area (acres)
1933 Fire	261,222	21,527	---	239,696
1939 Fire	209,690	19,030	15,527	189,660
1945 Fire	182,370	2,240	10,899	180,130
1951 Fire	32,700	N/A	N/A	32,700
Fires Combined	360,882	5,946	---	354,936

Source: Modified after Oregon Department of Forestry 1990

The following findings can be linked to sediment production in the river network of the Tillamook Bay Basin (Plate 1).

- Large portions of the Tillamook Basin had been burned by turn of the 20th century.
- The first major fire in the Tillamook Basin in the 1900s was in 1918.
- In 1933, the first and largest in a series of fires burned large sections of the basin, including the Miami, Kilchis, and Wilson River drainages and minor areas of the Trask River drainage.
- Fires in 1939, 1945, and 1951 reburned the northern sections of the basin as well as burning unburned forested areas in the western sections of the upper watershed. The fire pattern extended to the southern basin.

After the Tillamook Burn in 1933. salvage of fire-killed timber resulted in a rapid increase in timber harvest. Harvest peaked in 1952 at about 610 million board feet after the last major fire in 1951. The fires and salvage logging left thousand of acres bare to coastal winter storms. Erosion processes were accelerated and thousands of tons of sediment were washed into the streams to eventually be deposited in the river systems and bay. However, the amount of sediment and its rate in reaching the bay has been reduced since the reforestation program became effective (Tillamook Bay Task Force et al. 1978).

Figure 2 provides a qualitative sediment load in tons per square mile per year for the fire noted. Based on the fire history, the 1918 fire sediment load appears to be under represented. The 1918 fire was the first major fire in the 1900s and its large geographic extent would indicate sediment load to be higher than presented by the Tillamook Bay Task Force (1978).

Figure 2 provides a modification to the sediment load volume, based on additional fire history analysis. The 1880 fire would have increased the sediment delivery to the channel network. The volume of the 1918 fire sediment load has been increased to reflect the geographic extent and the time period between the earlier 1880 fire. This graphic shows qualitative values combined with some numerical values. Regardless, the fire process will increase sediment supply, and an increase in sediment supply will produce modifications to the channel network.

The Tillamook Bay watershed is 89% forested uplands (TBNEP 1998); based on data presented in Tables 1 to 4 (Tillamook Bay Task Force et al., 1978), the current forest conditions account for almost 85% of the sediment yield. During a 29-year period (1918-1951), fire exposed over 70% of the upper basin to the direct impact of winter rains and storm systems. Under "natural" conditions, the Tertiary volcanic rocks lack a high degree of competence. Combining geology with topography, climate, and fire would increase the occurrence of slope failures. As the number of slope failures increased, the total sediment supply also increased.

Sea Level Variations

Modern deposition and erosion of river-borne sediment in the Tillamook Bay estuary began about 9,000 years ago when rising ocean levels entered the river valley (which had been formed by earlier ocean fluctuations). People who watch the recording fathometer in a fishing boat often see it trace the profile of a submerged shoreline as the boat passes a water depth of about 300 feet. This submerged shoreline was the coast when the last ice age was at its maximum, about 15,000 years ago. Dry land extended seaward (west). As the last ice age ended, melting glaciers shed great torrents of meltwater into the oceans, rapidly raising the sea to about its present level (Kraft 1971).

The rising ocean submerged the lower courses of the coastal rivers and then flooded into their new mouths, which converted them into tidewater estuaries and bays. Nearly every large stream becomes an estuary as it approaches the coast. Waves sweeping sediment along the beaches built sand spits across the mouths of the estuaries, converting them into nearly enclosed bays now shoaled with deep fills of trapped river mud. River water flowing out through the bar maintains an inlet connecting the bay to the open ocean. In short, this describes the last 15,000 years of geologic history of the Tillamook Bay Basin.

Following the natural progression of geologic events, the Tillamook Bay estuary will fill with sediment delivered by short drift and headland erosion and stream transport to the bay. Stratigraphic and radiocarbon analyses show that the Holocene fill in Tillamook Bay began to accumulate sometime before about 9,000 years ago (Glenn 1978) in deep parts of refill river valleys. According to Glenn (1978), the rate of accumulation generally coincides with the rates of worldwide sea level rise at a faster rate (greater than about 3 meters per 1,000 years) up to about 7,000 years ago, and at a slower rate (less than 2 meters per 1,000 years) since that time.

Effects of Sea Level Change

Komar and others (1997) analyzed the bathymetric data and concluded that the bay volume has risen 1.5 millimeters per year. From 1887 to 1954, they calculated the rate of bay sediment accumulation at 68 centimeters per 100 years. Core data found sediment deposits that correlate with the fire history in the western sections of the bay. Calculation based on this data indicates that sedimentation rates could exceed 79 centimeters per 100 years when coupled with sea level fluctuations. Currently, the Corps is revisiting this issue. Combining these conditions, the calculations show that sediment deposition is an active process in the bay-deltaic river zone.

Upper Watershed Segment

The five major rivers chiefly drain areas of volcanic and associated sedimentary rocks of Eocene age in the Oregon Coast Range (Walker and MacLeod 1991). Small streams and tributaries, and parts of the lower Tillamook and Miami Rivers, drain areas of sedimentary rocks of Oligocene to Miocene age in the rolling hills adjacent to the southern and northern margins of the Tillamook Bay area. Quaternary age gravels, sands, silts, and clays underlie terraces and floodplains in the lowlands around the City of Tillamook (Plates 1 and 2).

In the upper Tillamook Basin, landslide/mass movement topography is extensive. These mass failures are developed primarily in the soft and weathered Oligocene-Miocene sedimentary rocks, and in the sandstones and siltstones of the Astoria Formation. Relatively stable areas do occur in the Miocene volcanic rock units at Cape Meares and in the undifferentiated Eocene volcanic rocks in the southeastern section of the study area. The southern shoreline area of Tillamook Bay in the Tillamook River Basin also appears stable. The sandstone in these areas is assigned to the Astoria Formation. The lack of topographic relief aids in the stability factor. The Wilson River foothills area is dominated by mass movement features, which generate a knob and swale topographic pattern.

Major Watersheds

Miami River. The Miami River is the northern-most watershed in the Tillamook Bay Basin and in the study area. The total drainage basin covers about 36 square miles. The headwaters are about 14 miles to the east in the Coast Range. The highest point elevation in the drainage is approximately 1,700 feet above sea level. Only the lower 2 miles of the Miami River are included in the study area. According to the Corps (1972, 1977), this section has an average slope of 16 feet per mile. In the upper reaches, flows through Coast Range Tertiary volcanic rock have eroded deeply incised gorges and narrow canyons before opening to a wider alluvial plain. The alluvial plain and deltaic morphology dominate the 2-mile study reach.

Kilchis River. The Kilchis River is just south and east of the Miami River. The total drainage basin covers about 87 square miles and is 21 river miles long. The geology and terrain of the Kilchis is similar to that of the Miami watershed; its headwaters are in Coast Range Tertiary volcanics and have eroded a deep, narrow canyon before exiting onto the alluvial plain and flowing into the bay. Although a long river, the Kilchis River has slopes in its upper reaches exceeding an average of 50 feet per mile. The study reach is from river miles 5 to 0, and has a slope of about 8 feet per mile. Alluvial plain and deltaic morphology are dominant in the study reach.

Wilson River. The Wilson River flows about 44 river miles before entering Tillamook Bay. Only the lower 9 river miles are in the study area. The total drainage area is 193 square miles. The highest elevation is near Round Top Mountain at nearly 2,200 feet above sea level. The river’s average slope though the study area is about 6 feet per mile. Upland geology is again mainly Tertiary volcanics forming narrow steep gorges with rock-lined reaches. At the mountain apex, the alluvial plain becomes unconfined. Sedimentation processes control the western fluvial slope. The lower most portion flows across a wide but confined floodplain to the bay. The history of the Wilson River watershed is comparable to the other drainages in the study area; high erosion, impacts from several forest fires between 1930 and the early 1950s, and logging operations were common.

Trask River. The Trask River watershed encompasses about 176 square miles and the river is approximately 31 miles long. When combined with the Wilson, these rivers form the majority of the alluvial plain of the Tillamook Bay Basin. The Trask River is to the south of the Wilson River and northeast of the Tillamook River. Ten river miles comprise the study area with an average slope of 6 feet per mile. Both the Trask and Wilson Rivers are comparable; Tertiary volcanics and deep rock-lined gorge sections are evident before reaching the mountain apex. A large complex alluvial plain develops and slopes to the bay.

Tillamook River. The Tillamook River is the southern-most watershed. The headwaters drain a small upland valley at about 400 feet above sea level. Although it has a total river length of 17 miles, only river miles 0 though 2 are in the study area. The lower 8 river miles have a slope of 3.8 feet per mile; the slope in the study area appears to be less. The river flows through flat broad terrain and margins with the Trask River on the southern side of the bay. The total drainage area is 61 square miles but during major flood events, flood water can cover more than 2,300 acres. Geomorphically, the Tillamook River is a minor contributor of sediment, although it has a major impact during floods.

Deltaic – Bay Segment

Deltaic Setting and Processes

The concept of the delta is one of the oldest in geology, dating back to 400 B.C. when Herodotus observed that the alluvial plain at the month of the Nile was similar to the Greek letter Δ. The term has been used for this geographic feature ever since. The basis of the modern three-fold classification of deltas was established by Fisher and McGrowen (1969; also see Galloway 1975), who proposed a subdivision into river-, wave-, and tide-dominated types.

A delta is a body of sediment laid down by dynamic sedimentary processes in a zone of interaction where a river (fluvial system) enters a deeper and less turbulent body of water. When the fluvial system is large or a multi-river system (like the five rivers of the Tillamook Basin and the body of water of Tillamook Bay), the resulting sediment body is a product of complex sequences involving multiple environments ranging from fresh to saline water. The precise nature, horizontal and vertical distribution, and relative importance of the environment are determined by the characteristics of the river regime, coastal processes at work, the structural geologic setting, and climate factors (Fairbridge and Bourgeois 1978).

In the Tillamook Basin delta, the rivers regime involves a large load of fine-grained sediment; an appreciable range between high and low river stages; low wave energy, littoral current (if one), and tidal ranges in Tillamook Bay; active regional or local coastal submergence by rising sea level (Vincent 1989); and a climate that allows a variety and density of different vegetation. These variables have interacted within the context of cyclic and progressively slowing sea level modifications produced from the Holocene time. Both depositional and erosional processes have been involved.

There have been few, if any, attempts to provide basic interpretations and to illustrate the distribution and sequence of Tillamook Bay delta complexes; those that do exist have been frequently modified. One of the most widely referenced basic models is that of Kolb and VanLopik (1958) who initiated the much-copied "lollipop" diagram approach. Their model was used to define the Mississippi River delta complex and illustrates the complexity of these environments, the impact on river sedimentation processes, and other events.

Deltaic distributions are the most conspicuous of the subaerial environment and are evident because of the natural levee ridges that flank the stream channels. The pattern of distributions forms the skeletal framework of this multi-river delta complex. As long as distributary channels actively receive sediment, the mouth of the rivers will progress seaward at a rate directly related to the amount of discharge and sediment load, as well as the depth of the receiving body of water, Tillamook Bay. Distributary natural levee formation essentially involves the same fluvial processes that are generated to produce those in the alluvial plains and upland areas of the Tillamook Basin; however, a few differences in morphology and lithology do occur. The levees are more uniform in height and width, because far less meandering takes place in the distributary channels. Mean sea level is the dominant elevation-controlling factor. Rather than being laterally gradational with backwater, natural levees of the lower deltaic plain grade into and/or are interfingered with interdistributary deposits and bay-river deposits.

A variety of depositional environments occur in the deltaic plain. However, it is not within the scope of this report to provide a detailed deltaic analysis.

4. GEOMORPHIC SEDIMENTATION AND TRANSPORT CONCEPTS

River systems and tributary channels are important avenues of sediment transport that deliver eroded material from the upper hill slopes to the low agricultural lands. Variability in sediment delivery, hydraulic discharge, and channel slope give rise to spatial and temporal variations in channel morphology and response. Analysis and time-scale relationships provide an overview of channel response to changes in discharge and sediment supply from both land use and climatic conditions.

The river system of the Tillamook Bay Basin ranges in size from small ephemeral rivulets to the five major rivers draining the basin. Over decades to centuries, channel morphology has been influenced by both local and systematic downstream variation in sediment supply from upper basin hill slope processes, the ability of the channel network to transport these loads downslope and down-basin, and the effects of vegetation on channel processes.

Channel adjustments that altered discharge and sediment supply include changes in width, depth, velocity, slope, sediment size and roughness (a hydraulic element). The basic keys to understanding or describing the physics governing channel processes and to illustrate control on channel processes include the conservation of energy; sediment transport; flow of water through the channel network and at any point along a channel; energy dissipation by channel features; and geometry of the active channel zone.

The frequency and magnitude of precipitation events are documented for the Tillamook Bay Basin; these events cause both erosion and maintain channel geometry. Topographic relief of the upper basin provides the potential energy that drives these processes. Downslope movement of water converts the potential energy into kinetic energy, which is dissipated by friction and turbulence generated by the channel bed and bank.

Channel Response

Channel confinement influences channel response. Channel migration and avulsion are typically rare in confined channels. All upper watershed areas of the Tillamook Bay Basin are bedrock controlled. Channel geometry or migration and avulsion are linked to the geologic time scale. At the upland-to-valley transition area, channel configuration is unconfined. These unconfined channels form floodplains. Over time, out-of-channel bank events widen the floodplains and aggradation occurs.

Debris flows are a primary sedimentation agent of channel disturbance in the upland or mountain areas of the basin. Debris flows tend to be pulsed disturbances, the effects of which vary with slope and position in the watershed. Sediment transport of debris flow material can scour the steep channel to bedrock, depositing large volumes of sediment in the lowlands or floodplain areas. Benda and Cundy (1990) assess the potential impacts of debris flows, and differentiate areas of potential debris flow initiation, scour, and deposition.

The relatively simple set of channel processes noted above results in a wide array of possible channel responses to changes in sediment supply, discharge, and external influences such as woody debris flow obstruction. In response to changes in sediment supply or discharge, altered bed forms, or particle size, the channel system may widen, deepen, and/or change its slope through aggradation, degradation or modifications to channel sinuosity.

Channel Changes and Sediment Supply

There is extensive literature using both empirical evidence and conceptual models that show channel changes and common responses. The basic physics of channel change reveal a wide range of responses to changes in sediment supply; channel change can induce channel widening and aggradation, decrease channel features through pool filling, and decrease bed sediment size. Increased discharge can cause channel widening, incision, and bed armoring. The response of a river system to increased sediment supply depends on the ratio of transport capacity to the sediment supply. Significant aggradation, channel widening, bed filling, pool filling, or braiding occurs where the amount of introduced sediment overwhelms the local transport capacity. Pulse- or slug-type sediment delivery combined with mass movement or hill slope failures are the major cause of sediment supply to a river system. This generates spatial and temporal variability in sediment supply that will govern channel morphology in different reaches of the channel network.

5. Landforms and Geomorphic Processes

Erosional and Depositional Landscapes

The shape of a river channel is a consequence of the interaction of discharge or flow and the bed and bank boundary conditions. Flow in the river reacts to the bed and bank conditions or topographic features, such as bank roughness, gravel bars, pools and riffles, and sediment supply, as well as the boundary shear stress fields that control the sediment movement patterns. These processes adjust the channel morphology to maintain equilibrium by combining flow conditions, boundary shear stress fields, and cross-sectional patterns of sediment transport. Simply stated, if one process fluctuates, there will be a response in the other two processes. For example, an increase in sediment without an increase in flow or discharge conditions will result in deposition. On the other hand, erosion could occur with an increase in flow/discharge without modification of the other components.

Fluvial Environments and Processes

Mountainous sections in the Tillamook Bay Basin are volcanics of Tertiary age, which are highly weathered and subject to mass movements and other types of slope failure processes. Little, if any, consideration of geomorphic processes has occurred, other than slope failures with respect to logging actives. All investigators in the last several decades agree that upland slope failure is the major contributor to the current sediment loading process, which is currently passing through the basin. Watershed analysis in the early 1970s (DOGAMI 1972, 1973; Tillamook Basin Task Force et al. 1978) illustrate the variety and extent of slope failures and their linkage to weathering, erosion, and winter storms impacting the volcanic rocks in the upper basin. Harr (1983) and Hicks (1991) couple logging road construction, winter storms, and slope failure with increased sediment loading. Analyses in 2000-2001 (Bischoff et al. 2000, 2001) assessed watersheds with and without roads and concluded that there was a greater hydrologic impact to watersheds with roads. Again, slope failure was the dominant geomorphic process delivering sediment slugs to the current channel networks. The upper basin areas supply both sediment and hydrologic energy. All of the river basins have a rock “gorge” which increases the fluvial energy and transport capacity (Plate 4). Downslope, the river networks pass the mountain apex on to the alluvial plain. The Wilson and Trask Rivers dominate the main Tillamook Bay Basin to form an alluvial fan complex. The Tillamook and Kilchis Rivers add to the complex lower in the system and closer to the deltaic-bay zone. The Miami River has no geomorphic linkage.

The alluvial fan complex created by the rivers of the Tillamook Bay Basin has a complex depositional and erosion history. Alluvial fans have been recognized and investigated by geologic and geomorphologists since the mid-19th century, but mostly in arid climates where fans are exceptionally well developed. In the Tillamook Bay Basin, fans have not been delineated or are indefinite as a dominant landscape feature. From analysis of the basin and associated landforms, alluvial fans appear as the major geomorphic feature.

Alluvial fans typically occur at the mouths of drainage basins and are large-scale morphological features built up by bedload streams and in humid climates, by streams with high-suspended loads. Fans of all types develop where the stream emerges from the confines of a valley or gorge area into a basin. Exiting the confinement, degrees of freedom are obtained allowing for the horizontal expansion of the flow, deceleration, and deposition of some or the entire sediment load. The emergence from the valley or mountainous region into a basin will commonly be associated with a reduction in gradient, and this further favors deceleration and deposition (Plate 4). This geographic setting defines the Tillamook Bay study area. Basins into which fans build are quite variable (Knight 1975). The Tillamook Basin is adjacent to the Pacific Ocean in a tectonically active zone. Although vertical elevation is a function of many geomorphic processes, sediment supply, hydrology, and tectonics normally dominates.

The typical fan shows a decrease in slope from the apex, close to the point of emergence, to the toe giving a concave upwards profile. The Wilson/Trask fan complex illustrates the classic slope with the distal reaches entering the bay complex. This simple profile is commonly broken into a series of segments. Each slope segment has a roughly even slope; however, the slope of the segments decreases sharply at deposition or erosion zones along the profile in a proximal to distal traverse (Bull 1964) and ending in the bay. These segments can be attributed to pulses of tectonic activity, climatic or catastrophic events with the upper basin. Short-term catastrophic events illustrate sedimentation pattern changes on a human time scale. They may be associated with episodes of fan incision and/or growth where the main channel will migrate across the fan complex inducing erosion or deposition (Photo X).

The down-fan reduction in slope is commonly associated with a reduction in grain size, particularly the maximum particle size; data from the Gravel Harvest Study (Stinson and Stinson 1998) illustrates that size reduction is a process acting on the Wilson, Miami, and Kilchis Rivers. Tillamook Basin fans are classified as humid fans (dominated by a major stream channel). Historic records and subsurface data sets are lacking because of drill/well depth and geographic position in the basin. Gole and Chitale (1966) indicate that a time period of 250 years may be required for major channel migration (without human impact upon the landscape). A time period of this length is not possible in the Tillamook Basin.

Where coarse sediment is supplied from the upper watershed areas, as exemplified by the massive forest fires of the 1930s to early 1950s, fan development and channel modifications are common. Modifications include a downstream change from a meandering stable channel system, to a channel complex with upstream sheet bar complexes, to large or numerous individual gravel bar complexities. This progression from a highly developed gravel sheet bar complex is illustrated by the comparison of aerial photographs from 1939, 1965, and 2000 (Plates 4 to 14). Downstream bar complexities change to longitudinal/lateral bars and point bars; as gravel supply reduction occurs, bars die out or acreage and number is reduced.

Channel Pattern

Investigating the change in channel pattern or plan form is a major method used to study various aspects of changing river channels; it can be used to determine the impact on fluvial landforms and development on the alluvial plain created by sedimentation processes.

Changes to a channel's plan form can take place by bank erosion, deposition within the channel, and by chute development or avulsion involving a channel switching positions and gravel bar complex development. For streams in the Tillamook Basin that had an abundant sediment supply until the mid 1950s, the material in the channel is apt to be "overloose" and easily entrained. With the decline in total sediment supply since the mid 1950s, gravel transport has declined and fine-grained sediment transport has continued.

Each river basin has a dominant channel system and typical floodplain morphology. Relict channel (sloughs) are clearly visible in the lower reach of the fans/alluvial plain (Plates 4 to 14). The sloughs in the lower reach still function as passages during high water events. Human activities and apex channel stabilization have reduced access and function during high flow events. By 1939, the sloughs in the upper alluvial plain have been separated from the active channel. Geomorphically, main channel distributary separation generates an increase in bed aggradation and gravel bar erosion, and sediment supply is reduced by reforestation after the early 1950s. Bed aggradation should induce flooding on the upper alluvial plain, and fine grain deposition with an increase in alluvial plain in the upper reach near the apex. Flooding and floodwaters concentrate in the depressions of the relict channel/slough segments along the alluvial plain. Bed aggradation and distributary separation appear to present a drainage pattern that is an underfit system within the confines of the dominate channel on the alluvial plain.

In-channel Features: Form and Function

Depositional features occur when and where the flow velocity is insufficient to carry the sediment size or amount of material in the fluvial area. There are typical locations within a channel where deposition occurs, and the coupling of these sites and depositional shapes are classified as bar. The dominate type of bars or bar complexes found on gravel-bed rivers of the Tillamook alluvial plain will be presented to aid in understanding the geomorphic function.

Point Bar-Gravel Bar Types

Point bars are characteristic of meandering river systems (regardless of the sediment load) and tend to extend in the channel direction and downstream. They generally form parallel to the eroding bank line. The gravel unit will occur near the convex bank, and it often possesses a steep outer slope and a high water chute or secondary channel landward from the water. Sediment gradation is common in the up and down stream direction on the bar, along with a vertical grading. Gravel bars can grade into the floodplain if sediment loading is greater than transport capacity.

Mid-Channel Bars. These are single bar units that are common features in river systems that have received too much sediment. They are more numerous than point bars. Based on sediment load and hydrology, evolution to small island complexes may develop. Their diamond shape directs flow to the river banks causing bank line flow impingement, which can induce bank erosion or sequence vertical accretion and bank line attachment.

Lateral Bars. These are bars which occur as an attached bar with the bank line or terrace complex and are most commonly found in straight reaches of the channel. Based on form and function, they are sediment storage sites in a gravel or sand river. Their number and acreage appears to correspond to sediment load.

Diagonal or Transverse Bars. Diagonal bars form obliquely across the channel system and are not parallel to the flow. At full development stage, the complex will be attached to both banks. The bar slopes upward in a downstream direction with an avalanche face at the downstream end. Diagonal bar complexes were identified during this assessment.

Bars are established where material is deposited from the bedload. This occurs where the traction force of the stream declines. Typical locations for bars are at the apex of the channel fan and channel reaches where resistance to flow increases and slack water may occur along the convex bank; at places where the channel widens; and at channel junctions where the less powerful contributory may be in backwater. No formal criterion will be presented for the occurrence of bars in light of flow and sediment characteristics. Bars strictly defined as accumulations of sediment grains cannot occur if the flow depth (*d*) is approximately equal to the mean grain size (D).

Four major bar types were analyzed during the gravel bar investigation. Smith (1974) and Church and Jones (1982) identified gravel bar and/or gravel complex geomorphic development and sedimentation implications. Table 7 presents a gravel bar classification combined with morphology, function and sediment impact. The sediment storage function provided by Table 7 is the key function and method used to interpret the geomorphic process controlling the fluvial landform of the alluvial plain and distal deltaic reaches.

Table 7. Classification of Gravel Bar Formation and Function

Morphology	**Function**		
	Hydraulic Resistance	**Sediment Storage**	**Equivalent Bar Unit**
Attached			
Asymmetrical	Diagonal riffle	Lateral bar Point bar	Diagonal bar
Symmetrical	Transverse riffle	Transverse bar Channel junction bar	Transverse bar
Detached			
Asymmetrical	------	Point Bar or river bend spur	Longitudinal bar Transverse bar
Symmetrical	Longitudinal riffle	Medial bar	Longitudinal bar Transverse bar
Formation	River-bed: deformation by erosion/deposition; Non-fluvial: emplacement	Channel size: adjustment by deposition	Simple deposition

Source: Modified after Church and Jones, 1982

The bar surface is composed of lag concentrations of relatively coarse materials one grain thick which, at the proximal bar end, may be as coarse as those found in the adjacent channel. Both point bars and some detached bars will have a high water chute or channel landward of the main bar. In mature gravel bar complexes, this feature is active in high flow events. This zone is a non-aggrading channel and aids in island and mid-channel bar formation. Sediment storage bars become more prominent in channel systems as traction load sediment increases in abundance. As sediment supply/load normalizes, the geomorphic processes reverse. Analysis of the Wilson, Trask, and Kilchis Rivers demonstrate these processes. After the 1950s, sediment supply processes were declining due to reforestation in the Tillamook Burn areas.

Backswamp/Floodbasin

A backswamp/floodbasin in geomorphic terms is a flat, shallow, poorly drained, typically swampy or marshy floodplain area bounded by natural levees and other topographic high features. Some of these topographic high features are engineered for river stabilization. During overbank flood events, fine-grained sediment accumulation is the dominant geomorphic process. Some researchers may class this zone as intra-tidal marsh. The geomorphic environment is coupled to the deltaic and riverine zones and will not be discussed separately.

Crevasse splays are discrete mini-delta or thin lobes of sediment deposited on the distal side of natural levees and at the river-bay interface. A splay becomes a slight topographic rise or feature. These depositional features are coarser than the average natural or deltaic sediment because channelized floodwaters have a higher sediment transport capacity than floodwaters occurring as sheet flow. An increase in total sediment load coupled with high flow events also will produce crevasse splay deposits (cover photo of Kilchis River, 1939).

6. FLUVIAL AND GEOMORPHIC ANALYSIS

The Miami River has very limited aerial photographic data. While the Kilchis, Wilson, and Trask Rivers have historic and current aerial photographs (1939, 1965, 2000), only the 2000 photos had complete coverage of the study area. Longitudinal profiles were constructed from 1978 data sets from the Federal Emergency Management Agency (FEMA), and 2000 data sets from the Corps and Tillamook County. Field observations during high and low water periods provided first hand information, qualitative in nature.

Miami River Geomorphology

The Miami River Basin is dominated by gravel storage. Currently, no sediment source areas appear visible in the basin. Fine-grained sediment deposition is the controlling geomorphic process at the river-bay zone. The Miami River is the smallest of the watersheds in the Tillamook Basin. It drains heavily wooded steep terrain and appears to have a moderate slope to the bay. Geographically, the Miami River Basin is narrow and lacks major human development. The study reach is 2 miles in length, from river miles 0 to 2 (Plates 5 and 6).

The basin showed less sign of hill slope erosion or slope failure than the other river basins. Sediment storage sites are dominant in the basin. There were no identified long transport reaches. Numerous temporary storages sites indicate that this river is transport limited. Being transport limited means that high volumes of sediment can and are normally transported only during high flow or flood events. Flow would appear to be flashy and short in duration. Alder is the main riparian vegetation, and there is a lack of large woody debris within the active channel of the river. In the transition reach between the uplands and the lowlands (agricultural lands), the gravel bar complexes increase both in spatial and temporal occurrence. The large silt and sand bar-delta near the river's mouth indicates that a high volume of fines is transported out of the basin. The relationship of fines to gravels constituting the bar complexes should be analyzed.

River Miles 2-1. The Miami River is a gravel-rich system based on the high number of small lateral and point bar complexes; there appears to be a substantial supply of sediment to the river. Thalweg pattern appears to be stable and a riparian zone is present throughout the reach. Floodplain and riverbed elevations are within 4 to 6 feet in elevation difference. The channel appears stable and at high flow or flood events, it easily leaves its banks flowing onto the surrounding floodplain. Bed elevation data indicates minor bed aggradation averaging from 2 to 4 feet. The data sources and their differences may create a minor elevation difference, which could be plus or minus 1 foot based on professional judgment (Plate 6). Nevertheless, bed elevation data tends to indicate a net gain from 1978 to 2000. This net gain supports the analysis of a channel system laden with sediment. Based on the fire history, the system is adjusting to historic sediment loading and transport capacity.

River Miles 1-0. Bed aggradation appears to be dominant in the upper 0.5 mile. Erosion or degradation appears to be the dominant geomorphic process in the lower reach until just upstream of the Southern Pacific Railroad/Highway 101, where bed aggradation again is dominant. Although few gravel bar complexes occur in the reach, those that do occur are geographically small. Downstream of the Southern Pacific Railroad/Highway 101, deposition/bed aggradation is dominant. Riparian development appears equal in density and acreage as described for river miles 2 to 1.

In summary, bed aggradation is the dominant geomorphic process for the Miami River. Reduction of sediment delivered pre-1960 is still being passed through the system. Complexity and channel narrowing also could have occurred, based on findings on the Trask, Wilson, and Kilchis Rivers. It appears that minor amounts of engineering actions have been undertaken on this river. The Miami River could represent the prototype for the Tillamook Bay Basin: a system in transition from sediment rich and transport low, to one that is now moderate in sediment load but with the same hydrology. As the bed aggrades, this could lead to channel migration or a catastrophic channel relocation across the alluvial plain (Plate 5 and 6).

Kilchis River Geomorphology

The upper reaches of the Kilchis River appear limited in sediment supply. The fluvial processes are competent to transport the volume of material supplied. At the transition zone, deposition with minor bank erosion are the controlling geomorphic processes. Transport is the controlling process on the Kilchis River (Plates 7 to 10).

Channel morphology from the bay to the upland displays a channel system competent to transport a full range of sediment. The steep upper basin provides energy and sediment. Normal riffle pool morphology is dominant in the upper reaches in this bedrock-controlled channel. During storm events, hill slope failure and mass movement result in debris torrents cascading through the system. The November 1999 storm event is just one example. High sediment loading occurs and transport continues until transport energy is reduced or sediment supply depleted. At the transition zone, transport energy is reduced resulting in gravel deposition. This process occurs basin wide. Bank cavitation appears to constitute a major geomorphic process in the upper watershed. The amount of sediment generated by these processes would not compare to that generated by hill slope failures. Fine-grained sediments are passed to the bay. Overbank flooding occurs in the lower basin and appears to flow in “old” channels that cross the lower valley area and cause aggradation. Floodplain aggradation could induce active channel erosion and transport a higher volume of sediment to the bay.

River Miles 5-4. Between 1939-1965, the active channel appears to have undergone widening along with a reduction in the number and type of gravel bars (Tables 8 and 9). This reduction is coupled to an area reduction. There is a reduction in riparian zone area and density from 1939 to 1965. Basic channel morphology shows no significant modification. The increase in channel width in this reach could explain the loss or reduction in the riparian zone. Overall bar number is constant but total area appears to have decreased. This reduction can be accounted for by the development of a mid-channel island just up-channel from river mile 4. A new channel has developed along the right descending bank line in a high water chute across the 1939 point bar (Plate 7).

Table 8. Kilchis River Channel Features, 1939

River Mile (RM)	Channel Feature Acreage						Total
	Island	BD	LL	LR	HWC	PT	
RM -1 to 0	---	---	---	---	---	---	---
RM 0 to 1	---	---	0.36	1.8	---	---	---
RM 1 to 2	---	---	7	0.82	---	0.51	---
RM 2 to 3	---	2.1	0.55	1.59	---	9.82	---
RM 3 to 4	---	2.82	5.63	7.84	---	0.36	---
RM 4 to 5	---	0.01	4.34	1.16	---	6.78	---
RM 5 to 6	---	0.03	3.28	0	---	---	---
TOTAL	0.00	4.96	21.16	13.21	0.00	17.47	**56.80**

Key: Island = Vegetated Island
BD =Mid Channel Bar
LL = Lateral Bar, Left Bank
LR = Lateral Bar, Right Bank
HWC = High Water Channel
PT = Point Bar

Table 9. Kilchis River Channel Features, 1965

River Mile (RM)	Channel Feature Acreage						Total
	Island	BD	LL	LR	HWC	PT	
RM -1 to 0	---	---	---	---	---	---	---
RM 0 to 1	---	---	---	---	---	---	---
RM 1 to 2	---	0.13	3.23	---	---	1.47	---
RM 2 to 3	---	0.05	0.31	1.05	---	2.87	---
RM 3 to 4	---	0.7	0.94	5.46	---	0.18	---
RM 4 to 5	2.43	0.88	2.01	1.44	1.65	0.05	---
RM 5 to 6	---	---	2.13	---	---	---	---
TOTAL	2.43	1.76	8.62	7.95	1.65	4.57	**26.98**

Channel Feature Change Factor from Previous Photo Date

River Mile (RM)	Island	BD	LL	LR	HWC	PT
RM -1 to 0	---	---	---	---	---	---
RM 0 to 1	---	---	---	---	---	---
RM 1 to 2	---	---	0.5	---	---	2.9
RM 2 to 3	---	---	0.6	0.7	---	0.3
RM 3 to 4	---	0.2	0.2	0.7	---	0.5
RM 4 to 5	---	88.0	0.5	1.2	---	---
RM 5 to 6	---	---	0.6	---	---	---

Note: Change factor represents magnitude of acreage change of gravel deposits from 1939 to 1965 as observed from aerial photographs. For each respective river mile, a factor of 10.0 represents a ten-fold increase in the acreage of gravel bars from 1939 to 1965. A factor of 0.5 represents that the acreage of gravel bars was reduced to one half from 1939 to 1965.

Key: Island = Vegetated Island
BD =Mid Channel Bar
LL = Lateral Bar, Left Bank
LR = Lateral Bar, Right Bank
HWC = High Water Channel
PT = Point Bar

From 1965 to 2000 (Plates 8 and 9), there was a two-fold increase in total gravel bar number, coupled to a reduction in total gravel bar area (Table 10). This bar development displays no major impact on the morphological pattern of the channel reach. Some engineering features were constructed in this reach over the last 5 years. Sediment trapping and bar growth is appears to be the resulting short-term development. These actions appear to have induced a degree of stability to the reach and the riparian zone has redeveloped in both area and density since 1965. Comparison of longitudinal profile data is not possible due to the lack of data above river mile 4.

Table 10. Kilchis River Channel Features, 2000

River Mile (RM)	LL	LR	HWC	PT	Total
RM -1 to 0	---	---	---	---	---
RM 0 to 1	0.35	0.45	---	0.45	---
RM 1 to 2	2.75	0.86	---	1.25	---
RM 2 to 3	2.1	0.44	---	1.78	---
RM 3 to 4	3.61	1.77		2.57	---
RM 4 to 5	2.21	2.95	0.65	0.01	---
RM 5 to 6	0.05	0.18	0.33	2.52	---
TOTAL	11.07	6.65	0.98	8.58	**28.82**

Channel Feature Change Factor from Previous Photo Date

River Mile (RM)	LL	LR	HWC	PT
RM -1 to 0	---	---	---	---
RM 0 to 1	---	---	---	---
RM 1 to 2	0.9		---	0.9
RM 2 to 3	6.8	0.4	---	0.6
RM 3 to 4	3.8	0.3	---	14.3
RM 4 to 5	1.1	2.0	0.4	0.2

Key: LL = Lateral Bar, Left Bank LR = Lateral Bar, Right Bank
HWC = High Water Channel PT = Point Bar

River Miles 4-3. This reach of the Kilchis River has undergone the highest degree of geomorphic modification. In 1939, large point bars and mid-channel bar complexes had developed. These gravel complexes were serving as temporary in-channel sediment storage locations or zones. High sediment supply was generated as a result of the massive forest fires in the Tillamook Basin during the summer of 1932. The bare and highly decomposed material in the upper basin was laid bare to the winter rains. The coupling of these processes is the major factor in development of a channel system highly laden with sediment. By 1965, these gravel complexes were still dominating the channel geomorphic processes. Gravel bar consolidation reduced the total number of gravel bar complexes. There were still large point and mid-channel bars within the reach, however.

With the reforestation of the upper watershed, sediment supply has been reduced. During storm events, however, “natural” slope erosion processes would still be on going. These processes would still deliver sediment to the channel network. Channel data from 2000 indicates an increase in stability and an additional reduction in sediment supply. The profile slope shows an increase in slope. With the reduction in the number of mid-channel gravel bar complexes, there was a shorting of channel length resulting in the increase in slope. Bar size was reduced with the increase in slope and the reduction in total sediment supply. Combined with these processes, the large bar complexes were divided by erosion resulting in an increase in the development of lateral bar complexes. This reach was a sediment storage reach in 1939 and 1965. By 1965, the volume of sediment in temporary storage in this reach was on the decline. Longitudinal profile data from 1978 and 2000 indicate that the upper half was an erosion and transport zone, whereas the lower half was in pseudo-equilibrium. The riparian zone appears simpler in 1939 and 1965. Density and area show no major variations. Increased channel stability between 1965 and 2000 also provided for an increase in the riparian zone area and density.

River Miles 3-2. Channel complexity and gravel bar development show a marked decline from 1939 to 2000 (Plates 7 to 10). Gravel bar growth appears to have stopped, whereas erosion and transport of the gravel deposited from 1939 to 1965 was underway. In 1939, there were seven main gravel bar complexes; by 1965, the number was reduced to five and they were smaller in area. By 2000, the number of gravel bars had increased again to seven as in 1939, whereas the area of gravel storage was four-fold less. Channel stability also increased based on the area distribution and density of the riparian zone.

During the 1965 period, gravel harvesting occurred on one of the major point bars within the reach. The duration of this activity and the long-term geomorphic impact are unknown; the short-term impact would have been minor. This reach converted from a sediment storage reach in 1939 to a transport reach by 2000. Analysis of the longitudinal profile data from 1978 and 2000 provides proof that the reach slope increased and degradation dominated. Degradation indicates a shortage of sediment supply in this reach plus a reduction in total sediment supply/input in the system.

River Miles 2-1. Sediment in temporary storage was reduced from 1939 to 2000. Large lateral gravel bar complexes were reduced in size and complexity by a combination of fluvial processes. Fluvial erosion in conjunction with a developing riparian zone contributed to increasing the channel stability and bar erosion. The riparian zone though river mile 2 increased in area and density. Temporary sediment storage sites remained geographically constant from 1939 to 2000. The number appears to have maintained a constant value. The channel width appears to have been reduced. Channel stabilization has increased with a reduction in gravel bar size and an increase in riparian zone development.

Slope data indicates a flattening and some aggrading. Erosion is dominant in the upper reach while aggrading and slope reduction control the lower half of the reach. Combining these conditions results in a channel reach that is less complex. The stable channel morphology increases the transport processes reach-wide. During the period of record, there appears to be little channel modification, resulting in a reach that is transgressing to greater stability and sediment transport efficacy.

River Miles 1-0. This reach shows very little geomorphic modification from 1939 to 2000 (Photograph 1). Channel width and plan-view pattern have remained constant. Gravel bar development throughout the time period also appears constant (less than 3 bars). The lower quarter of the reach is subject to minor mounts of narrowing. Controlling factors appear to be coupled to delta processes in the inertial zone and flushing of gravel sediment to the bay. Bar erosion or development shows no variance from 1939 to 2000. Riparian zone reduction is the norm, which is opposite riparian development upstream of river mile 1.

Aerial photographic analysis for 1939,1965, and 2000 indicate splay deposits along the lower half of the reach. A major deposit is present on 1939 imagery and can still be detected on 2000 imagery. There is no longitudinal profile data, so analysis is not possible. The geologic setting and ongoing processes in the river/bay transitional zone are predominately aggrading. Field observations indicate gravel has been and is being deposited in this lower zone. Large flow events serve as the conveyance element.

In summary, Tables 8-10 show gravel bar data for the Kilchis River in 1939, 1965, and 2000. Analysis of this data indicates that the total number of gravel bars decreased from 1939 to 1965; the number then increased to 1939 values in 2000. Gravel bar acreage decreased from 56.8 acres in 1939 to 22.9 acres in 1965, and to 26.7 acres in 2000. The large acreage in 1939 could be linked to the massive forest fires occurring in the upper basin in 1932. Subsequent fires from 1932 to 1950 aided sediment supply to all rivers within the basin. Reforestation and lack of massive forest fires after 1950 has reduced sediment supply. Hydrologic conditions have not changed over the last 100 years (Corps 2001).

Discharge data is only available for the Wilson River. High flow events occurring throughout the basin generally have similar conditions and hydrologic conditions appear to have maintained basic values. Based on this assumption, only sediment supply and/or input values have undergone modification. High sediment supply was generated as a result of the massive forest fires during the summer of 1932. The bare and highly decomposed material in the upper basin was laid bare to winter rains. The coupling of these processes is the major factor in development of channel system highly laden with sediment. By 1965, gravel complexes were still dominating the channel geomorphic processes. Gravel bar complexes, both in aerial extent and number, were reduced from 1939 to 1965, which reworked and redistributed the temporarily stored sediment.

Analysis indicates the Kilchis River is less complex, more stable, and has larger and denser riparian zones. Sections of the lower river from river miles 2-3 are aggrading in areas from river miles 2-3 that are dominated by transport; the reach from river miles 3-5 appears to be stable. Input and output could be relatively equal. The dominant river process in 1939 was sediment input and temporary storage. There was a greater supply of sediment than energy to transport the sediment load. By 1965, the Kilchis River was still sediment rich and transport poor. Gravel development was still high, but transport was reducing the volume (number and size) of gravel bar complexes. A state of pseudo-equilibrium was becoming dominant. In 2000, the Kilchis River appears to be sediment poor. Sediment reduction along with no major fluctuation in hydrologic conditions is creating a high energy/transport system. The inverse, which occurred from 1939 to 2000, created a river system that can transport a high amount of sediment during major flow events. Sediment movement terminates in Tillamook Bay, at the river/bay transition zone. Sedimentation is resulting in aggradation at the river mouth (river mile 0 and into the bay), (Plates 7 to 10).

Kilchis River Overlap Analysis

Six river miles of the Kilchis River under went continuity or overlay analysis. River patterns based on 1939, 1965, and 2000 aerial photographs produced spatial and temporal river pattern data. Table 11 presents this data. Based on the analysis, 48.5% of the Kilchis River is non-congruent. Only 4.0% or 3.7 acres are congruent between 1939 and 2000. This indicates that a long-term degree of river freedom exists. Continuities increased to 13.0% or 21.5 acres by comparing river continuity or overlay for 1965 and 2000 (Plate 10).

Table 11. Kilchis River Channel Overlap Analysis, 1939-1965-2000

Length	Overlap	Kilchis River	Acreage	% of Total
5.26 miles	0	No Overlap	44.1	48.5
	2	1939/2000 Overlap	3.7	4.0
	3	1965/2000 Overlap	11.9	13.0
	4	1939/1965/2000 Overlap	21.5	23.6
	Total Acreage (for all 3 years)		90.9	---

Note: “Overlap” is the attribute in the Arc/View shape files.

This data shows that the Kilchis River Basin hydrology has remained constant during the period of record resulting in a constant transport capacity and a non-steady sediment supply. Variations in sedimentation rates and in channel geomorphic processes have induced channel pattern modifications; gravel bar complexes and bed aggradation and degradatation indicates A system that is still out of phase or a river system that is in non-quasi-equilibrium is generated. (Tables 8, 9, and 10, Plate 10). High sediment supply and sediment in transport prior to the early 1950s have impacted fluvial processes. After the 1950s, sediment supply and sediment in transport have progressed to a new quasi-equilibrium condition, a system dominated by bed aggradation and a reduction in gravel bar complexes. Channel slope conditions have modified as bed aggradation reaches impact the channel processes (Plate 10).

Comparing 1965 and 2000 channel positions, overlap percentage has increased (Table 11 and Plate 10). As overlap or congruence increases, channel freedom decreases and stability appears to increase. Increased channel stability appears coupled to a reduction in transport capacity and an increase in out-of-channel flow higher on the alluvial plain. Human impacts are currently not measurable. Nevertheless, they have reduced channel freedom and appear to add to a sense of channel stability.

Wilson River Geomorphology

Sediment supply is the controlling geomorphic process in the upper drainage of the Wilson River. Debris flows and erosion sites are numerous in the upper area. The river is sediment driven and high sediment supply feeds the upper system. Erosion and transport are dominant in the uplands. At the transition zone, deposition and floodplain aggradation are dominant. The river appears rich in sediment within the active channel and in the lowest terraces associated with the active channel. The upper river is bedrock controlled with a veneer of sediment stored in the active channel area. Numerous locations occur that indicate historic and current mass movement events in the upper watershed. Hill slope failure is the main geomorphic process currently delivering sediment to the channel. The river also appears to have a large volume of sediment in temporary storage within the active channel. The size of this sediment deposition is unknown. No estimations are present of possible volumes of transport, other than to say there is a high possibility that a large volume of sediment is available for transport during major flow events. The amount of woody debris on channel bar complexes and terrace deposits appears high. This could increase channel blockage and increase possible erosion/sediment transport to the lowlands (Plates 11 to 14).

River Miles 8-7. These upper river miles represent a major temporary sediment storage reach. From 1939 to 2000, there was a reduction in total acreage from 10.31 to 7.97 acres Tables 12 to 14). Temporary storage appears to be dominant. Riparian density and acreage show a similar increase. Channel stability shows an increasing tendency and conversely, channel complexity appears to decrease. Thalweg migration was normal during the period. Combining these conditions shows a channel reach with high transport and in-phase with the sediment supply entering and exiting the reach. Development of a stable riparian zone aids channel bank stabilization. Flood photographs show that floodwater exits the channel in this reach. This energy reduction reduces sediment transport and bank erosion. Bed elevation data illustrates minor bed aggradation for the period of record (1978 to 2000, Plate 14).

Table 12. Wilson River Channel Features, 1939

River Mile (RM)	Channel Feature Acreage						Total
	Island	BD	LL	LR	HWC	PT	
RM -1 to 0	4.49	---	---	0.28	---	0.4	---
RM 0 to 1	2.58	---	0.07	0.01	---	---	---
RM 1 to 2	---	0.26	---	---	---	---	---
RM 2 to 3	---		0.8	0.26	---	0.88	---
RM 3 to 4	---	0.04	2.03	1.05	---	---	---
RM 4 to 5	---	3.79	9.9	10.42	---	3.12	---
RM 5 to 6	1.13	---	1.32	3.71	---	8.32	---
RM 6 to 7	1.54	---	2.65	3.19	2.6	8.23	---
RM 7 to 8	3.63	---	1	1.47	4.03	---	---
TOTAL	13.37	4.09	17.77	20.39	6.63	20.95	**83.2**

Key: Island = Vegetated Island; BD =Mid Channel Bar; LR = Lateral Bar, Right Bank; HWC = High Water Channel

LL = Lateral Bar, Left Bank PT = Point Bar

Table 13. Wilson River Channel Features, 1965

River Mile (RM)	Channel Feature Acreage						Total
	Island	BD	LL	LR	HWC	PT	
RM -1 to 0	---	0.75	0.25	---	---	---	---
RM 0 to 1	---	1.65	---	0.76	---	---	---
RM 1 to 2	---	---	0.34	0.05	---	---	---
RM 2 to 3	---	0.03	0.46	0.06	---	0.23	---
RM 3 to 4	---	0.43	---	0.22	---	1.19	---
RM 4 to 5	---	0.38	0.7	0.69	---	5.73	---
RM 5 to 6	---	0.05	0.1	0.53	---	9.15	---
RM 6 to 7	---	12.01	10.64	4.5	1.03	---	---
RM 7 to 8	---	---	3.03	2.81	2.16	0.84	---
TOTAL	0	15.3	15.52	9.62	3.19	17.14	**60.77**

Channel Feature Change Factor from Previous Photo Date

River Mile (RM)	Island	BD	LL	LR	HWC	PT
RM -1 to 0	---	---	---	---	---	---
RM 0 to 1	---	---	---	76.0	---	---
RM 1 to 2	---	---	---	---	---	---
RM 2 to 3	---	---	0.6	0.2	---	0.3
RM 3 to 4	---	10.8	0.0	0.2	---	
RM 4 to 5	---	0.1	0.1	0.1	---	1.8
RM 5 to 6	---	---	0.1	0.1	---	1.1
RM 6 to 7	---	---	4.0	1.4	0.4	---
RM 7 to 8	---	---	3.0	1.9	0.5	---

Note: Change factor represents magnitude of acreage change of gravel deposits from 1939 to 1965 as observed from aerial photographs. For each respective river mile, a factor of 10.0 represents a ten-fold increase in the acreage of gravel bars from 1939 to 1965. A factor of 0.5 represents that the acreage of gravel bars was reduced to one half from 1939 to 1965.

Key: Island = Vegetated Island; BD =Mid Channel Bar; LL = Lateral Bar, Left Bank; LR = Lateral Bar, Right Bank; HWC = High Water Channel; PT = Point Bar

River Miles 6-7. Temporary sediment storage in this reach peaked in 1965 with 28.18 acres of gravel bar complexes. Channel width and complexity also peaked during this period. The riparian zone was under attack by bank erosion and gravel deposition. Although there was nearly 10 additional acres in 1965 than in 1939, both years had five gravel complexes. A three-fold decrease in gravel bar array occurred by 2000, but there was no significant reduction in bar count. Riparian density and acreage shows a major increase by 2000 (Plates 11 to 14). Bed elevation data for 1978 and 2000 indicate that the complete reach was aggrading. Coupling this process to complexity, an increase in riparian zone, and gravel storage indicates a channel in pseudo-equilibrium with the hydrologic and sediment conditions. Stabilization of the riparian zone and bed aggradation indicates a possible reduction in channel discharge capacity. Floodwaters appear to exit the channel system upstream of river mile 7.

Table 14. Wilson River Channel Features, 2000

River Mile (RM)	Channel Feature Acreage						Total
	Island	BD	LL	LR	HWC	PT	
RM -1 to 0	0.04	0	---	1.88	---	---	---
RM 0 to 1	0.09	---	0.38	---	---	---	---
RM 1 to 2	---	---	---	---	---	0.18	---
RM 2 to 3	---	0.29	0.26	0.86	---	---	---
RM 3 to 4	---	0.51	1.08	0.26	---	---	---
RM 4 to 5	---		1.99	0.07	0.13	2.35	---
RM 5 to 6	---	0.04	1.79	0.67	0.27	3.26	---
RM 6 to 7	---	0.37	4.13	1.28	---	2.55	---
RM 7 to 8	---	0.96	5.13	---	---	1.88	---
RM 8 to 9	---	---	---	0.31	---	---	---
TOTAL	0.13	2.17	14.76	5.33	0.4	10.22	**33.01**

Channel Feature Change Factor from Previous Photo Date

River Mile (RM)	Island	BD	LL	LR	HWC	PT
RM -1 to 0	---	---	---	---	---	---
RM 0 to 1	---	---	---	---	---	---
RM 1 to 2	---	---	---	---	---	---
RM 2 to 3	---	9.7	0.6	14.3	---	---
RM 3 to 4	---	1.2	---	1.2	---	---
RM 4 to 5	---	---	2.8	0.1	---	0.4
RM 5 to 6	---	0.8	17.9	1.3	---	0.4
RM 6 to 7	---	---	0.4	0.3	---	---
RM 7 to 8	---	---	---	0.0	---	2.2
RM 8 to 9	---	---	---	---	---	---

Key: Island = Vegetated Island
BD =Mid Channel Bar
LL = Lateral Bar, Left Bank
LR = Lateral Bar, Right Bank
HWC = High Water Channel
PT = Point Bar

River Miles 5-6. Over the study period, major changes to the channel thalweg have modified this reach. From 1978 to present, the lower half of the reach has undergone the brunt of the thalweg perturbations along with bed degradation. In 1939, there was 14.48 acres of temporary storage in 5 major gravel complexes; the number of gravel complexes has decreased to 4 with only 6.03 acres. An increase in acreage and density in the riparian zone also occurred, inducing a stability increase and a reduction in complexity.

River Miles 4-5. In 1939, this reach was highly complex and was dominated by massive areas and numbers of temporary gravel sites (Photograph 2 and Plate 11). Lateral gravel bars were dominant (Table 12). Lateral gravel bar complexes indicate high sediment transport rates plus a high degree of channel complexity. High flow or storm events increase the occurrence of bank erosion and general aggrading in association with the large lateral gravel bar complexes. The resulting process is a reduction in riparian zone, an increase in temporary sediment storage, and aggrading. By 2000, temporary storage sites decreased from 27.23 to 4.54 acres. Analysis of bed elevation data from 1978 to 2000 shows that bed elevation has increased. Coupling this data with channel thalweg data supports a reduction in both complexity and acreage of temporary sediment storage locations.

River Miles 3-4. Channel stability in this reach increased from 1930 to 1965. Bar area and number of temporary gravel complexes also decreased and are coupled to the increase in stability. Sediment reduction in bar number and area produced a decrease in channel complexity. Bank erosion resulted in minor degrees of channel path/thalweg migration. From 1939 to 1965, riparian vegetation is comparable, and by 2000, the density and acreage of the riparian zone showed a marked increase (Plates 11 to 13).

River Miles 2-3. During the study period, this reach was in pseudo-equilibrium with hydrology and sediment supply. Temporary sediment volumes declined in 1965 and 2000, reflecting increasing stability and sediment production in the upper watershed. Channel narrowing is the dominant geomorphic process occurring from 1965 to 2000. Riparian zone area and density increased from 1939 to 2000. Channel path stabilization resulting from sediment supply supported the increases in these zones along the reach.

River Miles 1-2. No major geomorphic channel modification occurred from 1939 to 2000. Engineering operations have restricted major channel perturbations. Gravel bar complexes also reflect minor sedimentation process within this reach. Lack of gravel storage locations indicates a transport section. Discharge and sediment supply are in pseudo-equilibrium and long profile data support this position. Slope appears stable during the study period. Channel complexity is not a factor (there is none) (Plates 11 to 14).

River Miles Below 1. This reach has islands and a minor number of gravel bars. The presence of an island below river mile 1 indicates a high influx of sediment reaching the lower river bay/interface reach. Normal wave and tidal action could redistribute sediment delivered if this reach was in geomorphic equilibrium. The basin fire history supports high sedimentation. Constant hydrologic conditions will move sediment bayward mainly during storm/high-flow events. Island and bar development declined by 30% from 1939 to 1965, and declined another 10% from 1965 to 2000 (Tables 13 and 14). Factors controlling sediment transport can be coupled to reforestation of the upper watershed. Engineering operations in this reach have been undertaken, resulting in only minor sediment redistribution and minor river perturbations in the delta/bay dominant geomorphic zone.

In summary, the Wilson River is an aggrading system, and 7 of the 9 river miles analyzed are aggrading. Geomorphic data indicate the river is storing less sediment and developing a denser and wider riparian zone. Bed aggradation may be caused by a combination of natural and man-induced narrowing. Construction of revetments, levees, and other channelization features may be factors coupled to the aggrading nature of the Wilson River. A reduction in sediment supply or loading with no reduction in hydrology also appears to be factors. Bed aggradation may induce floodwater to exit the channel system at lower discharges.

Sediment supply/loading appear less based on fire and reforestation history. High sediment supply/load occurred from 1933 to the early 1950s. Fires laid bare the highly erosive volcanic material to winter storm events resulting in massive sediment delivery to the channel system. The lack of major forest fires during the last fifty years has resulted in a major reduction of sediment yield. During 1933-1951, the Wilson River was sediment rich and transport capability poor, resulting in a massive period of sediment transport from the upper basin to the bay. The reduction in acreage and number of gravel bar complexes from 1939 to 2000 indicates the river is transferring from sediment rich back to sediment normal, while maintaining the same hydrology. Bed aggradation appears coupled to riparian zone development and complexity reduction. Long profile data indicate pseudo-equilibrium of sediment introduced to the system and sediment in temporary storage (Plate 14). Riparian zone development reduces bank/bed erosion, only if high flow or flood events exit onto the floodplain near the valley apex. Observations of flooding during 1996 and 1999 indicate that this occurs. In-channel energy is reduced and sediment transport is reduced resulting in bed aggradation. Minor flood events appear to remove the gravel bar complexes and/or reduce their acreage and total number.

Wilson River Overlap Analysis

Table 15 shows a spatial and temporal discontinuity in the Wilson River geographic positioning for the study dates (1939, 1965, 2001). Total overlap or congruence is 24.4% or 58.8 acres from a total of 240.9 acres. Analysis of the data indicates a congruence increase over time. Coupling basin sediment supply and transport processes, end erosion events continuity will increase if sediment supply and delivery remain in the current state of quasi-equilibrium. Continuity overlap comparisons from 1939 to 1965 illustrate major spatial variations; data for 1965-2000 illustrate a reduction in the discontinuity, 7.9% to 12.2%. Channel freedom and in-channel transport capabilities appear reduced, resulting in reaches of bed aggradation (Plate 14).

Table 15. Wilson River Channel Overlap Analysis, 1939-1965-2000

Length	Overlap	Kilchis River	Acreage	% of Total
8.60 miles	0	No Overlap	127.5	52.9
	1	1939/1965 Overlap	19.1	7.9
	2	1939/2000 Overlap	6.0	2.5
	3	1965/2000 Overlap	29.5	12.2
	4	1939/1965/2000 Overlap	58.8	24.4
	Total Acreage (for all 3 years)		240.9	---

Note: “Overlap” is the attribute in the Arc/View shape files.

Basin hydrology has remained constant during the period of record, resulting in a constant transport capacity and a non-steady sediment supply. Variations in sedimentation rates and in-channel geomorphic processes have induced channel pattern modifications; gravel bar complexes and bed aggradation and degradation. This generated a river system that is out of phase or in non-quasi-equilibrium. High sediment supply and sediment in transport prior to the early 1950s have impacted fluvial processes. After the 1950s, sediment supply and sediment in transport have progressed to a new quasi-equilibrium condition, a system dominated by bed aggradation and a reduction in gravel bar complexes (Tables 12,13, and 15). Channel slope conditions have modified as bed aggradation reaches impact the channel processes.

Comparing 1965-2000 channel positions, overlap percentage has increased (Table 15 and Plate 14). As overlap or congruence increases, channel freedom decreases and stability appears to increase. Human impacts are currently not measurable. Nevertheless, they have reduced channel freedom and appear to add to a sense of channel stability. Combining geomorphic processes with the human impact shows that the Wilson River has lost a high degree of freedom or sinuosity, and ability to transport bed sediment. Bed aggradation is the effect, resulting in a reduction in channel cross-sectional area to convey discharge or the high flow events.

The gravel harvesting events of the 1990s are not distinguishable based on the type and temporal variables. No implied conclusion is stated as to the status of gravel harvest activities on the Wilson River.

Trask River Geomorphology

Sediment supply in the upper basin, by debris flow events, is the controlling geomorphic process in the Trask River. Transport and supply appear equal in the upper basin. Deposition controls the lower basin area. Fine grain deposition is aggrading the floodplain in the lower basin. Upper basin sediment supply and transport capacity appears in balance. This river appears to be the major sediment production basin in the Tillamook Bay Basin (Table 4).

The upper Trask River (upland reach) is bedrock controlled. Degradation and lateral movement are minimal and channel geometry is bedrock controlled (Plate 4). Sediment delivery appears to be coupled to hill slope failures (mass movement events), which could bulk to debris flows. The forested upland hills appear to supply a relatively small amount of large woody material (tree material). Lag deposits of this material are stranded along the high flow line or locked in the eroded cuts within in the bedrock bed. At the transition from uplands to valley, in-channel sediment storage increases. Lateral and point bar complexes are present. This reach has incised about 5 to 10 feet. Incision decreases bayward and transport of fine silts and sand volume increases. From the transition zone to the bay bank (river miles 0-3) section, bank erosion zones increase. The volume and size of sediment produced by this geomorphic process is unknown. The occurrence of tributary debris flow or blow out channels appears to increase the higher in the basin one proceeds. The steep hill slope failure occurrence requires additional analysis. The sediment bulking or loading in the upper watershed creates a channel system that is transport-limited during storm events (Plates 15 to 18).

River Mile 8-7. A zone of temporary storage is the controlling sediment process in this reach. Point bar features dominated sediment storage in 1939; by 2000, no point bar complexes existed (Tables 16 to 18 and Plates 15 to 17). Lateral bar occurrence trends decline in both acreage and number by 2000. The riparian zone shows a marked increase from 1939 to 2000, indicating a reduction in sediment load and channel plain view migration. The combination of these geomorphic processes indicates an increase in channel stability, which aids in the development of the riparian zone. Analysis of flood event photographs show that floodwaters are exiting onto the alluvial plain and inducing flooding. Aggradation processes are supported by the bed elevation increase data between 1978 and 2000.

Table 16. Trask River Channel Features, 1939

River Mile (RM)	Channel Feature Acreage						Total
	Island	BD	LL	LR	HWC	PT	
RM -1 to 0	---	18.63	---	---	---	---	18.63
RM 0 to 1	---	---	0.05	0.18	---	---	0.23
RM 1 to 2	---	0.41	---	---	---	---	0.41
RM 2 to 3	---	---	---	---	---	0.26	0.26
RM 3 to 4	---	---	---	1.32	---	0.08	1.40
RM 4 to 5	---	1.41	0.78	3.92	---	6.11	12.22
RM 5 to 6	---	0.18	8.38	13.30	---	---	21.86
RM 6 to 7	---	0.05	9.18	6.79	---	---	16.02
RM 7 to 8	---	---	6.51	---	0.32	12.27	19.10
TOTAL	---	20.68	24.90	25.51	0.32	18.72	**90.13**

Key: Island = Vegetated Island; BD =Mid Channel Bar; LL = Lateral Bar, Left Bank; LR = Lateral Bar, Right Bank; HWC = High Water Channel; PT = Point Bar

River Mile 6-7. Lateral bar complexes dominate the temporary sediment storage features in 1939, and the trend continues although acreage has been reduced (50.41 acres in 1939, 25.98 acres in 1965, and 14.72 acres in 2000; Tables 16 to 18). Channel pattern migrations declines and bed aggradation continues. Point bar development remains constant between 1965 and 2000. Bed aggradation and channel narrowing stability appears to increase. The riparian zone area and density also continues to increase. Stabilization of the riparian zone and bed aggradation indicates a possible reduction in channel discharge capacity. Floodwater exits the channel system to the alluvial plain in this reach (Photograph3). Return flow occurs in this reach, and data indicates that this is a major channel bank erosion process. The result is an increase in fine-grained sediment supply. Out-of-channel flooding deposits fine-grained sediment on the alluvial plain and induces minor alluvial plain elevation increases.

River Mile 5-6. Gravel bar complex area and number show a marked decrease form 1939 to 2000 in this reach. The trend is coupled with the geomorphic processes acting upon the lower basin (alluvial plain) by those events in the upper basin (mountain reaches). In 1939, gravel bar features accounted for 21.86 acres of sediment storage elements. Channel stability appears to have increased where temporary storage site areas have decreased. Riparian area and density are increasing because of slower migration and gravel transport. Longitudinal profile data indicates that bed degradation has occurred in the upper most section from 1978 to 2000 (Plate 18). Bed aggradation still dominates the reach, inducing channel cross-section reduction and increasing out-of-channel flood flows.

Table 17. Trask River Channel Features, 1965

River Mile (RM)	Channel Feature Acreage						Total
	Island	BD	LL	LR	HWC	PT	
RM -1 to 0	29.28	---	---	---	---	---	---
RM 0 to 1	---	---	0.61	0.32	---	0.1	---
RM 1 to 2	---	0.28	---	---	---	---	---
RM 2 to 3	---	---	---	---	---	0.13	---
RM 3 to 4	---	---	0.22	---	---	0.86	---
RM 4 to 5	---	---	0.67	1.83	---	3.23	---
RM 5 to 6	1.79	0.92	7.74	3.29	---	---	---
RM 6 to 7	---	0.31	8.1	2.71	---	0.82	---
RM 7 to 8	---	4.14	0.05	0.44	---	---	---
TOTAL	31.07	5.65	17.39	8.59	0	5.14	**67.84**

Channel Feature Change Factor from Previous Photo Date

River Mile (RM)	Island	BD	LL	LR	HWC	PT
RM -1 to 0	---	---	---	---	---	---
RM 0 to 1	---	---	12.2	1.8	---	---
RM 1 to 2	---	0.7	---	---	---	---
RM 2 to 3	---	---	---	---	---	0.5
RM 3 to 4	---	---	---	---	---	10.8
RM 4 to 5	---	---	0.9	0.5	---	0.5
RM 5 to 6	---	5.1	0.9	0.2	---	---
RM 6 to 7	---	6.2	0.9	0.4	---	---
RM 7 to 8	---	---	---	---	---	---

Note: Change factor represents magnitude of acreage change of gravel deposits from 1939 to 1965 as observed from aerial photographs. For each respective river mile, a factor of 10.0 represents a ten-fold increase in the acreage of gravel bars from 1939 to 1965. A factor of 0.5 represents that the acreage of gravel bars was reduced to one half from 1939 to 1965.

Key:
Island = Vegetated Island
BD =Mid Channel Bar
LL = Lateral Bar, Left Bank
LR = Lateral Bar, Right Bank
HWC = High Water Channel
PT = Point Bar

River Mile 4-5. Analysis of the gravel bar complex indicates a high volume of sediment was still in temporary storage in this reach. The trend shows a decline of 50% from 1939 to

2000. Gravel bar number also trended lower and channel migration and cross-sectional area show similar results (Tables 16 to 18, Plate 15 to 18). Longitudinal profile analysis indicates the lower 0.5-mile is trending to bed degradation, as compared to upstream aggradation. Meander pattern modification has decreased and stability appears to be increasing. Coupled to these geomorphic processes and sediment supply history, in-channel sedimentation processes have changed from depositional to erosional. Water well log number 81 (Highway 101 and the Trask River Bridge) shows that the Trask River is currently flowing through historic deltaic sediment (Plate 3). The fine-grained sediment requires less hydraulic energy for transport. During the dry period, bank dry raveling occurs and is then transported during higher flow event. The combination of up-area streambed armoring and lower reach bank erosion could increase fine grain sedimentation in the bay.

Table 18. Trask River Channel Features, 2000

River Mile (RM)	Channel Feature Acreage						Total
	Island	BD	LL	LR	HWC	PT	
RM -1 to 0	35	4.32	1.31	---	---	---	---
RM 0 to 1	---	0.3	0.97	0.35	---	0.07	---
RM 1 to 2	---	0.49	0.1	0.43	0.22	---	---
RM 2 to 3	---	---	0.34	---	---	0.09	---
RM 3 to 4	---	---	0.14	0.11	---	0.13	---
RM 4 to 5	---	---	0.79	1.55	---	2.01	---
RM 5 to 6	---	---	0.95	0.54	---	0.28	---
RM 6 to 7	---	0.14	0.77	3.59	---	0.94	---
RM 7 to 8	---	0.19	2.5	0.27	---	---	---
TOTAL	35	5.44	7.87	6.84	0.22	3.52	**58.89**

Channel Feature Change Factor from Previous Photo Date

River Mile (RM)	Island	BD	LL	LR	HWC	PT
RM -1 to 0	1.2	---	---	---	---	---
RM 0 to 1	---	---	1.6	1.1	---	0.7
RM 1 to 2	---	1.8	---	---	---	---
RM 2 to 3	---	---	---	---	---	0.7
RM 3 to 4	---	---	0.6	---	---	0.2
RM 4 to 5	---	---	1.2	0.8	---	0.6
RM 5 to 6	---	---	---	0.2	---	---
RM 6 to 7	---	0.5	0.1	1.3	---	1.1
RM 7 to 8	---	---	50.0	0.6	---	---

Key:
Island = Vegetated Island
BD =Mid Channel Bar
LL = Lateral Bar, Left Bank
LR = Lateral Bar, Right Bank
HWC = High Water Channel
PT = Point Bar

River Mile 3-0. In a reversal of sediment processes, 1965 and 2000 sedimentary features are more numerous and have more acreage than this reach had in 1939 (Plates 16, 17 and 18).

Bed degradation dominates river miles 2.5 to 4 and sediment transport exceeds deposition. This reach has been channelized by levees and other structures. The narrow and channelized section creates increased velocity resulting in a transport-dominated reach. Below river mile 0 to river mile 2.5, the deposition of fine-grained sediment is dominant. This deposition results in the development of island and bar complexes (Table 16 to 18, Plate 16 and 17). This depositional process occurs in all the Tillamook Bay Basin Rivers. Reduction in hydraulic energy results in deposition and the development of a sediment wedge.

In summary, the Trask River is an aggrading system with minor reaches of degradation. High sediment loads resulted from the forest fires of the 1930s to 1950s. The Trask is no different than the other rivers in the basin; during the 1930s to early 1950s, sediment supply exceeded transport capacity, which resulted in channel bed aggradation and a perceived increase in channel stability. The reduction in channel cross-sectional area and bed elevation resulted in an earlier out-of-channel flow with no increase in discharge rates. These geomorphic processes are "normal" and represent a channel system returning to a state of quasi-equilibrium. Observations during the 1996 and 1999 flood events indicate out-of-channel flow in the upper alluvial plain area. The reduction in gravel bar and island complexes from 1939 to 2000 support the findings that sediment supply is returning to "normal." Nevertheless, these "normal" volumes may be high and are a function of basin geology and climatic conditions.

Trask River Overlap Analysis

The Trask River overlap analysis (Table 19 and Plate 18) shows that only 23.7% of the total active river channel area occupies the same geographical location. A total of 116 acres or 48.8% of the total channel show no correlation in channel positions during the study period (Table 19). Years 1965 and 2000 show the highest degree of location correlation, 13.6% or 56.3 acres. Spatial and temporal discontinuities or continuities directly couple to channel stability. The higher the degree of discontinuity, the higher the degree of channel freedom, or channel migration (meandering). This geomorphic process is influenced by sediment supply, sediment in transport, basin discharge events or frequency of high flow events, channel slope, and human impact. Data presented indicates that basin hydrology has remained constant. Sedimentation processes have undergone a period of flux, impacting the quasi-equilibrium condition of the river system. High sediment supply and sediment in transport prior to the early 1950s impacted fluvial processes. After the 1950s, sediment supply and sediment in transport have progressed to a new quasi-equilibrium condition, a system dominated by bed aggradation and a reduction in gravel bar complexes (Tables 16 to 18). Channel slope conditions have been modified as bed aggradation reaches impact the channel processes.

Table 19. Trask River Channel Overlap Analysis, 1939-1965-2000

Length	Overlap	Kilchis River	Acreage	% of Total
8.20 miles	0	No Overlap	116.1	48.8
	1	1939/1965 Overlap	22.3	9.4

	2	1939/2000 Overlap	10.7	4.5
	3	1965/2000 Overlap	32.4	13.6
	4	1939/1965/2000 Overlap	56.3	23.7
	Total Acreage (for all 3 years)		237.7	---

Note: "Overlap" is the attribute in the Arc/View shape files.

Comparing 1965-2000 channel positions, overlap percentage has increased to 13.6% or 32.4 acres (Table 19 and Plate 18). As overlap or congruence increases, channel freedom decreases and stability appears to increase. Human impacts are currently not measurable. Nevertheless, they have reduced channel freedom and appear to add to a sense of channel stability. Combining geomorphic processes and human impact indicates that the Trask River has lost a high degree of freedom or sinuosity, and an ability to transport bed sediment. Bed aggradation is the effect, resulting in a reduction in channel cross-sectional area to convey discharge or high flow events.

Tillamook River Geomorphology

Deposition and aggradation are the dominant geomorphic processes in the Tillamook River. The river appears to have the lowest gradient of all rivers in the Tillamook Bay Basin. Only minor areas of gravel sediment are evident (Plate 19). The system generates a high volume of fine sediment. The river lacks the similar geomorphic forms of the other rivers in the basin. Upland reaches are non-descript forms; there is a low gradient channel and well-defined riparian zone. Bank cavitation is the primary sediment providing process. This type of bank failure supplies small woody material to the channel. The impact of this woody material to the overall system has not been quantified. However, the low channel gradient likely would not provide the sediment or discharge velocity for any channel impact associated with the woody debris. No transition reach appears within the system, which results in a lack of any major reach having temporary sediment storage. The lower river is confined by a set of low levees of unknown composition and engineering quality. During high flow events, water will overtop these structures resulting in lowland flooding. Tillamook County has identified these locations and has installed gravel ramparts to reduce erosion of the road prism. The lower river flows into the bay and may provide mostly fine-grained material.

Sinuosity and Longitudinal Profile

Meandering rivers are those having a sinuosity index of 1.5 or greater (Leopold et al, 1964). The sinuosity index is a ratio of channel length to down valley straight-line distance. Rivers with a sinuosity index below 1.5 are classified as straight or sinuous. However, this does not imply these rivers are lacking in symmetric curvature. Leopold et al. (1964) used this index to classify river channel morphology and stability. Assessment of sinuosity shows fluvial geomorphic processes and modifications over time. River patterns show no distinct boundaries but a continuum from one pattern type to another. Basin geomorphic events along with human activities will impact results of sinuosity analysis in the alluvial plain, as is the case for the Tillamook Bay Basin alluvial plain.

Nevertheless, the sinuosity index shows reaches that are confined or unconfined across the alluvial plain. Sediment supply, transport rates and slope combine to impact the sinuosity index and interpretations. The lack of sediment yield and transport volumes in the basin are unknown with the exception of the 1978 general erosion volumes. Linking basin history, longitudinal profile, and sinuosity analysis indicates that a number of reaches are still responding to geomorphic events occurring in the early half of the century. Analysis completed by Philip Williams and Associates and others (PWA et al. 2001) for 1955 and 1985 show minor modifications in the sinuosity index. A sinuosity index analysis for 1939, 1965 and 2000 was completed for this assessment and a comparison analysis performed. Sinuosity analysis was completed for the five rivers of the Tillamook Bay Basin (Miami, Kilchis, Wilson, Wilson, and Trask Rivers), as well as a longitudinal profile analysis for all rivers except for the Tillamook River. This is because the study reach composites for the lower 2 river miles are at or below mean tidal range. Analysis would fail to provide useable data sets. The concepts of stability and sinuosity show sediment supply declining from those of the pre-1950s. Bed aggradation is still a dominant geomorphic process, which increases channel bed and bank instability. Bed aggradation results in channel area reduction, allowing high flow events of decreasing discharge to exit the mainstem channel area. Systems that are sediment rich and manipulated by human activities (revetment-levee construction) respond by aggradation and down valley sediment transport. During major flow events, sediment slugs will phase through the river system.

Aggregating the individual river sinuosity, longitudinal profile, and gravel bar complex analysis to a basin model indicates channel adjustments are proceeding. Bed aggradation processes have reduced channel cross-section area and hydraulic energy. Channel stability appears to be increasing, along with an increase in riparian zone area and density (Plates 6, 10, 14, and18). The reduction in cross-section area appears to induce out of channel flooding at discharges that historically (pre-1950s) could be retained within the channel cross-section area. Gravel bar complex acreage and bars numbers have declined, indicating a basic reduction of sediment supply from the upper basin areas to a “normal” volume or rate. Quantifying the volume or rate currently is not possible without a detailed basin sediment budget study.

In select reaches, bed armoring will develop and induce additional gravel sediment trapping, which could increase fine grain sediment transport bayward. A reduction in gravel transport could increase bank erosion in the lower alluvial plain (river miles 0 to 4). Bank and bed erosion in the upper alluvial plain will remain low during channel forming discharges. Bank erosion will occur and couple with reach geomorphic conditions. Major periods of bank erosion or channel preparation will increase as aggradation continues. Combining these geomorphic processes could generate a major channel alignment from the mountain/upland apex and the upper alluvial plain. Gravel harvest activities along the upper channel reaches could prolong major channel migration. These activities could increase gravel size sediment transport rates though the system to the bay, and reduce the current stability conditions.

Miami River

The Miami River is a low sinuosity river and data indicates that river mile 4 and above have sinuosity indexes greater than 1.50, resulting in a classification of a meandering river reach. Sinuosity index values have remained constant (Table 20). Channel bed aggradation occurred between 1978 and 2000 (Plate 5). Channel migration across the alluvial plain during the last +100 years appears minimal. Bed aggradation appears to have induced a degree of channel stability. Coupling hydrology conditions and bed processes, there appears to be an increase in out-of-channel flow. This is a location and discharge event function. The increase in out-of-channel flow reduces the erosion impacts to bed and bank conditions. Less in-channel hydraulic energy equals to lower rates of bed and bank erosion, and in-channel sediment transport.

Table 20. Sinuosity Indices for the Miami River from 1939 to 2000

River Mile	1939	1955	1965	1985	2000
0.0-1.0	1.08	1.25	1.24	1.24	1.25
1.0-2.0	1.05	1.18	1.10	1.08	1.07
2.0-3.0	1.10	1.29	1.30	1.32	1.30

Note: Data for 1955 and 1985 is taken from PWA et al. 2001; data for 1939, 1965, and 2000 was developed for this assessment.

Kilchis River

Sinuosity and longitudinal profile analyses (Table 21 and Plate 10) illustrate the relationship between channel meandering and bed aggradation. Five different years of sinuosity data and two different years of longitudinal profile data show that the reach from river miles 2.0 to 3.2 is a meandering (sinuosity index >1.5) and aggrading reach. Gravel bar complexity, acreage, and development has declined from 1939 to 2000 (Tables 8 to 10). The analysis shows that:

- River mile <1: an increase in sinuosity, the long-term trend is downward.
- River mile 2-3: a meandering channel reach.
- River mile 2-3: an aggradation reach.
- River mile 1-2: a degrading reach and transport dominated reach.
- River mile <0-1: sinuosity increase and bed aggradation.
- Bed aggradation is occurring.
- A reduction in gravel bar complexes, in acreage and number.

Sediment deposition is dominant from river mile 1.0 and below. Deposition in this reach has formed a sediment wedge at the delta and river interface. Analysis of 1939 aerial photographs show that a large amount of gravel type material was deposited before 1939. Additional sedimentation has continued, but at a slower rate. Nevertheless, the rate is not quantifiable, and recent deposition has not completely obscured the 1939 deposition. Coupling this analysis and basin history, the Kilchis River is trending to a new condition of quasi-equilibrium. The reduction in sediment supplies and bed aggradation decreases the transport rate to the bay. Bed aggradation from river miles 2 to 3 increases out-of-channel flow and alluvial plain flooding.

Table 21. Sinuosity Indices for the Kilchis River from 1939 to 2000

River Mile	1939	1955	1965	1985	2000
0.0-1.0	1.27	1.37	1.40	1.43	1.38
1.0-2.0	1.05	1.15	1.10	1.06	1..04
2.0-3.0	1.62	1.82	1.81	1.81	1.78
3.0-4.0	1.11	1.21	1.20	1.21	1.20
4.0-5.0	1.09	1.08	1.05	1.02	101

Note: Data for 1955 and 1985 is taken from PWA et al. 2001; data for 1939, 1965, and 2000 was developed for this assessment.

Wilson River

Combining the five data sets of sinuosity analysis with the two longitudinal profile data sets shows that the Wilson River is trending to a new phase of quasi-equilibrium. The reduction in sediment supply from the upper basin, the constant hydrology and channel cross-sectional area reduction indicates a stable channel (Table 22 and Plate 14). The analysis shows that:

- River mile 0-3: a transport dominated reach.
- River mile 2-4: a low sinuosity-straight, engineered reach.
- River mile 4-6: a degradation dominated reach; sediment transport > deposition.
- River mile 5-6+: meandering channel; aggradation processes dominate; deposition is greater than erosion.
- A reduction in gravel bar complexes, in acreage and number.

Sinuosity index analysis indicates that from 1939 to 1985, the trend increased; the period from 1985 to 2000 illustrates an index reduction, but is still higher than the 1939 levels. Reaches of low sinuosity (river miles 1 to 4) appear to establish a balance between sediment supply, hydrology and is a transport dominated reach. River miles <0 to 1 is dominated by sediment deposition. A sediment wedge has developed and has increased in area, and illustrates an up-channel growth pattern. A reduction in channel cross-section and bed aggradation induces a factor of stability by a reduction of in-channel energy. This reduction is linked with sediment transport and channel cross-section erosion to reduce channel capacity. The reduction in channel capacity could increase deposition of large gravel material and a winnowing of the fine-grained material. This assessment is qualitative and will remain so until a basin sediment budget is developed.

Table 22. Sinuosity Indices for the Wilson River from 1939 to 2000

River Mile	1939	1955	1965	1985	2000
0.0-1.0	1.16	1.21	1.20	1.19	1.19
1.0-2.0	1.25	1.32	1.32	1.32	1.32
2.0-3.0	1.09	1.09	1.10	1.09	1.09
3.0-4.0	1.10	1.10	1.10	1.10	1.10
4.0-5.0	1.37	1.48	1.50	1.51	1.54
5.0-6.0	1.53	1.70	1.71	1.25	1.70
6.0-7.0	1.24	1.17	1.19	1.25	1.28
7.0-8.0	1.80	1.08	1.08	1.08	1.05

Note: Data for 1955 and 1985 is taken from PWA et al. 2001; data for 1939, 1965, and 2000 was developed for this assessment.

Trask River

Compiling the sinuosity analysis data conducted by PWA et al. (2001) and the data from analysis in this assessment shows that:

- In the study reach, sinuosity index is below 1.5.
- Sinuosity index analysis indicates an increase of less than 0.10.
- Minor sinuosity index values increase up-channel.
- River mile 7-8: lowest index values.
- River mile <0-1: no significant variations.
- River mile 2-4: 1939, 1955 and 1965 show minor increase in index values.
- 1985-2000: reduction in index values.

The sinuosity index (Table 23) and channel overlay and longitudinal profile (Plate 18) coupled with basin sedimentation pattern and processes appear to support an increase in channel stability. River miles 2-4 is a transport dominated reach where river mile 0-1 is dominated by finer-grained sediment deposition. Bar and island channel forms have developed and analysis indicates they have increased in size during the last 35 years. Above river mile 5, deposition processes dominate. Channel bed aggradation occurs from 1978 to 2000. This results in a reduction in channel cross-sectional area and a perceived increase in channel stability that could be linked with out-of-bank flooding at lower discharges.

Table 23. Sinuosity Indices for the Trask River from 1939 to 2000

River Mile	1939	1955	1965	1985	2000
0.0-1.0	1.07	1.08	1.10	1.12	1.10
1.0-2.0	1.09	1.09	0.09	1.12	1.11
2.0-3.0	1.11	1.21	1.24	1.18	1.15
3.0-4.0	1.14	1.15	1.15	1.19	1.20
4.0-5.0	1.06	1.05	1.05	1.08	1.12
5.0-6.0	1.09	1.14	1.12	1.18	1.15
6.0-7.0	1.13	1.15	1.12	1.16	1.15
7.0-8.0	1.02	1.03	1.01	1.11	1.10

Note: Data for 1955 and 1985 is taken from PWA et al. 2001; data for 1939, 1965, and 2000 was developed for this assessment.

Tillamook River

Only river miles 0 to 2 are included in the study reach. The Tillamook River is at or within the tidal range of Tillamook Bay. Because of this and the short study reach, no longitudinal profile was constructed; however, a sinuosity analysis of the reach was constructed. Data from years 1939, 1965 and 2000 were combined with that from PWA et al. (2001). The analysis shows that no sinuosity modifications have occurred during the study period (Table 24 and Plate 19).

Table 24. Sinuosity Indices for the Tillamook River from 1939 to 2000

River Mile	1939	1955	1965	1985	2000
0.0-1.0	1.12	1.12	1.11	1.10	1.10
1.0-2.0	0.04	0.04	0.03	0.03	0.03
2.0.3.0	1.12	1.08	1.09	1.08	1.09

Note: Data for 1955 and 1985 is taken from PWA et al. 2001; data for 1939, 1965, and 2000 was developed for this assessment.

7. Future Geomorphic Landscapes

Controlling Geomorphic Processes by River Basin

The river systems in the Tillamook Bay Basin are attempting to return to a state of quasi-equilibrium. Abnormally high sediment supply occurred from 1930 to the mid-1950s. Slope failure events in the upper basin areas dominated the geomorphic processes that were overloading the fluvial system. Deforestation resulting from the devastating forest fires between 1933 and 1951, the climatic conditions of the area, and the highly erodible volcanic and marine sediments combined to form the abnormally high sediment supply. Tables 25 and 26 summarize the controlling geomorphic processes for each river basin. Although the tables reflect the geomorphic processes occurring in each river basin, they are not site specific nor do they provide a numerical inventory solely as method of classification of these controlling processes (Photograph 4). Table 25 combines in-channel processes and sediment supply, and Table 26 links to external channel sediment supply and in-channel processes. Tables 25 and 26 represent a qualitative rating for the controlling geomorphic processes for each basin, and the values of high, moderate and low are used. This is only the initial phase for constructing a total basin analysis, which would consist of a basin-wide geomorphic framework and sediment budget.

Table 25. Internal Channel Sediment Supply Processes

River Basin - Geomorphic Processes ID for River Basins

River Basin	Cut Back Cavitation	Bar Erosion (Accretion or erosion)	Bed Movement (Aggradation or degradation)	Woody Debris in Channel or on Terrace
Miami River	Low	Low	Moderate	Low
Kilchis River	Moderate	Moderate	Moderate	Low
Wilson River	Moderate	Moderate	Moderate	Low
Trask River	Moderate	Moderate	High	Low
Tillamook River	Low	Low	Moderate	Low

Table 26. Basin Controlling Geomorphic Processes

River Basin - Controlling Geomorphic Process Degree/Rating

River Basin	Sediment Supply	Deposition/Aggradation	Erosion/Degradation
Miami River	Low	Moderate	Moderate
Kilchis River	Moderate	Moderate	Moderate
Wilson River	High	Moderate	Moderate
Trask River	High	High	High
Tillamook River	Low	Low	Low

This information provides an understanding of the controlling fluvial geomorphic processes shaping the Tillamook alluvial plain. The combination of external and internal geomorphic processes result in limiting the channel response. Hydrology data for the Wilson River (period of record 1930 to date; see Appendix A) indicates a constant energy source and/or stream power. During the high sediment supply period, in-channel energy and/or stream power capacity was overwhelmed by the sediment supply. After the mid 1950s to date, sediment supply reduction has occurred. Analysis shows channel freedom and migrations combined with major gravel complex development and migration. As the river systems exit the upper basin areas flow onto the upper Tillamook alluvial plain, a reduction of channel energy and/or stream power occurs, which results in gravel deposition and gravel bar development for several miles downstream of the valley apex on to the alluvial plain. With reforestation in the upper basin areas, the abnormally high sediment supply and delivery rates have declined. With this decline, or a return to a more "normal" sediment supply from the upper basin area, the transport capacity has increased (Photographs 5 and 6).

In-channel sediment transport has increased and the acreage and number of gravel bar complexes have declined. Gravel bar analysis (Tables 8-10, 12-14, and 16-18) shows a 2-fold reduction of gravel bar acreage and a reduction in bar number. Channel overlap analysis (Tables 11, 15, and 19) from 1939 to 1965 show that channel migration across the upper alluvial plain had a high degree of freedom. High volumes of gravel in transport or in temporary storage in the upper channel areas aided in increasing channel freedom (Plates 5 to 19). With the reduction in sediment supply, a corresponding reduction in channel freedom appears to have occurred.

Erosion of the gravel bar complexes occurred after the mid-1950s. The channels on the upper alluvial plain was still sediment rich resulting in unilateral bar development and erosion. Fine and medium grain sediment transport increased down the alluvial plain, channel dynamics were modified and resulted in bed aggradation in the upper and middle channel reaches of the Tillamook alluvial plain. The natural widening processes or increase in cross-sectional area was denied. This is a natural process in channel network development. This function is required to transport the combination of increased water volume and sediment. Channels on the lower alluvial plain have a larger cross-sectional area than that those on the upper alluvial plain or headwater areas. Cross-sectional areas of the channels on the lower and upper Tillamook alluvial plain have similar geometry (Plates 5 to 19). The channels of the Tillamook alluvial plain create a dichotomy in the pyramid concept of fluvial geomorphology. This means that the channel cross-sectional area will generally increase from the headwaters to the sink. The failure to allow the channel cross-sectional area to increase impacts the linkage between cross-sectional area, sediment transport, and discharge. Human activities also are coupled to the failure in allowing this geomorphic process to develop. The narrowing or failure to increase channel area in the lower alluvial plain results in the disruption of normal geomorphic events and/or processes.

Erosion and reduction in gravel bar complexes in the upper alluvial plain supports bed aggradation, an apparent increase in channel stability, and is associated with an increasing riparian zone (Photographs 5 and 6). The lack of cross-sectional area and migration freedom in the lower alluvial plain reduces the amount of sediment and the size of the sediment that can be transported through the lower channels to the bay. The lower few river miles of each river are transport high zones. The reduction of cross-sectional area increases the in-channel energy resulting in the high transport. Sediments supplied to these reaches passes to the bay and are deposited at the river/bay interface. A depositional wedge has developed that increased channel narrowing and reducing channel depth. The impact of the reduction in channel migration freedom and narrowing on the mid-alluvial plain is a reduction in gravel movement and bar development. The reduction in migration freedom increases the development of the riparian zone. The increasing riparian zone aids in stabilizing temporary storage gravel and decreases channel cross-sectional areas. Gravel that was confined in massive gravel bars or temporary sediment storage sites was populated with riparian vegetation (decreasing the mobility and increasing energy requirements for entrainment). This appears to allow high flow or flood event to exit the current channel at lower stage elevations (Plate 20 and Photographs 7, 8 and 9).

The reduction in channel area also reduces in-channel energy. Combined, these processes culminate in bed aggradation, bed armoring, and a reduction in gravel transport quantities at historic discharge levels. As gravel sediment transport decreases, an increase in fine-grained sediment transport occurs. The removal of the fine-grained sediment matrix creates a framework of interlocked gravel that increases the armor layer depth. This requires high in-channel stream energy to dislodge and induce gravel transport. The channel reaches downstream of the aggrading zone show a historic increase in bank erosion. The geomorphic processes controlling this bank erosion are return flow from the alluvial plain and the change in cohesive strength of the finer-grained bank sediment.

Comparing the 1939, 1965, and 2000 photographs shows that bank protection actions have reduced the migration freedom and failed to allow the natural channel widening processes to proceed. These actions have stopped the development of the fluvial pyramid (Plates 5 to 19).

Table 27 provides a geomorphic framework explaining these channel character by reach and the resulting geomorphic output. Based on the data collected during this study, the rivers in the Tillamook Bay Basin are attempting to return to a quasi-state of equilibrium. This trend is hindered by the reduction of the channel area on the alluvial plain. Analysis of historic aerial photographs shows a reduction of the channel net on the alluvial plain by the removal of sloughs from the channel network (Dougherty, Hall, and Hoquarten Sloughs).

An evaluation of the 1939 period shows that the Tillamook Bay Basin rivers are ones of massive erosion and sediment yield from the upper watershed. With constant hydrology, all systems were overloaded with sediment and massive sediment transport though the basin to the bay. The high sediment supply increased the degree of channel freedom in the upper alluvial plain. The gravel introduced into the system created major gravel bar complexes and induced bank erosion and major sediment deposition at the mouth of the rivers.

By 1965, there was a major reduction in sediment supply from the upper basin. As reforestation continued in the upper basin, the constant hydrology increased the in-channel erosion of the gravel bar complexes. Bed and bank erosion appears to have decreased resulting in an increase in the riparian zone. High volumes of fine-grained sediment still were depositing in the bay. During high flow or flood events, gravel slugs were delivered to the bay interface. However, the channel still was unable to pyramid and move to a quasi-equilibrium condition. The sloughs of the basin were undergoing additional reduction in conductivity. The wedge at the river month areas on the Kilchis, Wilson, and Trask Rivers continued to develop.

Future Channel Dynamics

An analysis of imagery from 2000 and field investigations show that the rivers are trending to a state of quasi-equilibrium. The migration freedom decreases as the riparian zone area increases in size and density. The reduction in gravel sediment transport continues to result in an increase to the amount of fine-grained sediment deposited in the bay. The major sloughs on the upper alluvial plain were still disconnected from the channel network, while the lower alluvial plain (below Highway 101) sloughs maintain hydrologic conductivity. The disconnection from the upper alluvial plain impacts the sediment transport and high flow or flood routing. Fine-grained sediment deposition at the mouth area continues and may show indications of transgression up to the lower channel area.

Based on the historical and current geomorphic processes, bay sedimentation will continue allowing gravel transport to occur during major flow or flood events. Sediment supply will continue at current volumes. These rates will maintain constant unless another catastrophic event occurs, such as a forest fire and/or a sea floor tectonic event. Over time, riparian zone development and the reduction of in-channel cross-sectional area may generate catastrophic channel relocation on the upper alluvial plain. Gravel sediment transport will continue to slow as channel narrowing and riparian zone development advances. Bank and bed erosion will continue through the middle section of the alluvial plain generating high volumes of fine-grained sediment to the bay. This increased trend in bed and bank erosion is an attempt by the channel system to reconstruct a fluvial pyramid. If these processes are left unchecked, the fluvial system will complete this reconstruction.

At the mouth of the rivers, the sediment wedge will continue to grow and could advance upstream or impact the structural features that have restricted channel freedom, resulting in erosion and/or failure. Over geologic time, Tillamook Bay will fill and a larger delta complex will result. The geographic areas east of the tectonic high in the bay will fill first; the results of infilling already have been identified (as early as the 1940s). Unless channel freedom and cross-sectional area is not reestablished, selective bay filling will continue along with flooding in the lower and middle reaches of the Tillamook alluvial plain.

Table 27. Geomorphic Changes along the Kilchis, Wilson and Trask Rivers Projected for the Entire Tillamook Basin

Channel Character	Reach	Imagery Date 1939	Imagery Date 1965	Imagery Date 2000
General Basin	Upper Basin-Tribs.	Slope Failure Rate: high-tributary yield sediment to mainstem.	Slope Failure Rate: reduction-tributary yield sediment to mainstem.	Slope Failure Rate: level off-tributary yield sediment to mainstem.
	'Rock gorge'	Transport zone	Transport zone	Transport zone
	Alluvial Plain Apex	Transport and deposition rates - high	Transport < Deposition >	Transport = Deposition =
Fine grain sediment deposition occurs on alluvial plain. In-channel deposition may cause high flows to exit channel.	Upper Alluvial Plain	Increased sediment supply. Increased bar development. Increased bank erosion. Increased channel instability. Channel width increases. **Channel Aggrading**	Moderation in sediment supply. Decrease in bar development. Decrease in bar acreage. Decreased bank erosion. Channel narrowing increased.	Continued reduction in sediment supply. Decrease in bar development. Decrease in bar acreage. Decreased bank erosion. Increased channel narrowing continues. Channel/bank stability.
Alluvial plain-floodplain flood common during high flows. Fine grain sediment deposition on floodplain.	Middle Alluvial Plain	Increase sediment supply. Increase bar development. Increase bank erosion. Increase channel instability. **Channel Aggrading**	Moderation in sediment supply. Decrease in bar development. Decrease in bar acreage. Decreased bank erosion.	Continued reduction in sediment supply. Decrease in bar development. Decrease in bar acreage. Decreased bank erosion. Increased channel narrowing continues. Channel/bank stability.
Alluvial plain-floodplain flood common during high flows.	Lower Alluvial Plain	Numerous gravel bars/acreage small. Bank erosion minor. Channel pattern stable. Transport > Deposition <	Moderation in sediment supply. Decrease in bar development. Acreage declines. Decrease in bar number. Decreased bank erosion. Channel stable. Transport > Deposition <	Continued reduction in sediment supply. Decrease in bar acreage & number. Decreased bank erosion. Continued channel narrowing. Increase in riparian zone. Channel/bank increased stability. Transport > Deposition <
Flood during all flood events	River-Deltaic	Natural levees & splay deposits dominant. Deposition > Constructed levees aid sediment accumulation & river mouths. **Channel/Bay Aggrading**	Natural levees & splay deposits dominate. Deposition > Constructed levees aid sediment accumulation and river mouths. **Channel/Bay Aggrading**	Natural levees & splay deposits dominate. In-channel sediment wedges are a dominant sedimentary structure. Deposition > Constructed levees aid sediment accumulation and river mouths. **Channel/Bay Aggrading**

8. CONCLUSIONS AND RECOMMENDATIONS

In summary, positional landscapes prevail in the Tillamook Bay Basin area. Erosion is the dominant geomorphic process occurring in the upland/mountain regions. Mass movement or slope failure supply the bulk of the sediment yield available for transport to the lower watershed. Coupling the Tillamook Basin fire history and hydrology support and aids the mass movement processes.

Given the scale of the rivers in the Tillamook Bay Basin, with the floodplain and the long relaxation time involved in fluvial processes, it appears unlikely that the river-floodplain and river-bay zones are in equilibrium. This is not to say that these systems are not coupled, but that erosion and sedimentation events and location adjust on different time-scales and to a different frequency distribution. It appears that the major forest fire events of the 1930s and 1950s were the most significant sediment producers from the upland/mountainous regions in the basin. The fire events and burn patterns appear to have produced pseudo-cycles in which periods of high quantities of sediment were generated and then delivered to the channel networks of the Tillamook Bay Basin. During initial sediment generation from the uplands, areas the floodplain and river/bay zones could have been in a stable geomorphic state or equilibrium.

Due to changing sediment supply and transport location, the geometry of the channel system and related floodplain has quite different effects on the bay or river/bay transition zone. The partial uncoupling of the river-floodplain and river/bay transition zones has been greatly increased by human actions. These include deliberately increasing flood deposits on some floodplain locations, reducing flood deposits through the constructions of "embankments" and some dredging, the prevention of avulsion and migration by embankments and revetments, and filling or blocking secondary channels and sloughs in the basin.

The recommendations for controlling or reducing the flooding impact can be presented with two perspectives: the geologic and the geomorphic. The geologic perspective is strictly based on geomorphic processes and events of geologic time. The channel system within the Tillamook Bay Basin is attempting to return to an equilibrium state by way of tectonics, climatic conditions, and basin geology. Left alone, the alluvial plain will reestablish connectivity with the sloughs in order to regain the fluvial geomorphic pyramid. Bank and bed erosion is direct evidence that this process is evolving. Sediment wedge development at the rivers' mouths is the first phase to increasing sinuosity and channel freedom. The lower half of the alluvial plain could become a more complex alluvial fan and delta environment resulting from sedimentation processes. Failure to remove or modify a large percentage of structures that reduce channel freedom would preclude the natural process occurring. However, removal or modification of these structures is currently being analyzed. Nevertheless, the channel system will evolve to one of equilibrium and continuing human intervention will attempt to manage this evolution. Flooding is a process nature uses to maintain balance and advance the return of an equilibrium state.

The geomorphic perspective is a mix of geologic, geomorphic, and human intervention. Human actions, including engineering elements, will attempt to manage the Tillamook river systems to enhance geomorphic and geologic processes. The following recommendation may appear to be oversimplified; nevertheless, the basic elements are provided. The reestablishment of hydrologic conductivity between upper alluvial plain to the Tillamook Bay is needed. This could be completed by the reconnection of the sloughs and the mainstem channel systems. This would allow some fluvial pyramid development to proceed, as well as increase the degree of channel freedom in the deltaic area. However, the total removal of levees or other structural elements retarding channel freedom is not an acceptable solution. Allowing some set back of these structures would allow natural channel processes to develop. The increase in channel cross-sectional area would reduce high flow or flood events. There must be a combination of restoring natural channel processes, while at the same time controlling the degree of freedom of the channels with some engineering elements. The mix and location becomes a political situation; however, without some combination, there will be no reduction of flood events in the Tillamook Bay Basin.

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APPENDIX A: FIRE AND FLOOD RELATIONSHIPS

Data is based on the discharge record for the Wilson River and the major fire events in the Tillamook Basin.

River Flood and Major Fire Events			
Tillamook Bay Basin, Wilson River			
Year	**Flood Date/Peak Flow (cfs)**	**Fire Date**	**River Maps/Photos**
1887	Unknown		
1914	Unknown		
1915	1/14/15 = 7,500		
1916	Unknown		
1918		Fire	
1921	Unknown		
1931	Unknown		
1932	1/18/32 = 16,700	August 1933	
1933	12/19/32 = 12,900		
1934	12/12/33 = 30,000		
1935	1/22/35 = 14,300		
1936	1/12/36 = 19,500		
1937	12/22/36 = 16,600		
1938	12/27/37 = 21,200		
1939	2/14/39 = 15,800	August 1939	May 1939
1940	12/15/39 = 17,000		
1942	12/19/41 = 18.700		
1943	11/23/42 = 17,800		
1945	2/7/45 = 22,800		
1946	12/28/45 = 17,100		
1947	12/13/46 = 18,100		
1949	2/17/49 = 24,500		
1950	11/27/49 = 20,200		
1951	12/23/50 = 10,900	August 1951	
1954	12/9/53 = 20,300		
1955	11/18/54 = 14,800		
1956	12/21/55 = 21,100		
1957	12/9/56 = 17,500		
1958	12/19/57 = 16,400		
1959	11/18/58 = 15,000		
1961	11/24/60 = 19,900		
1962	11/22/61 = 21,700		
1963	2/3/63 = 21,700		
1964	1/25/64 = 25,000		
1965	12/22/64 = 32,100		April 1965
1966	1/5/66 = 17,100		

Year	Flood Date/Peak Flow (cfs)	Fire Date	River Maps/Photos
1967	12/13/66 = 20,100		
1968	2/4/68 = 15,900		
1969	12/3/68 = 11,300		
1970	1/18/70 = 12,600		
1971	12/6/70 = 18,800		
1972	1/20/72 = 36,000		
1973	12/21/72 = 22,000		
1974	1/15/74 = 20,600		
1975	1/13/75 = 14,100		
1976	12/4/75 = 29,400		
1977	3/7/77 = 6,680		
1978	12/13/77 = 32,000		
1979	3/5/79 = 13,300		
1980	1/12/80 = 16,300		
1981	12/26/80 = 25,100		
1982	1/24/82 = 19,200		
1983	12/3/82 = 18,700		
1984	2/12/84 = 8,450		
1985	11/2/84 = 7,800		
1986	2/23/86 = 15,500		
1987	2/1/87 = 18,900		
1988	12/9/87 = 26,100		
1989	1/10/89 = 10,000		
1990	12/4/89 = 31,000		
1991	4/5/91 = 25,800		
1992	1/28/92 = 13,000		
1993	11/21/92 = 11,600		
1994	2/24/94 = 8,180		
1995	11/30/94 = 20,000		
1996	2/8/96 = 35,000		
1997	12/29/96 = 15,400		
1998	10/30/97 = 21,900		
1999	12/27/98 = 35,350		
2000	11/25/99 = 25,400		March 2000

APPENDIX B: DETAILED GRAVEL ANALYSIS AT SELECTED SITES ON THE MIAMI RIVER

Gravel Size Data for Selected Rivers in the Tillamook Bay Basin

Data is from the Tillamook County Soil and Water Conservation District in cooperation with the U.S. Department of Agriculture, Natural Resource Conservation Service analysis and as reported by Randy Stinson and Sheila Stinson (February 20, 1998). Sediment samples were collected from the Miami, Kilchis, and Wilson River systems within the Tillamook Bay Basin. Samples were collected and particle size distribution of the substrate and armor layer. The finding of the study indicated that the effect of gravel bar harvesting has had no apparent impact to the particle size distribution or volume of gravel recruited annually in the stream. Taking this as a given, this indicates that the channel processes are at or near equilibrium. The analysis illustrates channels that fine downstream and can be couples to slope and basic energy conditions.

Miami River

Armor Layer:

- 3-inch gravel is less than 5% of through out sample reach (RM 1-3.75).
- 1½-inch gravel is greater than 10% from RM 1 and up the system.

Substrata:

- At Moss Creek, 3-inch gravel appears and this is a common situation from most tributaries.
- There was no information for the mainstem.

Kilchis River

Armor Layer:

- No 3-inch gravel below RM 3, except in 1995-1996, both of which were major flood years.
- 1½-inch gravel appears greater than 10% from RM 3 and up system.

Substrata:

- 3-inch gravel is less than 10% of the sediments sample until RM 5 and above.

Wilson River

Armor Layer:

- 3-inch gravel appears greater than 5% at or above RM 7.95
- 1½ inch gravel is greater than 10% from RM 4.2

Substrata:

- No samples were collected from the mainstem, only tributaries.

The 3-inch samples were the largest size sampled this analysis. The Armor Layer Toe Count counted all gravel larger than 3 inches in size. No gravel larger than 3 inches was found below the following river miles:

Miami River:	river mile 3.75
Kilchis River:	river mile 3.4
Wilson River:	river mile 6

Analysis of this data indicates that the sampled rivers display normal grading and that major flow events (large floods) will pulse or slug gravel sediment down the system.

PHOTOGRAPH PLATES

Photograph Number 1: Kilchis River 1939; River mile 0-1.

Large sediment deposit at the river – delta interface, it is still visible on the 2000 Photograph. The presents of the sedimentary element are an indication that recent sediment rates have slowed.

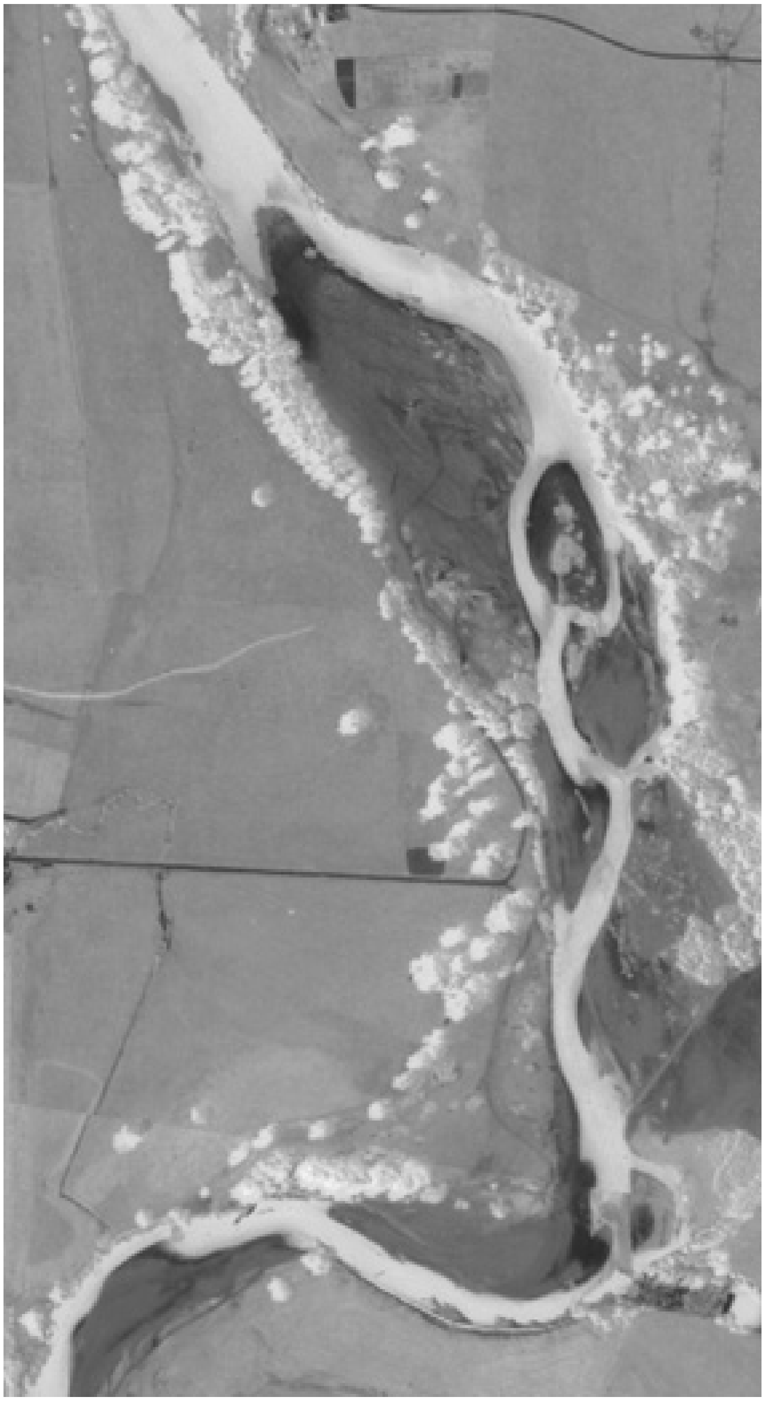

Photo 2: Wilson River 1939; River mile 4 to 5.

Extensive Gravel Bar complexes with limited riparian development. Gravel deposition occurring resulting in bed aggradation. High sediment loading associated with basin fire history. This large gravel bar complex is just up stream of Daugherty Slough.

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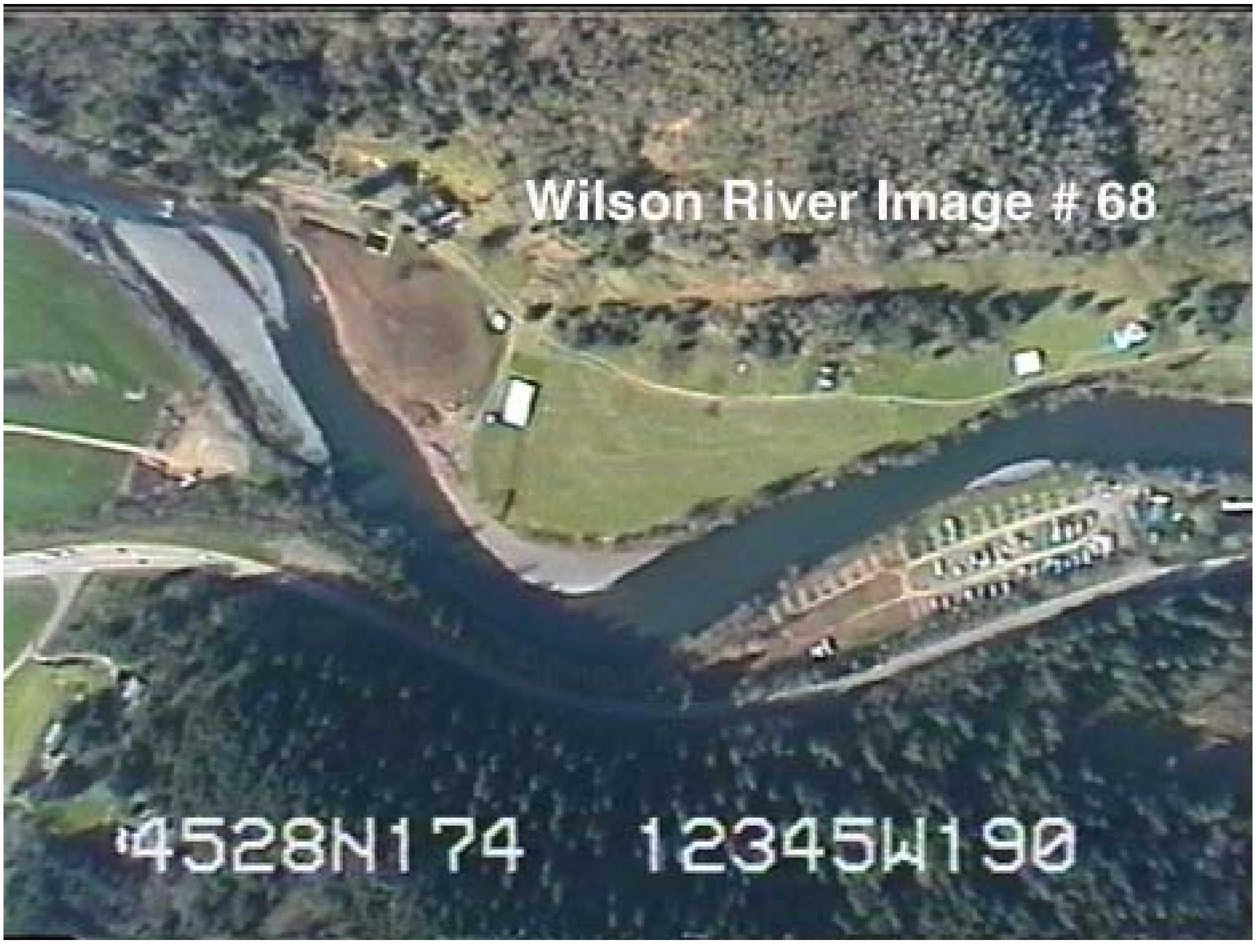
Photography Number 3: Trask River 1939; River mile 6 –7.

Extensive Gravel Bar complexes with limited riparian development. Gravel deposition occurring resulting in bed aggradation. High sediment loading associated with basin fire history

Photography Number 4: Wilson River November 1999.

Upper Basin Area; illustrating the slope Failures in the Upper Wilson Basin resulting from the November 1999 winter. (Wilson River Image 92)



Photography Number 5: Wilson River November 1999.

Upper Basin and Alluvial Plain Apex. Gravel Bar Complex indicates refreshment from storm related gravel transport. (Wilson River Image 68)

Photography Number 6: Wilson River November 1999, Middle Alluvial Plain.

Fine grain sediment deposited on agricultural land after flood event. Notice the large riparian zone and minor gravel bar complexes.
(Wilson River Image 73)

Photography Number 7: Wilson River.

Alluvial Plain at Flood Stage and Out of Channel Flow.
(Wilson River Image 50)

Photography Number 8: Trask River November 1999.

Lower Alluvial Plain at Flood Stage and Out of Channel Flow. (Trask River Image 7)

Photography Number 9: Trask River November 1999.

Upper Alluvial Plain at Flood Stage and Out of Channel Flow. Fine grain sediments are depositing on the agricultural lands. (Trask River Image 5)

US Army Corps
of Engineers ®
Portland District

Tillamook Bay and Estuary, Oregon
General Investigation Feasibility Report

APPENDIX E

Modeling 2-Dimensional Unsteady Flow at the Confluence of Riverine and Estuarine Regimes

Modeling 2-Dimensional Unsteady Flow at the Confluence of Riverine and Estuarine Regimes

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Abstract

This paper describes the results of applying a 2-dimensional hydrodynamic model (ADCIRC) to evaluate several alternatives for decreasing the stage of multiple rivers that discharge into a coastal estuary. Reduction of river stage at the mouths of the rivers (in the backbay areas of the estuary) is desirable for reducing inland flooding caused by a backwater effect as the rivers discharge into the estuary.

The project location is Tillamook Bay, Oregon, which is situated on the U.S. Pacific Northwest Coast about 90 miles west of Portland, Oregon. Tillamook Bay is a shallow estuary with complex system of tidal channels and broad inter-tidal mudflats. The estuary receives riverine input from five rivers, all headwatered in the northern Coastal Range of Oregon. A number of narrow channels provide confined pathways for riverine flows entering the estuary from upland sources and the tidal flows entering and leaving the estuary from the ocean. During times of significant upland precipitation/run-off, the hydraulic conditions within the backbay area of the estuary become dominated by riverine flow. The situation becomes a battle of two flow regimes: Riverine vs. Estuarine. The objective of the work reported in this paper was to determine if an estuarine-based channel modification could reduce the water elevation in the back bay area of the estuary during high riverine flow events. Conventional wisdom could lead one to conclude that increasing the conveyance of estuary would reduce stage at the river mouths during a significant riverine flow event. However, based on the results reported herein, estuary-based alternatives are not effective for reducing the stage at the river mouths during a significant riverine flow event. The best method for reducing river stage and alleviate coastal flooding around Tillamook flooding is to (partially) restore the floodway for each of the major coastal rivers discharging into the bay.

Introduction

The motivation for the analysis reported in this paper lies in the chronic flooding that has occurred in the valleys and coastal plains of the Tillamook Bay region (figure 1). The most severe flooding occurs in and around the town of Tillamook. Just downstream of the Tillamook lies Tillamook Bay, a broad and shallow estuary (figures 2 and 3).

The Tillamook Bay estuary is located on the Pacific Northwest coast of Oregon, about 90 miles west or Portland (figure 4). At mid-tide, the estuary is 9 km long (N-S) and 4 km wide (E-W). The average depth of the estuary is about 1.8 m., with respect to mean tide level. The mean tidal range within Tillamook Bay is about 1.7 m.

Five rivers flow into Tillamook Bay. Four of the rivers pass through or nearby the town of Tillamook and flow into the southern end of the bay. During November-April, the town of Tillamook and adjacent areas are prone to flooding due to a backwater effect caused by high flows on nearby coastal streams and elevated water levels of Tillamook Bay. The Wilson and Trask Rivers are the two largest Rivers that flow into Tillamook Bay, and consequently, produce the largest floods. The town of Tillamook largely remains flood free, however, newly developed areas to the north and south of Tillamook experience severe flooding on a regular basis. The worst flooding occurs to the north of Tillamook along a strip of U.S. Highway 101, where flood waters come from the Wilson River, the Trask River, the Tillamook River and from high tides and storm surges in Tillamook Bay. Other coastal plain areas along the Trask, Tillamook and Kilchis Rivers have been historically flooded as well.

The majority of lands in the area are operated as dairy farms and many of the historic dairies are located on high points throughout the area. Many levees have been built in the Tillamook area, most are overtopped during river floodstage and some of the levees are high enough so as to avert overtopping. In either case, the presence of levees along the coastal rivers near Tillamook forces waters to flow through narrow channels, dramatically increasing river stage during high stream flow events. The difference between a river remaining within its banks or spilling over onto the coastal flood plain can be based on the water level at the river's mouth within the Tillamook Bay. If a significant run-off (streamflow) event occurs simultaneously with a spring tide and storm surge event, floodwaters overtop their banks upstream of the levees, resulting in inland flooding.

Climate of the U.S. Pacific Northwest Coast and Flooding at Tillamook Bay

In the northeast Pacific Ocean during winter, weather fronts associated with maritime cyclonic storms can extend over the ocean for 1000's of km and cover a latitude difference of 25 degrees (figure 4). When these maritime low-pressure systems make land fall on the U.S. Pacific Northwest, the coast can be subjected to hurricane-like conditions. The rainfall at coastal locations can be intense and sustained, especially in areas flanked by high relief catchments. Locations at the top of the Oregon Coast Range can receive over 200-inches of precipitation per year while the lowland valleys receive approximately 100-inches per year. Most of the precipitation falls as rain and most falls between the months of October and March. Intense winter storms can produce intense runoff events for coastal rivers. Several of the rivers that drain into Tillamook Bay can experience a rapid change in flow due to winter storm events; increasing from 10 cubic m/s to 300 cubic m/s in a matter of hours.

Offshore Tillamook Bay, wind fields associated with intense winter maritime low-pressure weather systems can create sustained wind speeds greater than 20m/s for fetches greater than 200 km. The resulting wind stress can produce ocean waves greater than 10 m high and a transient "set-up" of the mean water level of 0.3-1.3 m (storm surge for 1-6 hours duration), depending on storm evolution (figure 4).

The Tillamook Bay estuary is a broad shallow estuary with a large number of inter-tidal mudflats and a complex array of inter-connecting tidal channels. Astronomical tides at Tillamook Bay are mixed semi-diurnal; meaning that there are two tide cycles per day of unequal amplitude. The mean tidal range in the lower bay is 1.7 m. The average range of the highest daily tides is the vertical distance from mean lower low water (MLLW) to mean higher high water (MHHW) and is 2.4 m. Extreme tide ranges from –0.9 m MLLW to +3.6 m MLLW. NDVG = +3.0 m MLLW. Tides are modulated by the lunar cycle. During a full or new moon, spring tide occurs (twice monthly) and tide range is larger than average conditions. During half-moon, neap tide occurs (twice monthly) and tide range is smaller than average conditions. The seasonal average coastal water level during winter is 0.2-0.3 meters higher than summer due to dynamics of the northeast Pacific Ocean (figure 4).

The worst set of scenarios for flooding in the Tillamook area occurs in winter (the average bay water level is 0.25 m higher than in summer) when: An intense maritime low-pressure system makes land fall during a spring tide, while the 2 largest coastal streams in the area are near bankfull, and the soil of lowland/upland areas is saturated. This was the case in 1996, when devastating floods struck the Tillamook area.

Use of a 2-Dimensional Model to Investigate Coastal Stream Flooding

Hydraulic connectivity between the Pacific Ocean and Tillamook Bay occurs through a single (entrance) channel located at the northern end of the estuary. During the past 100 years, the entrance channel to Tillamook Bay has been modified by the construction of jetties for navigation purposes. The effect of entrance channel modification has been to transform the estuary entrance from a broad tidal delta to a jettied entrance. The jetties extend about 900 m offshore and act as a nozzle to provide a stabilized inlet that is 300 m wide having authorized navigable depth of 6 meters (figure 2).

Understanding the Problem. It has been alleged that the jetty entrance into Tillamook Bay is more restrictive than the pre-jetty configuration and conveyance of riverine floodwaters (through the estuary) has been reduced. If correct, this process could increase the backwater effect in the backbay area of the estuary, aggravating inland flooding at Tillamook. It has also been stated by local interests that a high degree of sedimentation has occurred within the Tillamook Bay estuary. If correct, this process could reduce the conveyance of river floodwaters out of the bay; adding to the backwater effect and exacerbating inland flooding at Tillamook. Consequently, local interests believed that the best way to alleviate coastal river flooding in the Tillamook area, is to improve conveyance within the estuary by modifying jetty entrance and/or removing sedimentation from the estuary tidal channels; via dredging.

The aggregate area of all 5 catchments that empty into Tillamook Bay is about 1,300 km^2 and the combined 1-yr flow event for peak instantaneous riverine discharge into Tillamook Bay is about 1,110 m^3/s. Under the 1-year flow event (such as the 14 November 2001 event), the cumulative volume of riverine flow into Tillamook Bay during the 24-hr peak of the hydrograph is about 72 km^2-m. The area of Tillamook Bay, as affected by estuarine tidal action, is 37 km^2 and the mean tide range is 1.7 m. On a daily basis, the volume of tidally-driven estuarine water passing through the entrance channel to Tillamook Bay is about 63 km^2-m. For a typical 1-year flow event, the cumulative volume of riverine flow into Tillamook Bay during the 24-hr peak of the hydrograph is (15%) greater than the volume of tidally-driven marine water that enters and leaves the estuary. Given the 1+:1 ratio of riverine flow during the 1-yr event vs. normal estuarine tidal flow capacity, it appeared that Tillamook Bay may not have the "reserve" conveyance necessary to avert a backwater situation at the river mouths during significant riverine flow events.

The above considerations indicated that improving conveyance of flow through Tillamook Bay estuary could alleviate the flooding of Tillamook and surrounding areas. Evaluating the interaction of coastal and riverine flow regimes within an estuary as complex as Tillamook Bay required a robust 2-dimensional approach.

Modeling Approach. The intent of the modeling activity was to first perform calibration-validation activities to a reasonable level of accuracy (+- 0.2 m), then evaluate the water level (stage) within the back bay of the estuary based on specific 1-year flow event, for existing conditions. In effect, modeling was performed at a reconnaissance level of accuracy. After simulating existing conditions within the back bay, the model was used to assess several alternatives for increasing the conveyance of riverine flow through the estuary. Alternative results were compared to the existing conditions. If the estuary "conveyance" alternatives reduced the stage within the back bay during the peak of the 1-yr flow event (as compared to the present condition), then it could be concluded that inland flooding was related to Tillamook Bay flow characteristics. It would follow that increasing conveyance within the estuary could reduce inland flooding near Tillamook.

If the model showed that the estuary "conveyance" alternatives did not reduce the stage within the back bay during the peak of the 1-yr flow event (as compared to the present condition), then it could be concluded that inland flooding was not related to conveyance issues within Tillamook Bay. If this scenario proved true, it would follow that the only feasible way to reduce riverine flooding inland from Tillamook Bay would be to change to hydraulic characteristics of the rivers and associated floodways.

Alternative Formulation - Estuary Conveyance Modification

To test hypotheses advanced in the previous section, several alternatives were developed to modify the conveyance of flow through Tillamook Bay estuary. The premise being, modification of the estuary conveyance will result in modification of stage at the river mouths into the estuary. The "conveyance alternatives" focused on modifying flow through the ocean entrance to the estuary or through the center channel of the mid-estuary. Specific alternatives for increasing estuary conveyance included:

A. Modifying the <u>**ocean entrance**</u> channel into the bay. Enlarging the ocean entrance to Tillamook Bay by removing 100+ m of Kenchloe Point & deepening the jetty entrance channel to –11 m NGVD (figure 5),

B. Modifying the central **tidal channel** through the bay. Enlarging the width (to 200 m) & deepening (to –2 m NGVD) the central tidal channel through the estuary (figure 5),
C. **Combine** both A and B, and
D. **Restricting tidal flow** into the bay. Filling-in the jetty entrance channel at the ocean entrance to the estuary to -2 m NGVD (the opposite of alternative A).

The above alternative plans could be considered by some to be radical, due to the extent of estuary modification that would be required to implement each alternative. If there is a hydraulic effect due to any one of the alternatives, then it should be easily observable within the model. This would give a clear indication if riverine flooding is (or is not) due to an estuary effect and whether an estuarine-based alternative exists to reduce riverine flooding. This is one reason why numerical modeling is so useful; to investigate scenarios that would otherwise be impossible to assess without first building a physical model or prototype. Each alternative was adapted to a computational grid on which the hydrodynamics of the estuary were simulated for a specific storm event using the ADCIRC model. The same was done for the baseline (present) condition. A consistent grid was used to simulate hydrodynamics for the baseline and alternative conditions, to permit unbiased comparison.

ADCIRC Hydrodynamic Model

The ADvanced CIRCulation (ADCIRC) numerical model was chosen for simulating the long-wave hydrodynamic processes in the study area. By specifying the tidal-elevation signal at the ocean boundary, the wind-induced shear stresses over the model domain, and riverine flow, the ADCIRC model can simulate time varying circulation (water velocity and stage) throughout Tillamook Bay. The ADCIRC model was developed in the USACE Dredging Research Program as a family of two- and three-dimensional finite element-based models (Luettich et al. 1992). Model attributes include the capability of:

A. Simulating tidal circulation and storm-surge propagation over large computational domains while simultaneously providing high resolution in areas of complex shoreline and bathymetry. The targeted areas of interest include continental shelves, nearshore areas, and estuaries.
B. Representing the pertinent physics of the equations of motion. These include tidal potential, Coriolis, and all nonlinear terms of the governing equations.
C. Calculating reliably and efficiently over time intervals ranging from days to years.

In two dimensions, the model formulation is based on the depth-averaged finite amplitude non-linear equations for conservation of mass and momentum. The formulation assumes that water is incompressible and barotropic, and that the pressure is hydrostatic. Rather than directly solving the Navier-Stokes and continuity equations, ADCIRC employs the Generalized Wave Continuity Equation (GWCE) for computing water-surface elevations and velocities. The GWCE-based solution scheme eliminates several problems associated with those finite-element schemes that solve the primitive forms of the continuity and momentum equations, including spurious modes of oscillation and artificial damping of the tidal signal. Forcing functions can include time-varying water-surface elevation, wind shear stress, atmospheric pressure gradient, and riverine input. The Coriolis force is included in the GWCE. Also, the study area can be described in ADCIRC through either a Cartesian (flat earth) or spherical coordinate system.

The ADCIRC model is based on a finite-element (FE) algorithm for spatially solving the GWCE over complicated bathymetry encompassed by irregular sea, coastal, and estuarine boundaries. The FE algorithm allows for flexible spatial discretization (grid generation) over the computational domain while retaining high stability. The advantage of this flexibility in developing a computational grid is that larger elements can be specified in open-ocean regions where less resolution is needed.   Smaller elements can be specified in the nearshore and estuary areas where finer resolution is required to resolve hydrodynamic details (in channels, around islands, and tidal flats). ADCIRC can also simulate wetting and drying of tidal flats, which was a crucial for successful modeling of estuarine flow in Tillamook Bay.   The GWCE is solved in time using an implicit Crank-Nicholson finite difference scheme. As with any numerical model that uses a "grid" to descretize the real world for computation, proper development of the model grid is the key to successful problem formulation and solution generation.

ADCIRC Computational Grid

In multi-dimensional finite element modeling of geophysical flow, a study area is defined by means of an unstructured grid composed of triangular elements to represent the terrain of interest (x,y,z). Elevation (bathymetry or topography, z) is specified at the vertices (x,y), referred to as nodes, of each element composing the grid. The time-varying water surface elevations and the horizontal velocities are computed at the nodes. Figure 6 shows the computational grid developed for this study. The Tillamook Bay estuary consists of numerous tidal flats and narrow channels. The grid was designed to carefully represent all the channels and tidal flats of the estuary. To prevent inadvertent drying of the tidal channels by the model, a minimum of three elements was required across the channel width. Numerical stability considerations limit the smallest size that the elements can get while keeping the time step within computationally feasible limits. The time step used for applying ADCIRC on the Tillamook Bay grid featured in this paper was 2 seconds. For an 8-day simulation on the subject grid, the ADCIRC model ran in about 10 hours on an Intel pentium-4 PC.

The computational grid featured in this paper encloses Tillamook Bay entirely and includes an idealized representation for the lower 1-3 km of each of the fives rivers flowing into the bay. The open-ocean boundary of the grid is situated a considerable distance (300-500 km, figure 4) from the project area to facilitate the proper generation of the tidal signal from the imposed tidal boundary-condition and allow proper development of coastal current from the imposed wind-field. The computational grid for the Tillamook Bay application consists of roughly 12,400 nodes and 23,000 elements. The largest elements reside along the western (ocean) grid boundary where nodal spacing is about 80 km. Smaller element sizes (about 20 m) are specified for resolving the tidal channels inside the bay. Grid development involved several iterations of model simulations and many grid modifications. In this application, the grid was *edited* in Cartesian coordinates (NAD27 SPCS Oregon North and NGVD, m) and the model was *run* with the grid in the spherical coordinate system (NAD 27 and NGVD, m).

Elevation and shoreline data used to generate the ADCIRC grid for the Tillamook Bay modeling effort was obtained from three sources. In the vicinity of the jetty entrance, bathymetry data was obtained in 2000 using a multibeam fathometer (data reported at 2 m intervals). Bathymetry for most of the estuary was compiled from conventional fathometer soundings conducted in 2001 (data collected at 3 m intervals along variable transects). Topography of mudflats was compiled from a controlled aerial survey conducted in 2001. Tidal channels in the back bay were surveyed during 2000-2001 using fathometer and land-based methods. Oceanographic bathymetry beyond the project area was obtained from a NOAA digital database. All survey data was compiled into a common ASCII (x,y,z) file, which was interpolated onto the ADCIRC grid (figures 3 and 5). Depths assigned to grid nodes were found by interpolating the three nodes contained in the database that encloses a given grid node. Nodal depths are interpolated with an algorithm that weights each sounding or data point inversely proportional to its distance from that node.

ADCIRC Model Simulations

During the process of establishing a numerical model to represent a given study area, calibration is performed to ensure the model adequately predicts hydrodynamic conditions. Accuracy of a model is determined by the accuracy of the boundary and forcing conditions, representation of the geometry of the study area (i.e., bathymetry and land-and-water interface), and, to a lesser extent, by the values of certain parameters, principally the bottom-friction coefficient. A satisfactory comparison between ADCIRC simulations and measurements in the calibration procedure gives confidence that the model adequately simulates hydrodynamic processes. Calibration and validation exercises were conducted via comparisons of water surface elevations (stage) calculated with the model to those measured within the domain.

The intent of this modeling effort was not to reproduce the exact water surface elevation (stage) *within the rivers* that drain into Tillamook Bay. Rather, the ADCIRC modeling effort focused on accurately reproducing stage within the estuary and backbay areas, and to qualitatively reproduce stage at the river mouths. When conveyance modifications were made to the estuary, it was deemed important to accurately depict the associated changes within the estuary. In this regard, “qualitative” estimates of river stage for the baseline and alternative plans could be compared with a reasonable level of certainty.

Model simulations were conducted for two times periods (Chawla 2002). In the first case (calibration), the forcing environment within Tillamook was dominated by tidal action; there was very low river discharge and no wind forcing (storm surge). The aim was to test how well the tidal oscillations are simulated by the ADCIRC model. In the second case (validation), the time period centered around a storm event which was accompanied by strong wind conditions and higher levels of river discharge into the estuary.

Observed Data. USACE-Portland District maintains 5 tidal gages inside the estuary (USACE 2003). Stage data from these gages was used to calibrate the Tillamook Bay ADCIRC model. The Garibaldi gage is located within 3 km of the ocean entrance to the bay and its hydraulic response is dominated by the ocean conditions at the mouth of the estuary. The remaining 4 gages were located further upstream to observe the stronger influence of river discharge on water surface elevation (WSE) data. The gages at Garibaldi, Dick Point, Wilson River, and Kilches River were used to validate the ADCIRC Tillamook Bay model (figure 6). Stage data was synchronously recorded at each gage using a 15 minute interval, in NAVD (0 NAVD = -1.036 NGVD). It is noted that during fall 2001, the Tillamook Bay stage gages had problems dealing with power fluctuation, hysteresis, and creeping datum offset. Other data use to specify model boundary conditions during model validation included wind field data (6 hour sampling interval) and riverine flow data (30-minute sampling interval, figure 7).

Calibration Run. The hydrodynamic model was calibrated by adjusting the bottom-friction and lateral diffusion (eddy viscosity) coefficients so that model-generated WSE time-series compare favorably to observed values. If needed, the computational grid was modified to resolve complex flow interactions. Calibration was based on a tidal flow test case was run for a 15-day simulation extending from 04/14/2001 to 04/29/2001. The run had a 5-day ramp-up period, which is included in the 15-day simulation period. The river discharge during this period was very low and thus the river boundaries were treated as closed boundaries for this test case. No winds were forced for this run. The only forcing on the ADCIRC model was due to tidal potential, which was applied along the offshore open boundary. During calibration, considerable effort was expended to refine the grid in the estuary entrance and back bay areas to capture the hydraulic connectivity of narrow tidal channels. Vast inter-tidal areas (mudflats) where topographic & bathymetric gradients are gradual and tidal excursion causes wetting and drying, were particularly troublesome for maintaining model stability. To address these issues, the computational grid was modified to eliminate ponding within mudflats, ambiguous terrain gradients. The orientation of grid elements (connectivity) was improved, to conform the grid to mudflat and tidal channel contour alignment. Collectively, these grid modifications significantly improved model results as compared to initial calibration runs.

The model simulations were found to be stable for time steps no greater than 2 seconds. This limitation is due to the numerical restrictions placed on the model by the smallest elements in the grid. The numerical solutions were found to be unstable for values of lateral diffusion greater than 1 to 5 m^2/s, depending on the value of other model parameters. This is contrary to conventional expectations, where an increased lateral diffusion would be expected to decrease instability. It is hypothesized that inside the narrow channels of the estuary, the lateral diffusion was having a negative impact by spreading the noise in the flow field into the much shallower tidal flat region, where the noise was amplified instead of being suppressed (Chawla 2002). Based on the final calibration runs, WSE for the ADCIRC model was within 0.2 meters of observed values, and performed reasonably well in simulating tidal flow conditions in the Tillamook estuary. Chawla (2002) describes calibration results in detail.

Validation Run. The emphasis of the work described here centers on replicating the stage within the Tillamook Bay during a spring tide event when there is considerable riverine flow and coastal storm surge. Such an event occurred on 14 November 2001 and is featured in this paper. The ADCIRC model was run for an 8 day simulation, including a 1 day ramp-up period, beginning at 08:00 9 November 2001 GMT. The storm peak conditions occurred on day 5 of the ADCIRC simulation. The model simulated WSE at the gage locations (figure 6) every 15 minutes during the 8 day run.

Several changes were made to the model to improve performance and allow specification of additional boundary conditions for the time-varying wind field and riverine input. Due to the large excursion of WSE during the validation run (superposition of spring tide, storm surge, and riverine flow), the model parameterization for bottom shear stress was changed for the validation run; a hybrid nonlinear bottom friction law was used. In deep water, the friction coefficient is constant and a quadratic bottom friction law results. In shallow water the friction coefficient increases as the depth decreases (e.g. as in a Manning-type friction law). The friction factor (Cf) varied such that in 0.05 m water depth Cf = 0.06, in 4 m depth Cf = 0.004, and in 10 m depth and greater Cf = 0.0025. The eddy diffusivity coefficient was set to a global value of 3 m^2/s.

Forcing mechanisms specified in the model include tide, tide-generating potential, river discharge, and the Coriolis force. Time-varying tidal elevations specified at nodes along the open ocean boundary were synthesized using eight tidal constituents: M_2, S_2, N_2, K_1, O_1, Q_1, P_1, and K_2 (obtained from the LeProvost data base). Because the model domain is of sufficient size that celestial attraction induces tide within the grid proper, tide-generating potential functions were included in the simulation calculations, and these functions incorporated the above listed eight tidal constituents. The wind field data supplied to the model was extracted from the NCEP database. Wind fields were input into the model having the spatial resolution of 2.5 deg longitude by 2.5 deg latitude and 6-hr intervals, as archived in the database. A snapshot of the time varying wind field is shown in figure 7. Maximum sustained wind speed during the storm was 21 m/s. Time-varying riverine flow was input to the model along the upstream boundary for each of the bay's 5 rivers (figures 3 & 6). Peak river flowrate observed during the storm was 430 cm/s (Wilson & Kilches Rivers).

Figures 8 & 9 compare ADCIRC <u>model</u> and <u>observed</u> values for WSE at four gage locations within Tillamook Bay (figure 6), for the "existing condition" bathymetry. Overall, there was little phase difference between the ADCIRC model and observed WSE. Model-generated peak values of WSE within the estuary are generally within 0.2 m of observed values. Note that during the storm, the model-generated WSE is about 0.1 to 0.2 m lower than observed values throughout the estuary; and was likely due to the model under predicting storm surge on the coast. This was to be expected, since the wind forcing data was deemed sufficient to reproduce the general effect of storm surge, but not detailed enough to produce exact results. In the riverine reach of the Wilson River (figure 9 upriver of the mouth) where riverine flow controlled WSE during the storm, model results during the storm do not attain the same level of peak values as the observations show. This was due to inadequate grid resolution and geometry description of the Wilson River and was expected due to the schematized representation of the rivers within the computational grid. Note that the tidal gages at Kilchis Cove and Wilson at Geinger came out of the water during low tides. This explains the cutoff in the tidal signals of these gages during low tides. During fall 2001, several of the stage gages were affected by low power supply and hysteresis (notably Dick Point) rendering exact comparison to the ADCIRC model problematic. In general, the model results agree with observations to an adequate level such that confidence was established in the model to reliably describe WSE throughout the estuary during a "storm" for the present configuration.

Alternative Runs. At the time of model validation, the computational grid for the existing condition of Tillamook Bay was modified to allow consistent grid definition (and comparison) for all alternatives. This meant that the same grid geometry (x,y) was used for all model runs. The four alternatives were represented within the grid by changing elevation (z) values at spec nodal points. Alternatives were focused on modifying hydraulic conveyance through the Tillamook Bay's jettied entrance and central part of the bay. Refer to section "Alternative Formulation - Estuary Conveyance Modification" for additional details.

Figure 10 compares ADCIRC results for the "existing condition" and alternatives (A, C, and D) at two gage locations within the back bay area of the estuary: At the Wilson River and Kilches Cove (figure 6). Results for the other locations and alternative B are omitted here for brevity. At first glance, the results appear confounding; but such is the case in tidal hydraulics. Despite the massive geometry changes associated with alternatives A and C, there is little change in peak WSE at any of the gage locations. Apparently, the present estuary condition is not "choked" and is near maximum efficiency for conveying a spring tide with the 1-year riverine flow event. This means that no reasonable level of estuary modification can increase conveyance of water through the estuary, such that the WSE within the back bay area of the estuary is reduced from its present high tide level. There is a small, but notable difference between alternatives A and C during low (ebbing) tide at the Wilson gage (top graph, figure 10). During low river flow, alternative C conveys the ebb tide out of the estuary back bay (Kilches Cove) more efficiently than the "existing condition" or alternative A (or B). During high river flow, alternative A conveys the ebb tide out of Kilches Cove more efficiently than alternative C (combined entrance deepening + central channel deepening). This is due to the deepened central channel (alternative B and C) modifying the ebb tide flow in Kilches Cove resulting in higher frictional effects and high stage at that location (during lowtide).

The concurrence of high river discharge on a high spring tide is the process that drives flooding in the Tillamook area: A high spring tide causes a backwater effect at the mouths of rivers discharging into Tillamook Bay. Aggressive modification of the estuary's channels will increase conveyance of estuarine water flowing *into and out* of the bay. Increasing the conveyance of floodwaters out of the bay is desirable, and will result in lowering of WSE during ebb (or low) tide. Decreasing the low tide WSE is not of primary concern; it is the WSE during high tide that causes problems. However, increasing the conveyance of estuarine water flowing into the bay will increase the WSE during flood (or high) tide. This is obviously not desirable. This is basically what alternative A-C did. Alternative D was intended to restrict the conveyance of marine water flowing into the bay, thus reducing WSE during high tide. Reducing conveyance would also have the effect of increasing WSE during ebb (low) tide. Figure 10 (dashed line) shows the result of running ADCIRC with a filled entrance channel (to –2 m NGVD). During low river flow conditions, alternative D had a significant impact on WSE at all of the gage locations, acting to reduce high tide WSE by more than 1 meter. During high river flow conditions, alternative D had little effect on high tide WSE in the back bay areas or at the river mouths in Tillamook Bay. This final result confirmed the following conclusion: Inland flooding at Tillamook was not related to conveyance issues within Tillamook Bay. The only feasible way to reduce riverine flooding inland from Tillamook Bay is to change to hydraulic characteristics of the rivers and associated floodways.

Conclusions

Using even a robust numerical model to simulate hydrodynamics within Tillamook Bay proved to be challenging when confronted with: constricted riverine geometry producing rapidly varying flow that exceeds 2 m/s, a semi-diurnal tide of 2.4 m within the estuary, broad mudflats which are wetted and dried during each tidal cycle, a complex system of interconnecting tidal channels, estuarine flow through the estuary's jettied entrance (to the ocean) exceeding 2 m/s, and a transient water level set-up due to strong wind forcing. Considerable effort was expended to conform the highly irregular bathyemtry of Tillamook Bay onto a numerical grid, to ensure stability for numerical modeling. The ADCIRC model produced acceptable results despite these handicaps, but the model was applied to its practical limit with respect to maintaining numerical stability within the backbay of the estuary.

Based on the results described in this paper, inland flooding near the town of Tillamook is not related to conveyance issues within Tillamook Bay. The only feasible way to reduce riverine flooding inland from Tillamook Bay is to change to hydraulic characteristics of the rivers and associated floodways.

Lessons learned include the following observations: It is essential to accurately resolve complex bathymetry of an estuary when simulating unsteady flow using a 2-D hydrodynamic model; Increasing the diffusion coefficient in a numerical model can increase instability; Use a spatially-variable friction factor is required to properly simulate 2-D flow within an estuary; Before calibrating/verifying a numerical model, ensure that the prototype data is accurate and consistent for the time period of interest; A numerical model can be used to assess the accuracy of prototype gage data.

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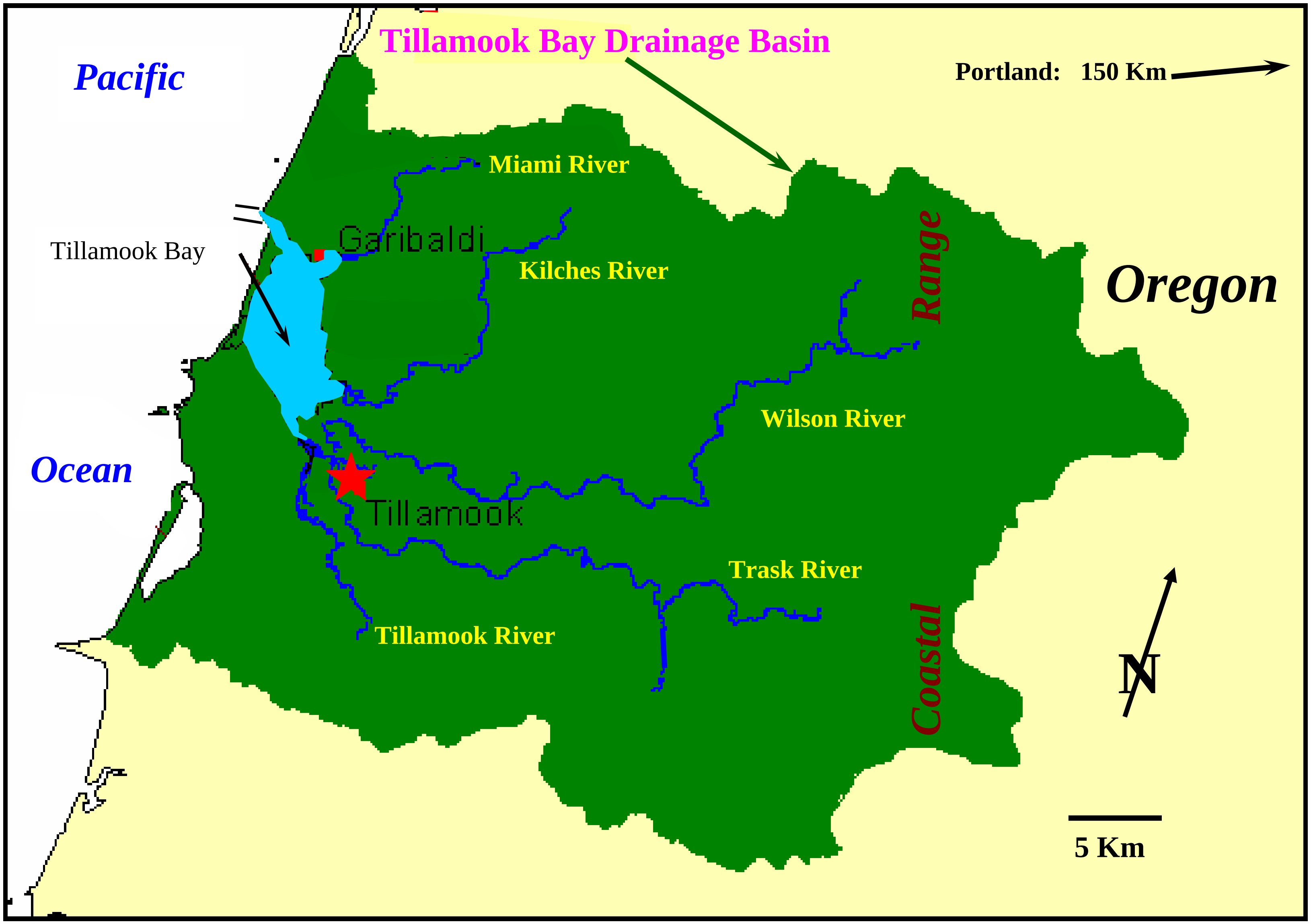


Figure 1. Site map for project area

Figure 2. TOP. Aerial view at north end of Tillamook Bay at extreme low tide, view is to the south. Note broad expanse of interconnected tidal flats and network of incised tidal channels. All tidal flats are submerged during high tide. BOTTOM. Aerial view at north end of Tillamook Bay showing jettied channel connecting the bay to the Pacific Ocean, view is to the northwest. Note constricted area of entrance near Kincheloe Point. Photo date is 4 June 2000 and tide was -2 ft MLLW, courtesy Port of Garibaldi

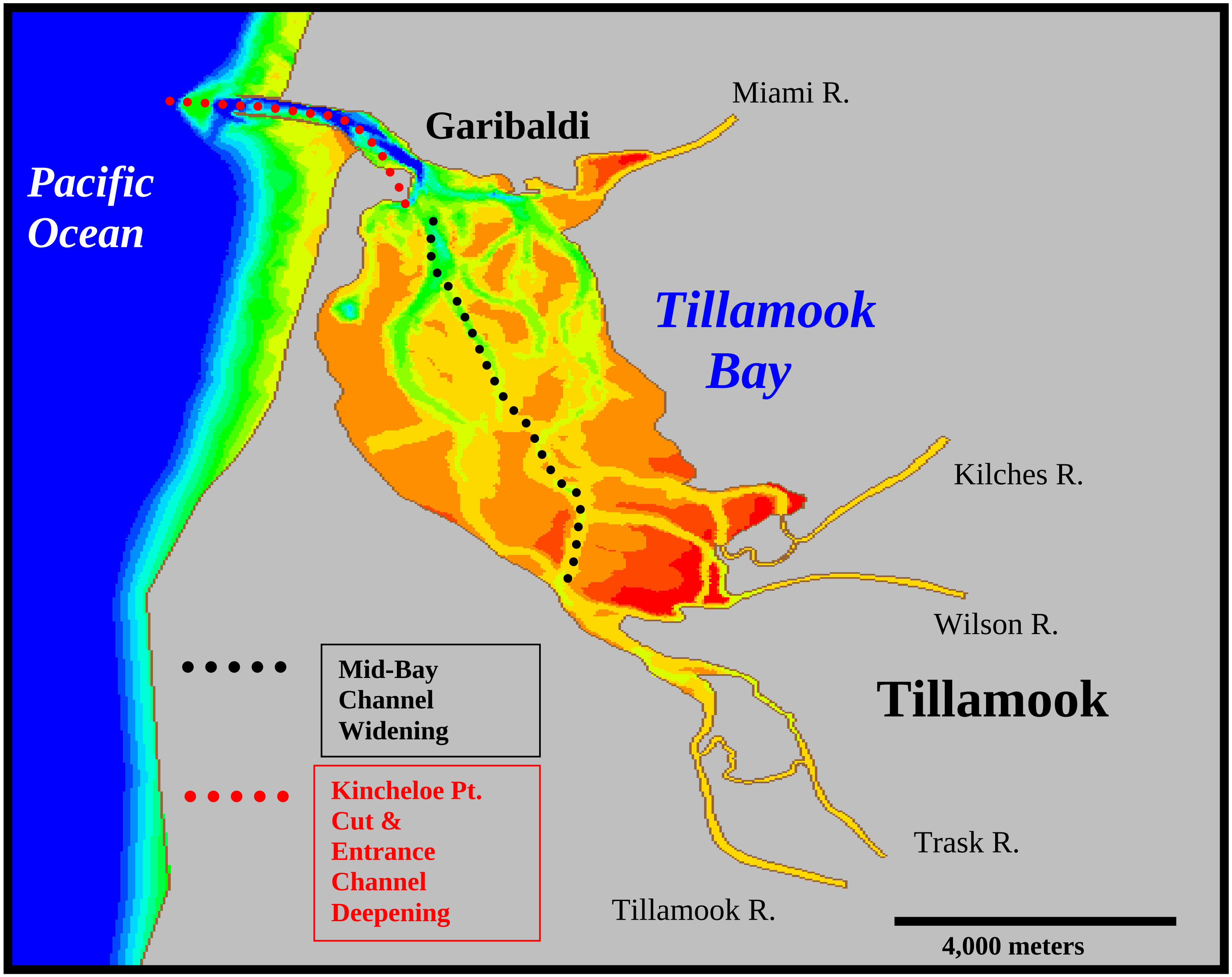
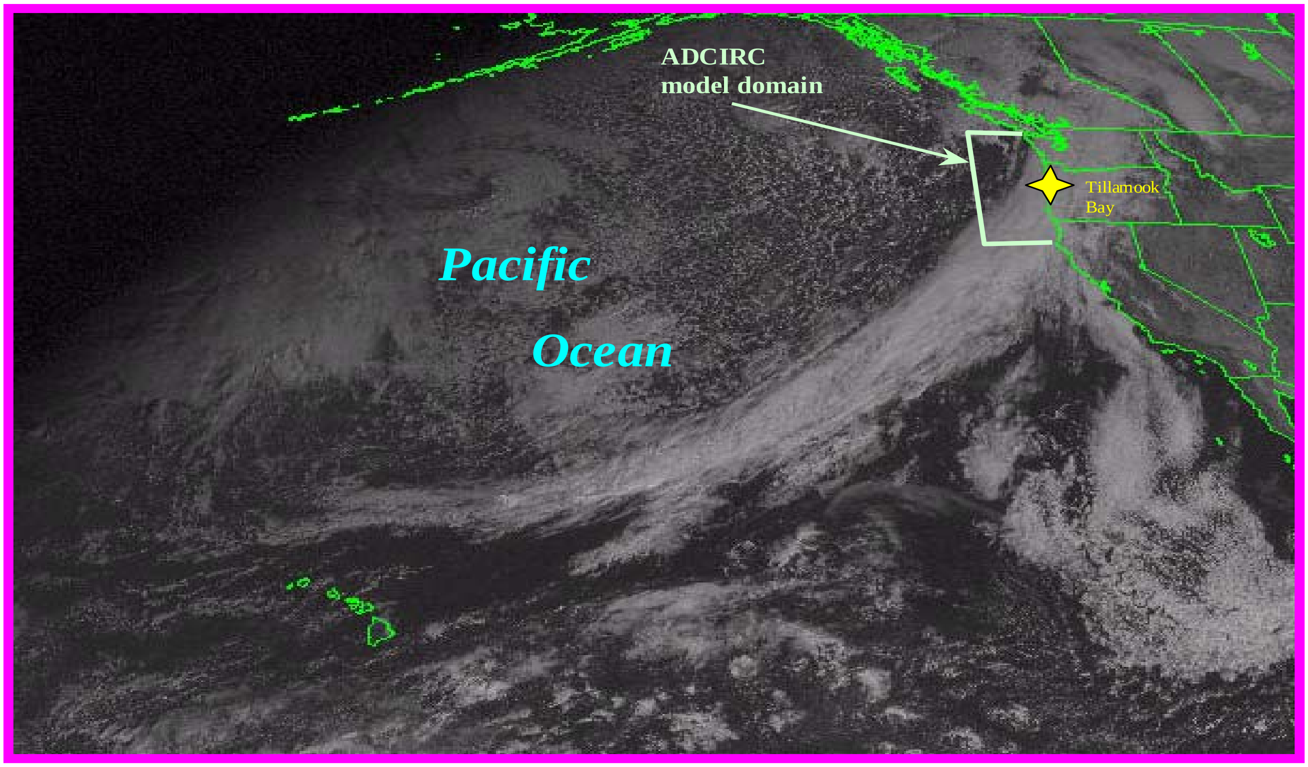


Figure 3. Present Tillamook Bay condition and alternative layout for plans A and B.



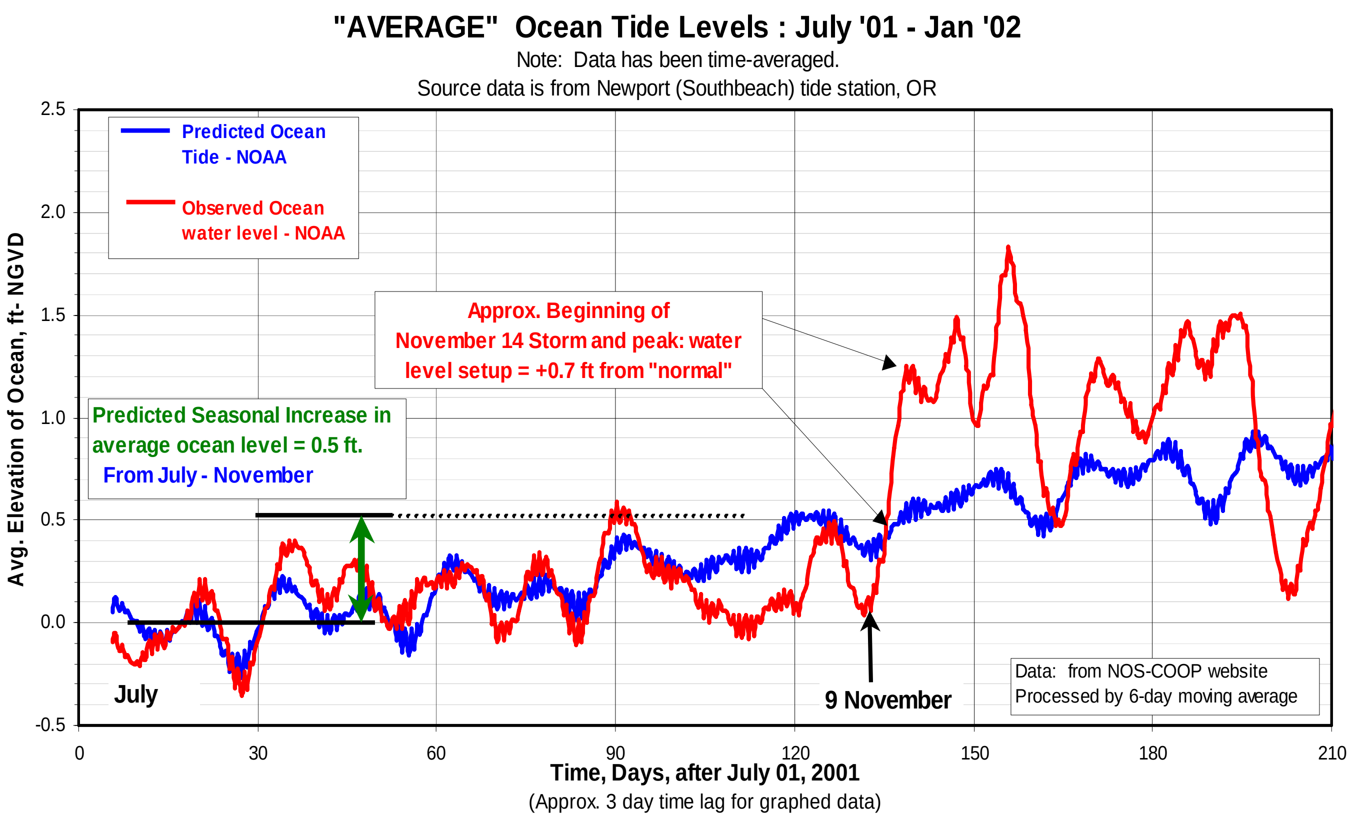
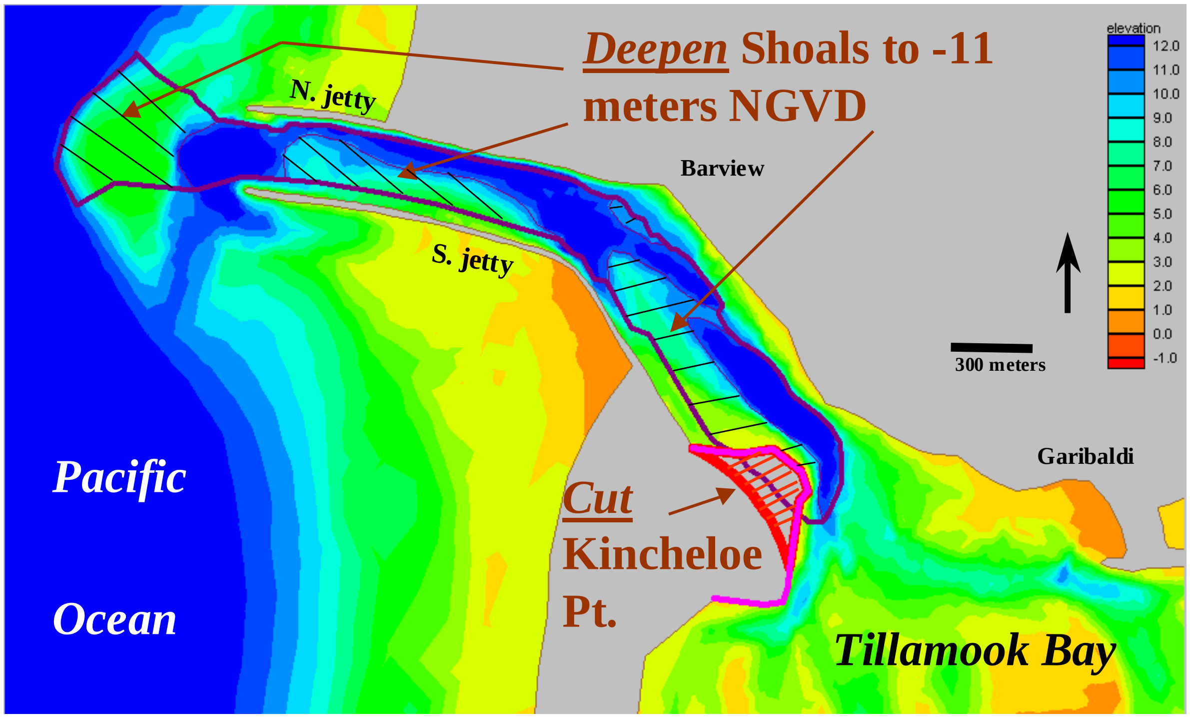


Figure 4. TOP. Satellite image of Northwest USA coast showing 14 November 2001 storm and ocean domain extent for Tillamook ADCIRC model. BOTTOM. Filtered tides for Tillamook Bay offshore showing season offset and transient set-up due to maritime storm. conditions

Kenchloe Pt. Cut and Entrance Channel Deepening



Tillamook Mid-Bay Channel Widening

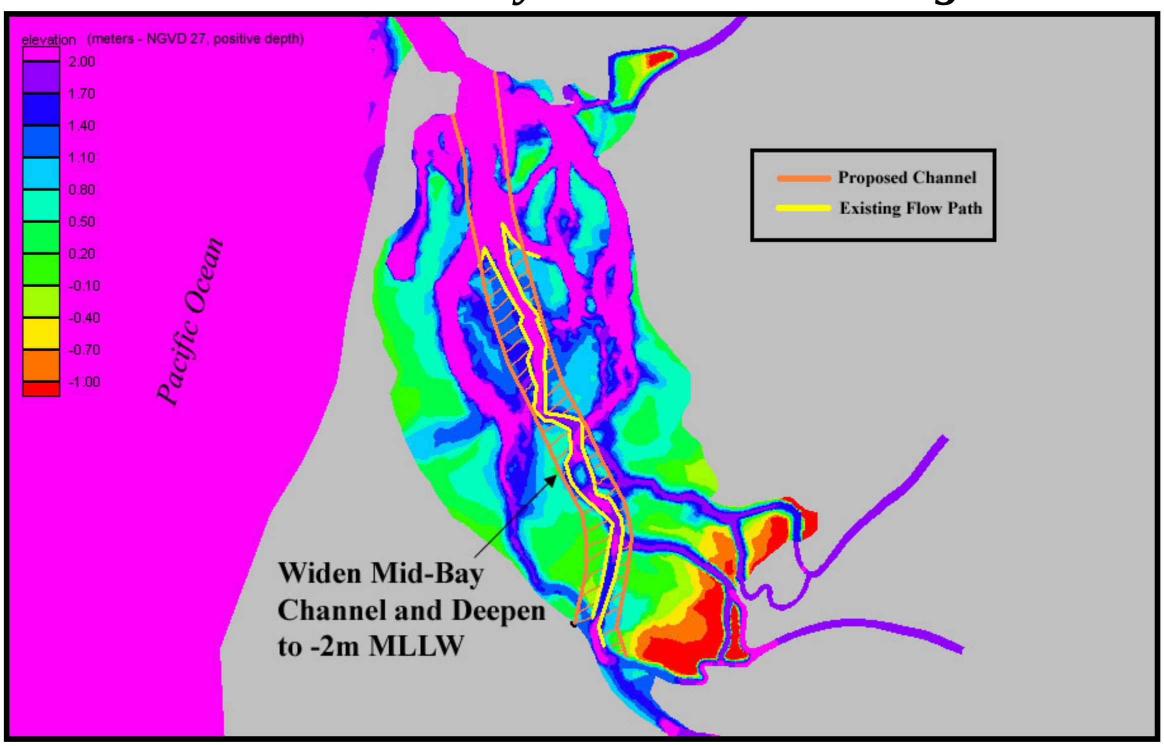
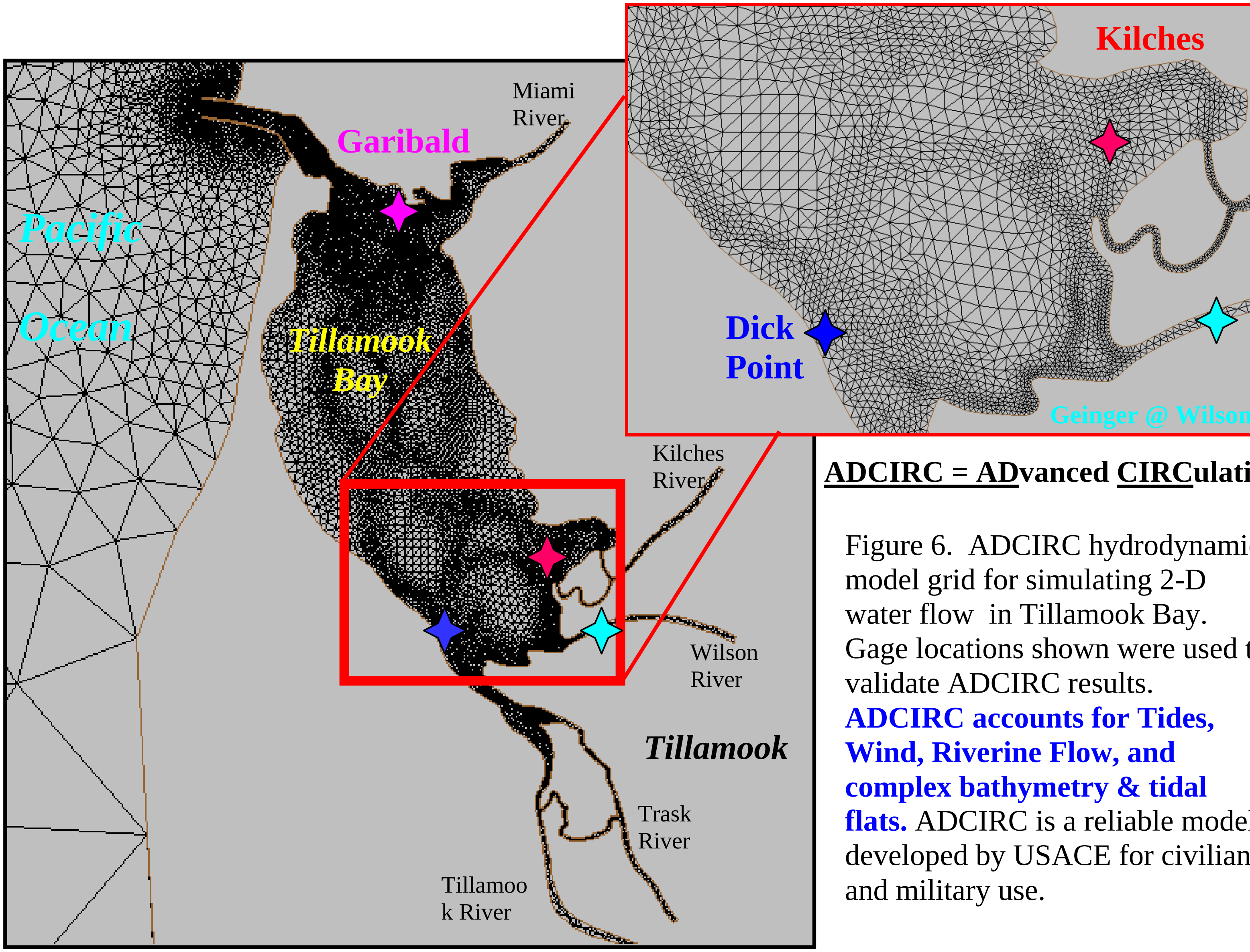
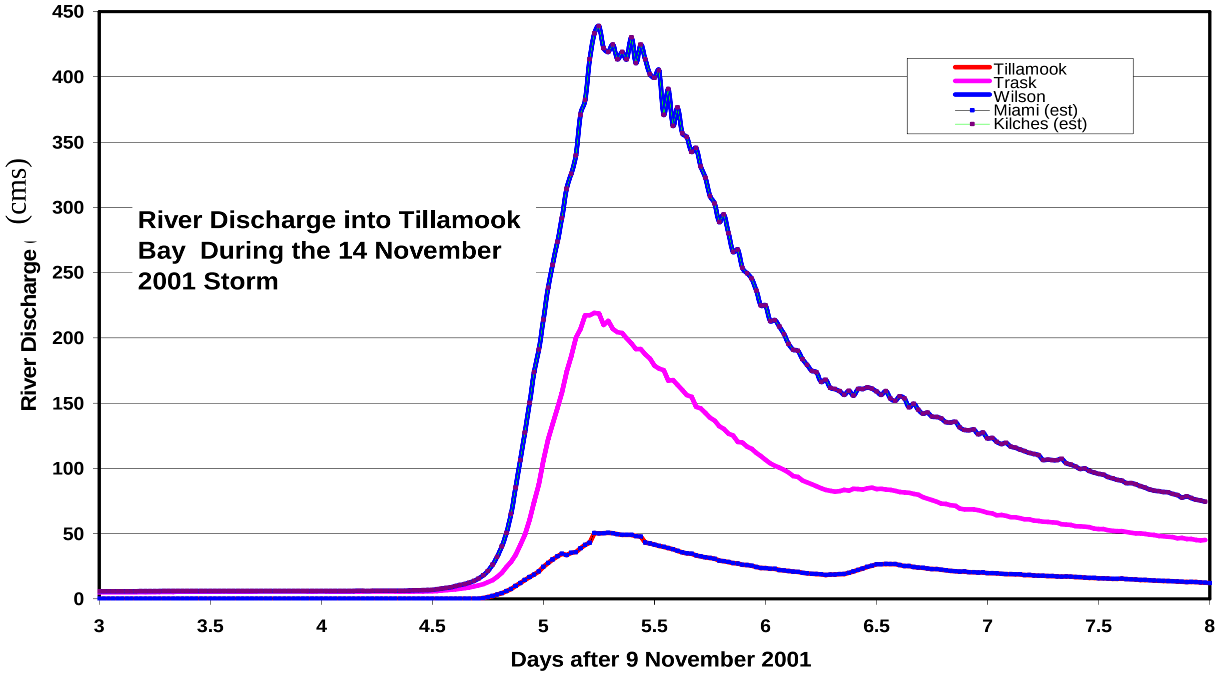


Figure 5. TOP. Alternative estuary modification plan A. BOTTOM. Alternative estuary modification plan B. Plan C is A + B



<u>ADCIRC = AD</u>vanced <u>CIRC</u>ulation

Figure 6. ADCIRC hydrodynamic model grid for simulating 2-D water flow in Tillamook Bay. Gage locations shown were used to validate ADCIRC results. **ADCIRC accounts for Tides, Wind, Riverine Flow, and complex bathymetry & tidal flats.** ADCIRC is a reliable model developed by USACE for civilian and military use.



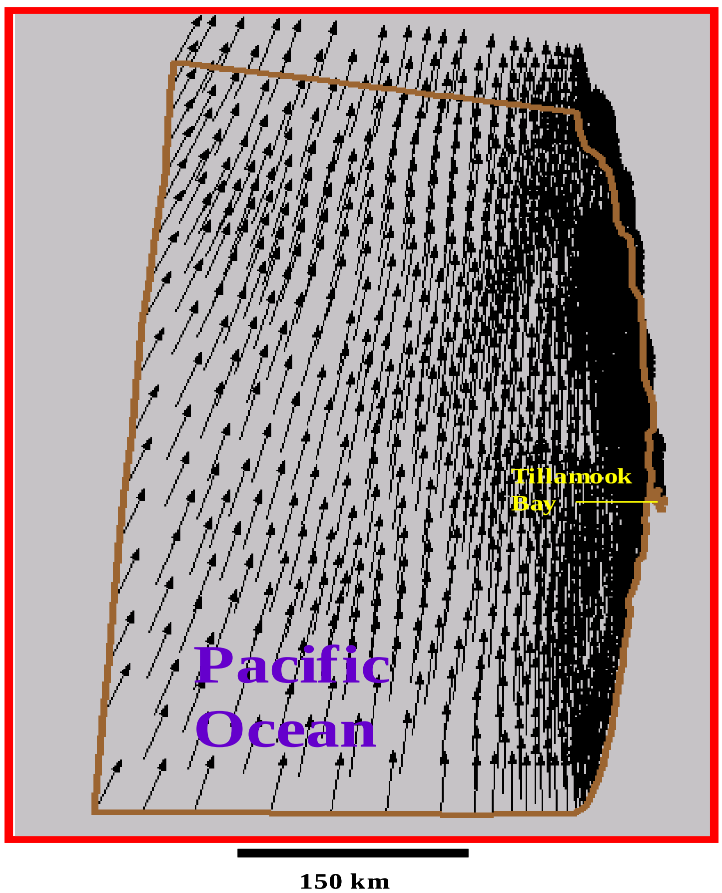
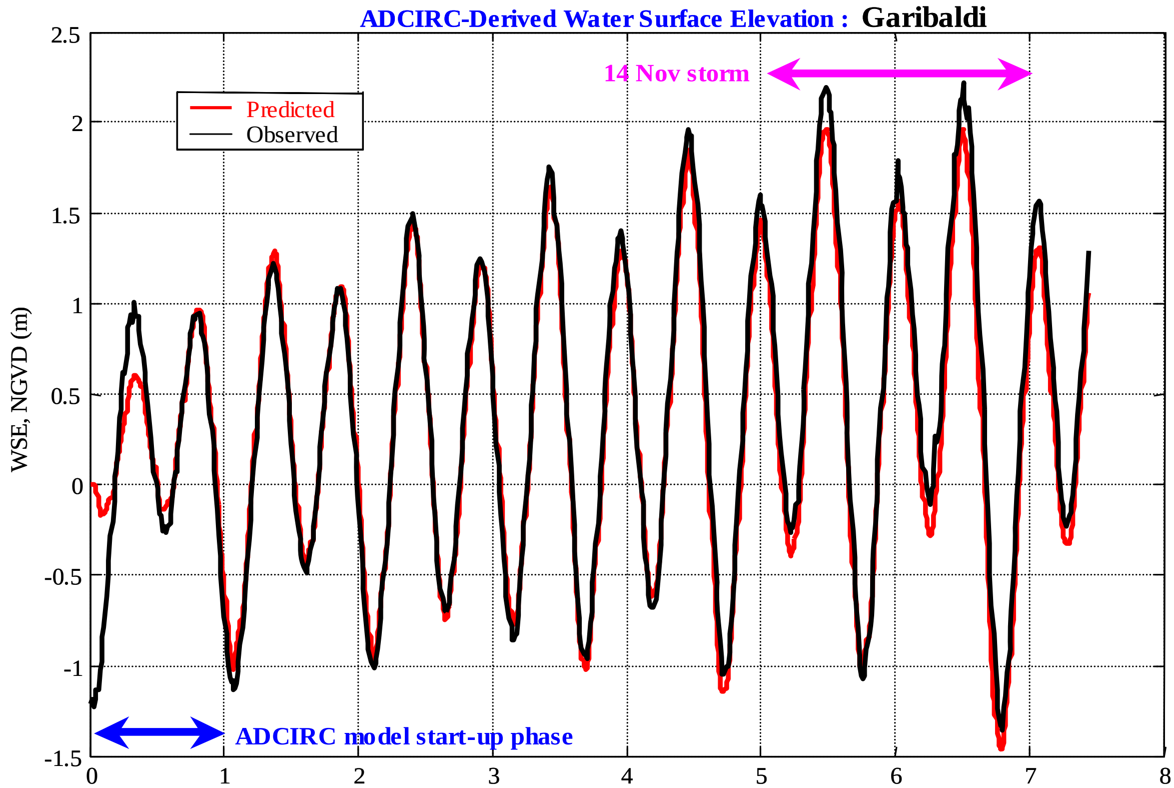


Figure 7. TOP. River flow hydrograph for 14 November 2001 storm.
BOTTOM. Windfield snapshot during passage of storm front over project area.



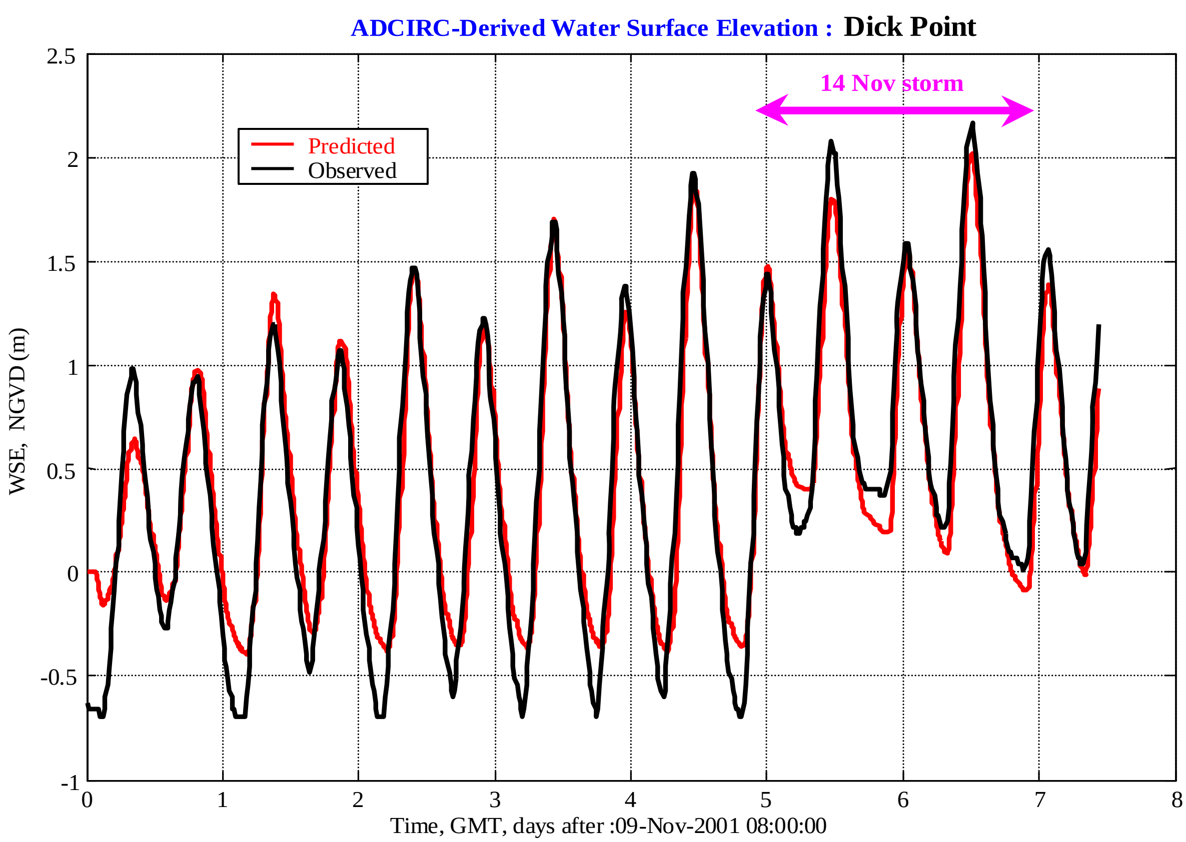


Figure 8. Validation results comparing observed WSE (stage) and ADCIRC model results

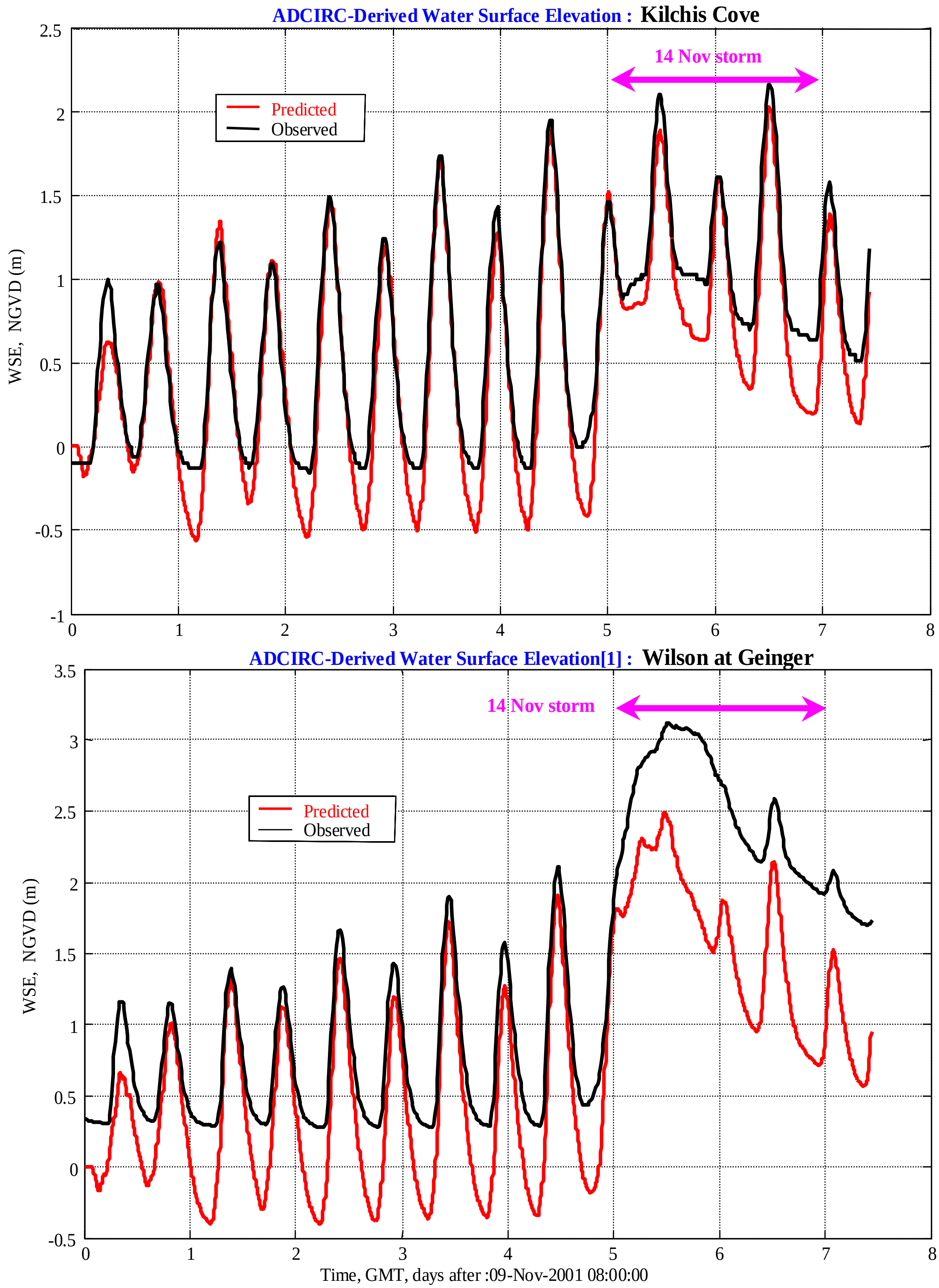
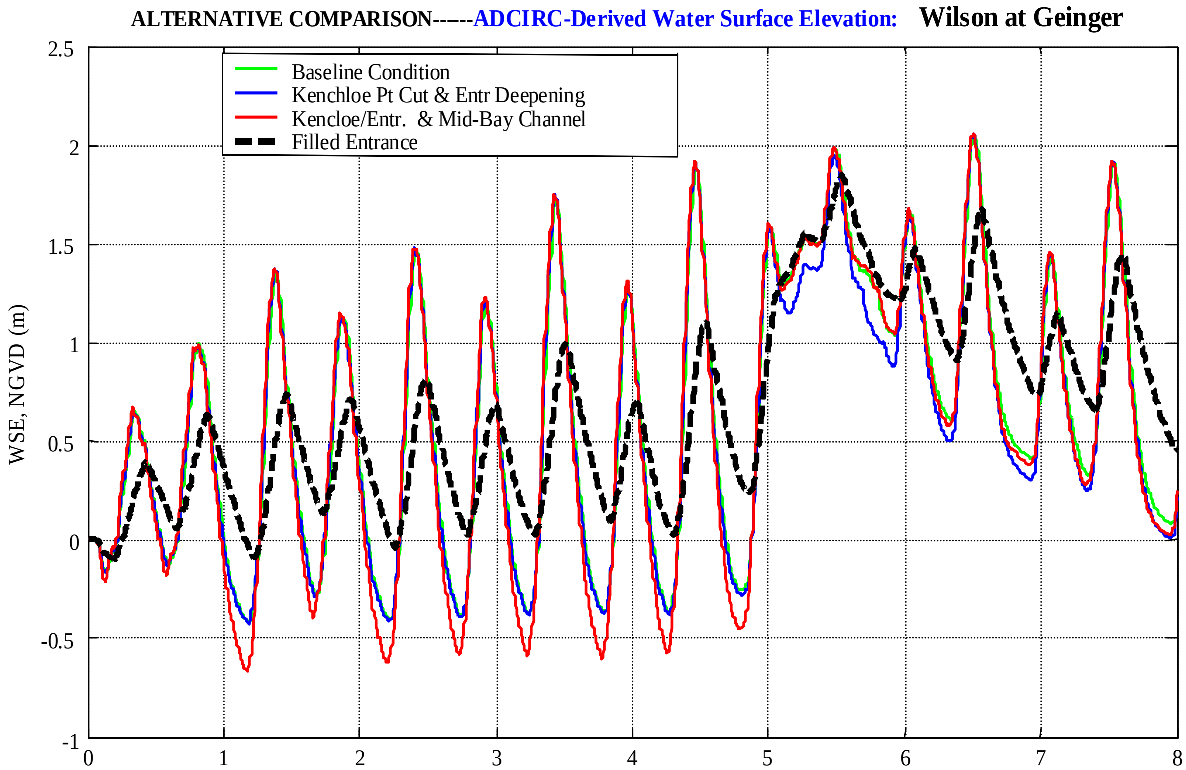


Figure 9. Validation results comparing observed WSE (stage) and ADCIRC model results.



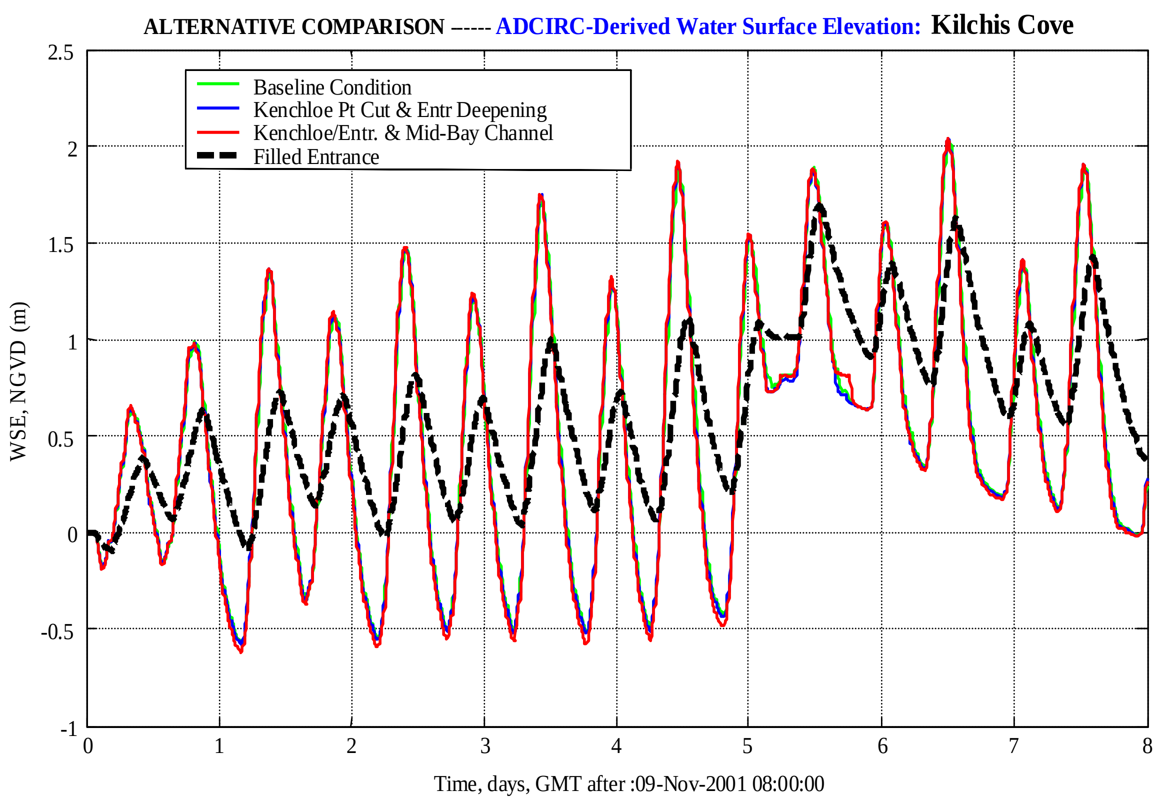


Figure 10. Alternative vs. existing condition results for WSE (stage) using the ADCIRC model.

NUMERICAL SIMULATION OF FLOW FIELDS IN THE TILLAMOOK BAY

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1.0 Introduction

The Tillamook Bay is a shallow estuary with a large number of mudflats. The estuarine environment is fairly complex, and the US Army Corp of Engineers – Portland District (CENWP) is involved in a joint project with Tillamook County to study the environmental impacts on the estuary. As part of the project CENWP is studying flood damage due to storms and the impacts of mitigation solutions. The Center for Coastal and Land Margin Research (CCALMR) at the Oregon Health and Science University (OHSU) has been contracted to provide CENWP with a working model of the Tillamook Bay. The development of a working model involves the development of a computational grid, and calibration studies with ADCIRC, which is a depth – averaged finite element circulation model, and the computational engine to be used in the simulations. This report is a culmination of the combined efforts of CENWP and CCALMR. The calibration studies have been carried out using tidal gages, for both storm and tidal conditions. The 2001 bathymetric survey data from CENWP has been incorporated in the development of the numerical grid.

2.0 Data

The Tillamook Bay estuary is a shallow estuary with a large number of inter-tidal mudflats. The estuary receives riverine inputs from five rivers – Tillamook, Trask, Wilson, Kilchis and Miami (see Figure 1). The river discharge contributions from the individual rivers (for the last 6 years) are shown in Figure 2. Major contributions of river discharge into the Tillamook estuary are via the Trask, Wilson and Kilchis rivers. A number of narrow channels provide the pathways for both the riverine discharge out of the estuary and the tidal flows in and out of the estuary. The existence of the narrow channels, interspersed with broad shallow tidal flats, make numerical simulations a challenging effort.

The USACE maintains 5 tidal gages inside the estuary (see Figure 1). The Garibaldi gage is located close to the mouth of the channel and is directly influenced by the ocean conditions at the mouth of the estuary. The remaining 4 gages are located further upstream and show a stronger influence of river discharge in their elevation data. The data from these gages has been used to validate the numerical model results. A comparison of tidal elevation data at Geinger with the data at the different gages shows that the Geinger gage consistently has a higher mean elevation than the other gages (see Figure 3). We hypothesize that this is due to an incorrect vertical datum at Geinger. For comparison purposes in this report, the data at Geinger has been consistently down-shifted by 0.5 m, a correction that needs to be verified in the field. Both the river discharge and tidal data has been obtained from CENWP.

3.0 Numerical Model

The numerical model used in this study is a two-dimensional finite element model known as ADCIRC. As used, ADCIRC simulates the depth-averaged barotropic flow conditions. It is a finite amplitude non-linear model and can also simulate wetting and drying of tidal flats, which is a crucial element of modeling Tillamook Bay. The vertical datum in the model runs was Mean Sea Level (MSL), which is the same as the NGVD datum. The bathymetry data was transformed from Mean Low Low Water (MLLW) to NGVD by adding 1m. The offshore tidal boundary conditions are specified in the frequency domain. Nine tidal components (see Table 1) have been chosen to represent the main tidal constituents observed at this site. Non – linear tidal components are not specified in the offshore bathymetry and allowed to develop within the model as the tides propagate onshore. The tidal amplitudes and phases are determined from an ocean tidal model (Myers and Baptista, 2001). Tidal amplitudes and phases remain fixed in the model. The nodal correction factors on the other hand depend upon the start of run and are determined using Mike Foreman's tidal analysis package. A mean offset component $\mathbf{Z_0}$ is provided to account for any offset not accounted for in the tidal forcings. For the calibration runs this offset was set to 0. The boundary condition at the river end is specified as a time series of flux per unit width. Apart from that, the model can also account for wind effects, which is specified as a time series of surface stresses and atmospheric pressure over the whole domain. Bottom friction effects have been accounted for by using a non-linear quadratic drag formulation. A spatially varying drag coefficient is specified using the manning formulation.

$$c_f = \frac{n^2 g}{h^{\frac{1}{3}}}$$

where, c_f is the bottom drag coefficient, n is the manning coefficient, h is the local depth and g is the acceleration due to gravity. After sensitivity analysis, we chose n = 0.030, for our runs.

The model outputs water elevation and horizontal velocities (along the north – south and east – west direction). The output files can be saved in binary or ascii format. The required input and output files are

- **Input Files**
    - Fort.15 This is the master control file specifying the length of the run, time step, ramp – up function, wetting and drying parameters, offshore tidal boundary conditions, nodal factors, time step for wind forcing, time step for river forcing, output storage type etc.
    - Fort.14 Grid file with bathymetry information. (Vertical datum is NGVD).
    - Fort.21 Drag coefficients for bottom friction
    - Fort.20 River discharge per unit width at all the river boundary nodes. Length of file dependant on the number of river boundary nodes, length of simulation and river discharge time step specified in Fort.15
    - Fort.22 Wind induced drag coefficients and atmospheric pressure over all the nodes as a function of time. Length of file depends upon length

of simulation, number of nodes in the grid and the wind forcing time step in Fort.15

- **Output Files**
  - Fort.63 Surface elevation data as a function of space and time. Ouput can be in ascii or binary format (specified in Fort.15). Output time step is specified in Fort.15
  - Fort.64 Horizontal velocity data. Horizontal velocity is output in the east – west and north – south coordinate system.

4.0 Numerical Grid

The Tillamook Bay estuary consists of numerous tidal flats and narrow channels. The grid was designed to carefully represent all the channels of the estuary. To prevent inadvertent drying of the channels by the model, a minimum of two elements is required across the channel width (a larger number is preferred). At the same time, numerical stability considerations limit the smallest size that the elements can get while keeping the time step within computationally feasible limits. The grid development involved several iterations of model simulations and grid modifications. The results presented in this report have been run on four different grids. Grid 1 is a fairly detailed grid of the Tillamook Bay estuary and the offshore bathymetry (see Figure 4). Grid 2 is a modified form of Grid 1 in which the offshore grid has been extended in the north and south directions. This was done to determine the effects of wind blowing over larger offshore domains on the dynamics within the estuary. Grid 3 is a further modified version of Grid 2, in which the river boundaries have been cut-off fairly close to the estuary. The final grid, Grid 4, was developed from Grid 1 by CENWP. It covers the same extent as Grid 1 did, except that in Grid 4 the river boundaries have been cut short and changed to allow easier passage of discharge into the estuary. Anomalous depths and badly shaped elements inside the estuary have also been removed after careful examination.

5.0 Model Simulations

Model simulations have been divided into two periods. In the first case we chose a time period with very low river discharge so that the main forcing was tidal. The aim was to test how well the tidal oscillations are simulated by the numerical model. In the second case we chose the time period centered around a storm event which was accompanied by strong wind conditions and higher levels of river discharge into the estuary.

5.1 Tidal flows test case

The tidal flow test case was run for a 15-day simulation extending from 04/14/2001 to 04/29/2001. The run had a 5-day ramp-up period, which is included in the 15-day simulation period. The river discharge during this period was very low (see Figure 6) and thus the river boundaries were treated as closed boundaries for this test case. No winds were forced for this run. Tides were forced from the output of a regional tidal model in the frequency domain, all along the offshore open boundary. The aim of this test was to observe how well the model propagates tides into the estuary. The model simulations were found to be stable for time steps no greater than 2 seconds. This limitation is due to the numerical restrictions placed on the model by the smallest elements in the grid. Simulations with time step greater than 2 seconds blew up due to numerical instabilities. Thus, a time step of 2 seconds has been used for all the calibration runs. It might be possible to run the model with a time step of 3 seconds if the resulting flow field is not very strong.

Figure 7 shows the model-to-data comparisons of a tidal run in which a large horizontal diffusion value of 10 m^2s^{-1} was used. This was done to remove noise due to boundary effects in the northern ocean boundary, and also to stabilize the solution at the mouth of the estuary. However, numerical instabilities continued to grow inside the estuary. These instabilities were linked to the horizontal diffusion and increased with increase in horizontal diffusion. The numerical solutions were found to be unstable for values of horizontal diffusion greater than 1 m^2s^{-1}. This is contrary to what we would expect, where the horizontal diffusion is expected to decrease noise. We hypothesized that inside the narrow channels of the estuary, the horizontal diffusion was having a negative impact by spreading the noise in the flow field into the much shallower tidal flat region, where the noise was amplified instead of being suppressed. Figure 8 shows the model data comparisons for a test case in which a spatially varying horizontal diffusion coefficient is used. For this simulation the horizontal diffusion coefficient was 3 m^2s^{-1} in the region around the mouth of the estuary, 50 m^2s^{-1} around the northern offshore boundary and 1 m^2s^{-1} everywhere else. The results are much better when compared to those in Figure 7. From personal communications with Michael Knutson at CENWP, it was found that the tidal gages at Kilchis and Geinger come out of the water during low tides. This would explain the cutoff in the tidal signals of these gages during low tides. There seems to be a phase lag between model and data results at Garibaldi. Since this phase lag was not observed at any of the other stations and tends to be constant, it is probably due to a clocking error in the signal. Both these simulations were conducted on Grid 1. Simulation results conducted with Grid 4 are shown in Figure 9. With Grid 4, the results at Dick-Point are much better. This is because in Grid 1, one of the channels feeding into Dick-Point was inadvertently drying. That problem was fixed with the modified grid of Grid 4. The simulations with Grid 4 also lead to stronger tidal signals at the upstream gages of Kilchis, Geinger and Carnahan. Due to the drying of the Geinger and Kilchis gages, it is not possible to determine how much off the model results are from the data during low tides. In conclusion, the model does reasonably well in simulating tidal flow conditions. The horizontal diffusion coefficient inside the estuary should not be allowed to be greater than 1 m^2s^{-1}, as that leads to the growth in numerical instabilities. To maintain channel connectivity it is important to have at least 3 elements across the channel if not more.

5.2 Storm Event

A storm front passed through the Tillamook Bay area around 11/14/2001. Accurate modeling of such storm events would prove extremely useful as it would provide engineers with regions of flooding. Sensitivity studies involving the effects of bathymetric changes on flooding patterns during storm events can also be attempted. With this goal in mind, we concentrated our efforts in trying to simulate the November 14th storm with the ADCIRC model.

Wind data obtained from a NOAA offshore buoy (Yaquina Bay buoy) showed strong offshore winds blowing in from the south during this time period (see Figure 10). Due to Coriolis forcing, the direct effect of strong winds blowing in from the south will be a setup at the mouth of the estuary. Since the numerical model requires a large ocean surface area to develop the required Coriolis effect, we carried out the simulations over larger grids (see Figure 5 for a comparison of the extents of coverage between the smaller and larger grids). The major problem with using the Yaquina Bay buoy data to represent winds is that it does not provide us with any spatial variations of the wind. Alternatively, we have used atmospheric forecast models to provide us with required wind forcing. The wind data was obtained from two numerical weather prediction models. The first is the Medium Range Forecast (MRF) produced by a Global Spectral Model (GSM) at the National Center for Environmental Prediction (NCEP). The MRF provides data on a relatively coarse grid at a low temporal frequency. Higher spatial and temporal resolution data is provided by a local forecast run of the Advanced Regional Prediction System (ARPS) at Oregon State University (OSU). A weighted average of these two sources is used to obtain the desired wind conditions, with the OSU data (when/where it exists) given a weighting twice that of the MRF data. Though this is not real data, it does provide us with both spatial and temporal wind information. The comparison between the forecast wind and buoy wind data is given in Figure 11. The observed river discharge also increased quite considerably during the storm event (see Figure 12), with the discharge at Wilson river increasing from almost 0 to over 400 cms in one day. The effect of both the wind setup and river discharge can be observed in the gage data (see Figure 13). The gage at Garibaldi was the only gage that was working consistently over this entire period. All the other gages stopped working during the storm. Once again the Geinger gage is showing a mean level much higher than any of the other gages, and just like in the tidal test case, we reduce the vertical datum by 0.5 m for comparison with model results. The Dick-Point gage is also showing a higher mean level, specially during the period before the storm when the discharge levels are low and the winds are not very strong. This might also be related to the vertical datum of the gage being shifted, but we do not know that for sure. As a result we did not try to adjust the datum of this gage.

For model simulations we now force the tides at the offshore boundaries, wind over the entire domain and river discharge per unit width at all the river open boundaries. Since river discharge data is available only for three rivers (Figure 12) we assume that the discharge at Miami river is the same as the discharge at Tillamook river and the discharge at Kilchis river is the same as the discharge at Wilson river. The basis for this assumption is the 5-year river discharge data in Figure 2, which shows some level of compatibility between Miami and Tillamook river and Wilson and Kilchis river respectively. Wind effects are accounted for by providing time series of surface stress over the entire domain. Surface stress is related to wind speed and direction by

$$\left(\tau_{Wx}, \tau_{Wy}\right) = \rho_a C_{Ds} \left|\vec{W}\right| \left(W_x, W_y\right)$$

where ρ_a is the air density [kgm^{-3}], C_{Ds} is the wind drag coefficient and $\vec{W}(x, y, t)$ is the wind velocity at 10m above the sea surface, with manitude $|W|$ and components W_x and W_y [ms^{-1}] . The drag coefficient C_{Ds} is parametrized such that the transfer of momentum from air to ocean increases with wind speed.

$$C_{Ds} = 10^{-3}\left(A_{W1} + A_{W2}\left|\vec{W}\right|\right)$$

where A_{W1} and A_{W2} are 0.75 and 0.067 respectively. These coefficients have been calibrated in literature for strong wind conditions (Garratt, 1977).

Numerical simulation results for the storm event are shown in Figure 14. The simulation was done on Grid 1. The net effects of wind setup and river discharge can be seen in Figure 15, where the tidal signature has been averaged out using a running average window with a window length of one day. The tidal signal at the Dick-Point gage is more damped in the model results when compared to the data and the observed wind setup is much higher than the simulated wind setup at the Garibaldi gage. Since this wind setup could be related to offshore wind forcing and subsequent turning of water mass towards the coast due to coriolis effects, one of the causes of the model performing poorly could be that the ocean part of the grid is too small to adequately generate enough transfer of water mass towards the coast. With this in mind the model was rerun with Grid 2, which extends over a larger domain in the ocean (see Figure 5 for a comparison of Grid 1 and Grid 2). The results of that simulation are given in Figure 16 and Figure 17. The model has some difficulty with the northern boundary of the grid and blows up after 12 days of simulation (see Figure 18). The setup in the model results at Garibaldi, though much more significant than before are still not adequate. This maybe because of local wind effects, which would amplify the setup at Garibaldi due to the north-south orientation of the estuary (see Figure 1). The wind information available to us is from a numerical model that is run on a much larger scale, and does not account for local winds. Another possibility is that the formulation used to wind speeds and direction to surface stresses is inadequate. This however is unlikely because these formulations have been used exhaustively in the literature. Apart from the setup issue, the tidal signature at Geinger shows a poor comparison between model and data results. This is probably due to the way the river bed was handled in the grid. In reality, the river bed slopes above the mean sea level a short distance upstream of the estuary. To allow transport of river flux from the river boundaries into the estuary without causing drying due to numerical instabilities, the upward slope of the river beds was removed from the grid. This probably led to a deeper penetration of the tides in the model. To prevent this the model was run on a different grid (Grid 3), which differed from Grid 2 in that the rivers were cut-off before the river beds sloped above the mean sea level, hence removing any need to change the bathymetry. The results of that run are shown in Figure 19 and Figure 20. The tidal signature is much better represented at Geinger in this simulation. In all of these simulations, the Kilchis river dries up during the strong discharge period due to the propagation of numerical noise (see Figure 21). This might be because we are forcing too strong a discharge into the rivers (note that we assumed the discharge in Kilchis river being the same as the discharge in the Wilson river). Based on the success that we had with using the USACE modified grid (Grid 4) in the tidal test cases (see Figure 9), we ran a simulation for the storm event on the particular grid. The results are shown in Figure 22 and Figure 23. It is best to compare these results with those of Grid 1, given in Figure 14 and Figure 15, since both grids cover a similar extent of region in the ocean. Wind setup at Garibaldi is better represented in Grid 4. This is very encouraging because the model performance should improve if we extend the ocean domain of Grid 4, as we did for Grid 1. The Kilchis river however continues to dry due to numerical instabilities and this is an area of concern as it effectively removes the estuarine effects of strong discharge in the Kilchis river.

6.0 Conclusions

The aim of this project has been to get the ADCIRC model to simulate flows in the Tillamook Bay estuary with reasonable level of accuracy. The study was divided into two parts. In the first part we concentrated on the abilities of the model to propagate tidal flow. To simulate tidal flow, 9 tidal components were forced at the offshore boundary. The tidal amplitudes and phases were determined from a regional tidal model. The tidal simulations were carried out in a period with low river discharge so as to minimize effects from other forcings (such as river discharge) on the gage data. Simulations were found to be highly sensitive to horizontal mixing coefficients, and a spatially varying diffusion coefficient was applied to simulate the flows. Comparisons with data have shown that with appropriate horizontal diffusion coefficients and grid, the model can simulate tidal flows reasonably well.

The second part of the study involved simulating a storm event. This was a more complex case, as the estuary was forced by tides, winds and river discharge. Atmospheric numerical models were used to determine the appropriate wind forcing conditions, while the river discharge was forced by measured data. Since actual discharge data was not available for all the rivers, some approximations had to be made for discharge conditions. Simulation results showed that setup near the mouth of the estuary depends on the offshore extent of the grid. The setup is higher for grids that cover a larger area over the ocean. The wind setup was however still insufficient. This could in principle be because we need a larger grid over the ocean, or the drag coefficients that convert wind speed to surface drag need to be larger. More likely, however, the model to data disparity could be due to local wind effects that are not captured by the atmospheric models that were used to determine the wind forcings. Another area of concern in the storm simulations has been the drying of the Kilchis river during periods of strong discharge. This drying is an artifact of numerical instability and needs to be addressed if the effects of Kilchis river are to be investigated.

Acknowledgements

The authors would like to thank Michael Knutson, Hans Moritz and Jessica Hays of the United States Army Corps of Engineers (USACE) for providing us with the data used in this study. Hans Moritz and Jessica Hays also developed one of the grids (Grid 4) used in this study. Dr. Mike Zulauf of the Center for Coastal and Land Margin Research (CCALMR) provided us with the required wind forcings for the storm condition simulations.

References

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1977 Garratt, J.R. "Review of drag coefficients over oceans and continents." Monthly Weather Rev. 105: 915-929.

Table 1: Tidal Components forced at the offshore boundary in ADCIRC

Tidal Components	Frequency (rad/sec)
Z_0	0.0000000000
M_2	0.0001405189
S_2	0.0001454441
N_2	0.0001378797
K_2	0.0001458423
K_1	0.0000729212
P_1	0.0000725106
O_1	0.0000675977
Q_1	0.0000649546

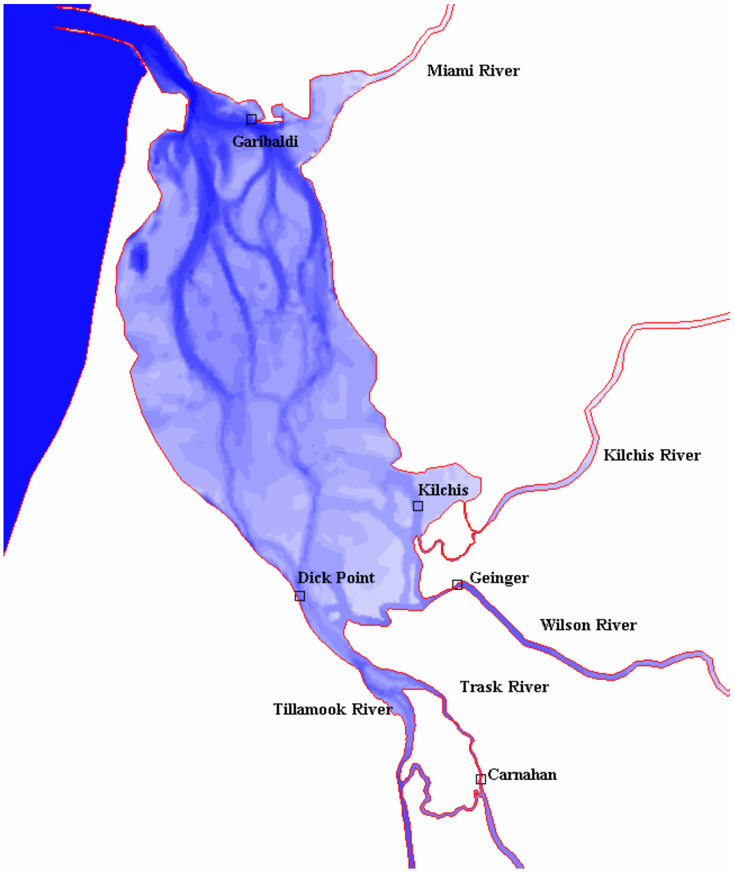

Figure 1: Tillamook Bay Estuary (Gage Locations marked by rectangles)

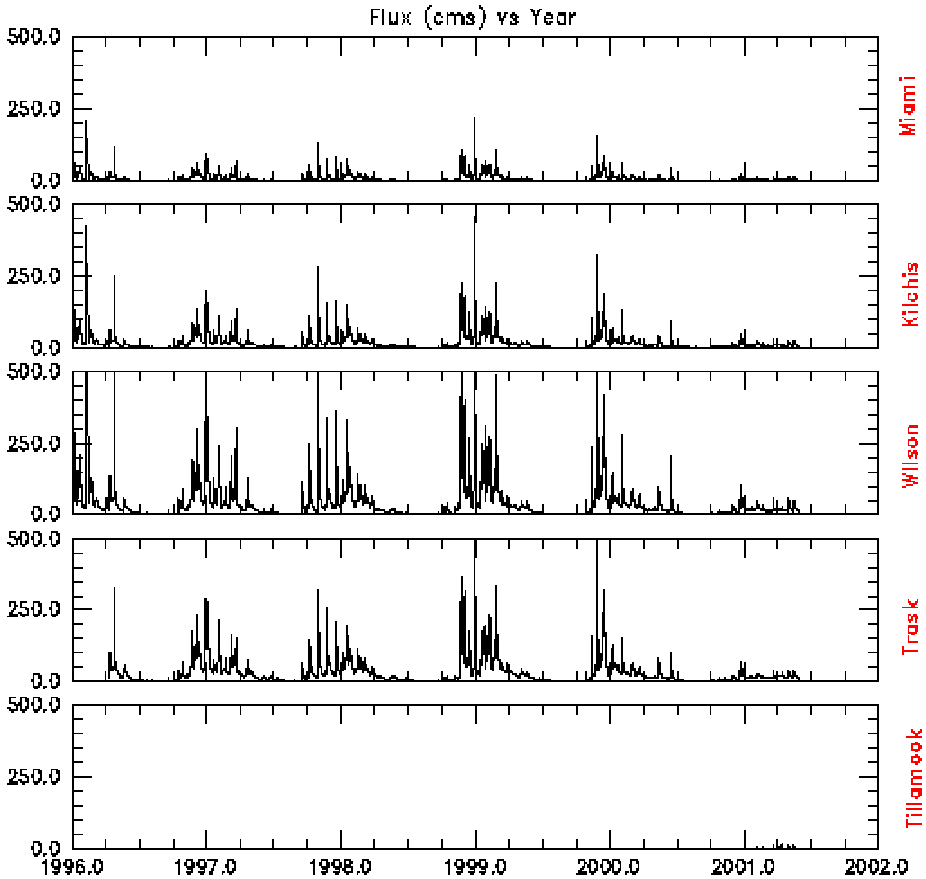

Figure 2: River discharge contributions from the 5 rivers into the Tillamook Estuary between 1996 and 2002.

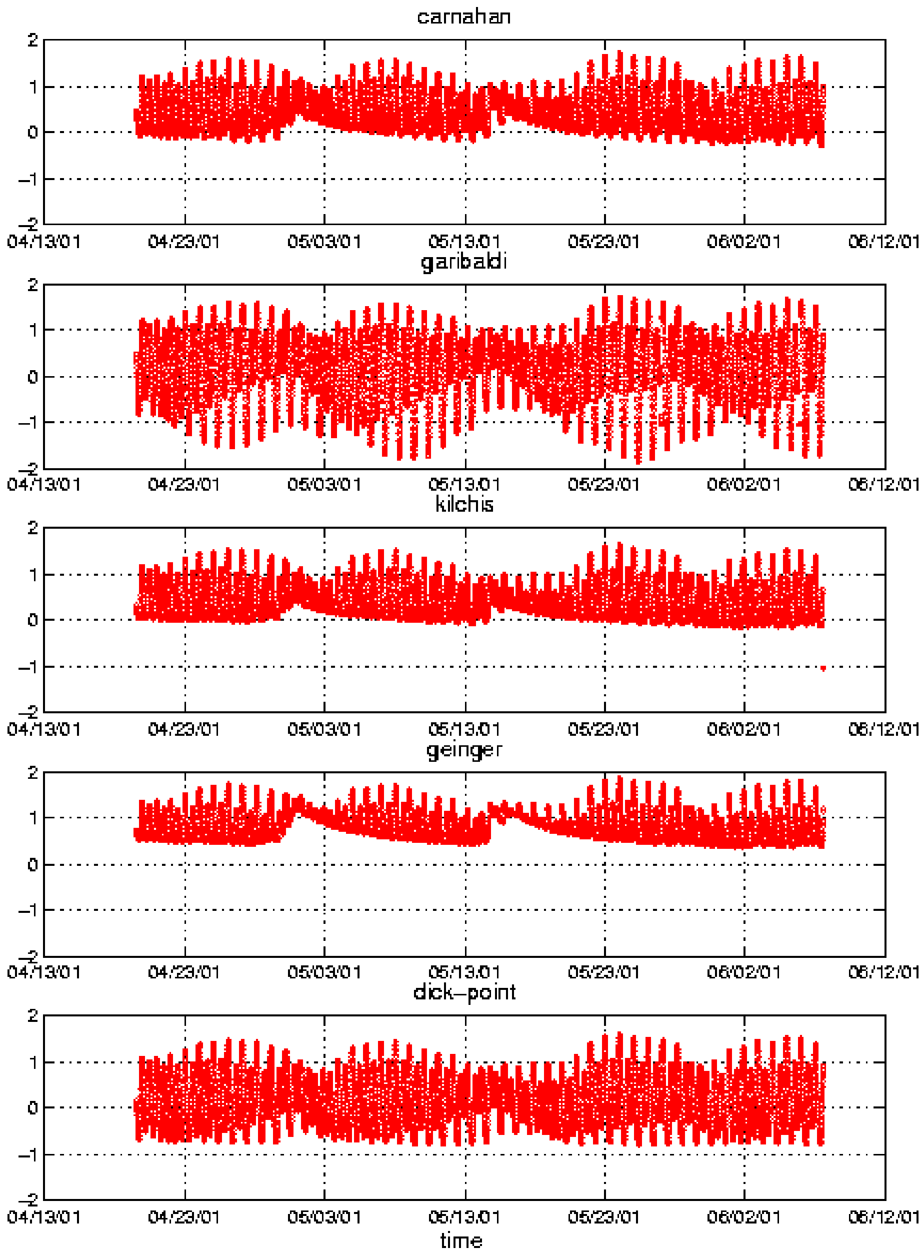

Figure 3: USACE gage data for a two month period

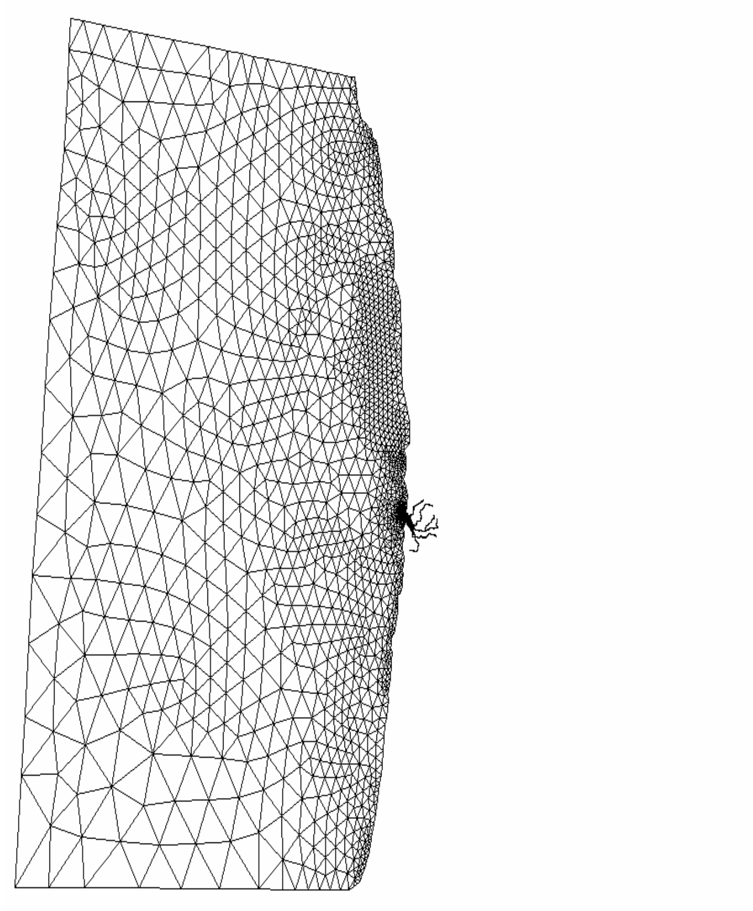

Figure 4: Tillamook Bay estuary GRID1

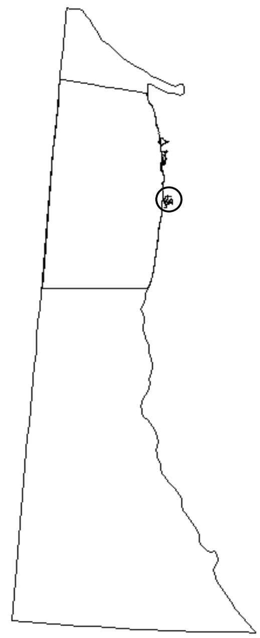

Figure 5: A comparison of offshore extent covered by the smaller grids (Grid 1 and Grid 4), and the larger grids (Grid 2 and Grid 3). Tillamook Bay estuary is circled in the image.

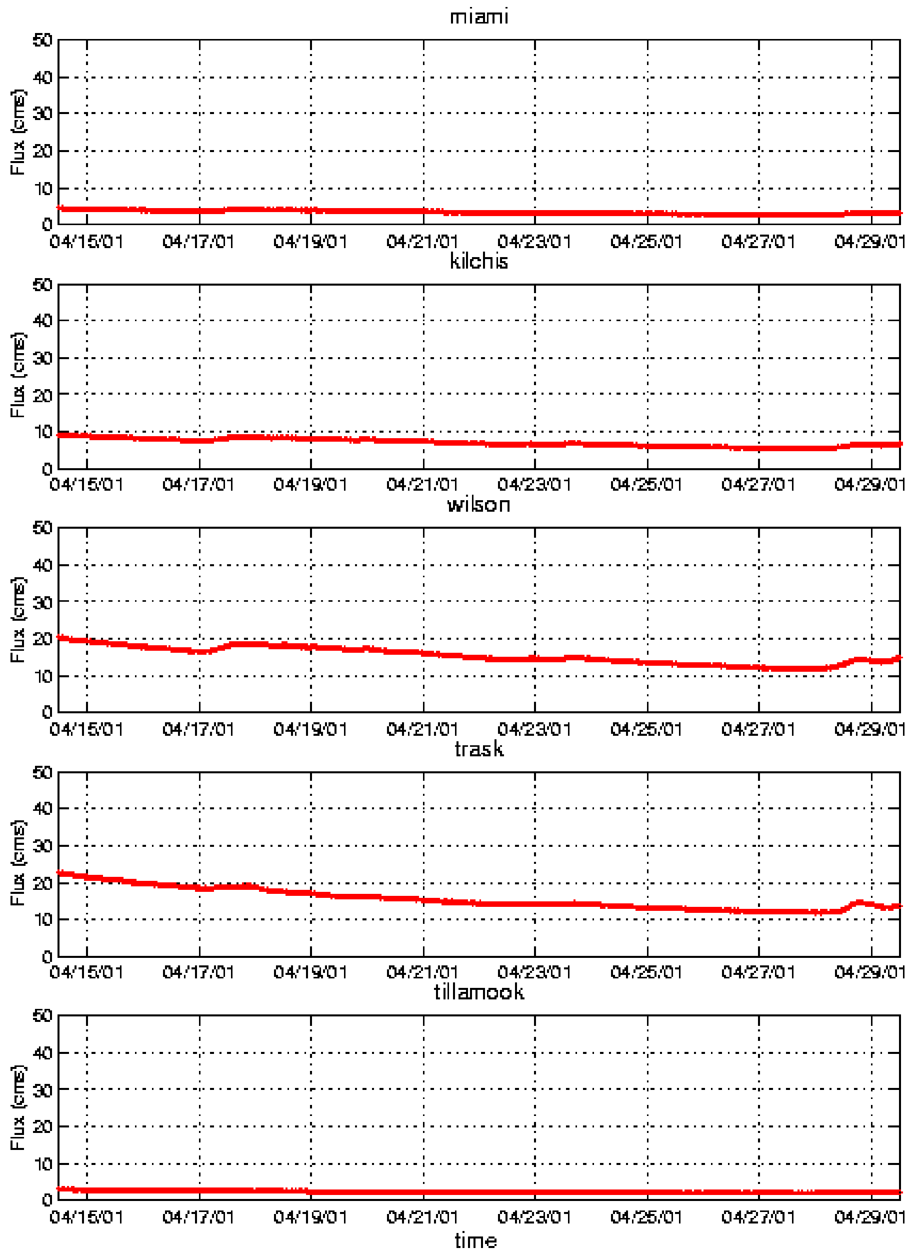

Figure 6: River discharge in cms for the time period of the tidal test case

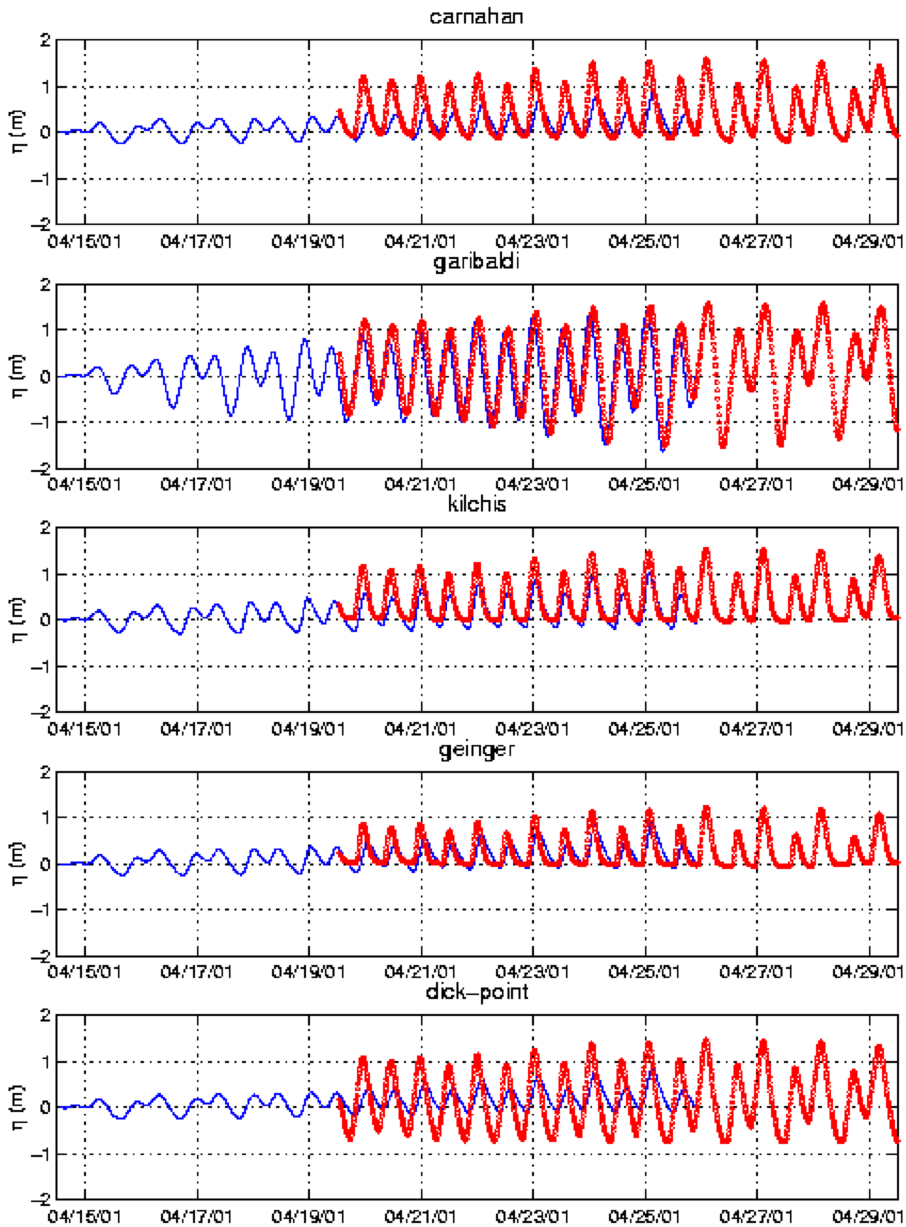

Figure 7: Model (Blue) to Data (Red) comparison of elevation (Tidal test case, constant horizontal diffusion, Grid1)

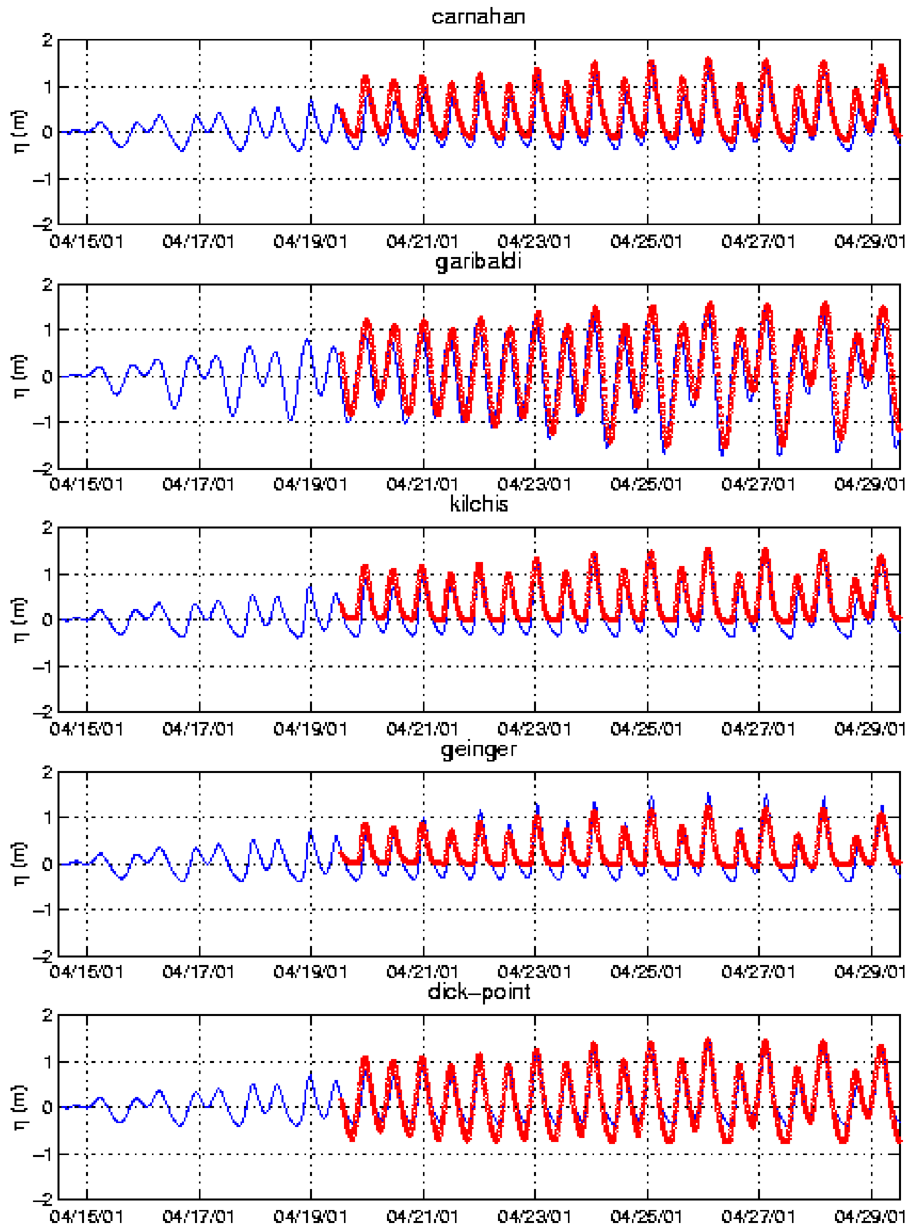

Figure 8: Model (Blue) to Data (Red) comparison of elevation (Tidal test case, spatially varying horizontal diffusion, Grid1)

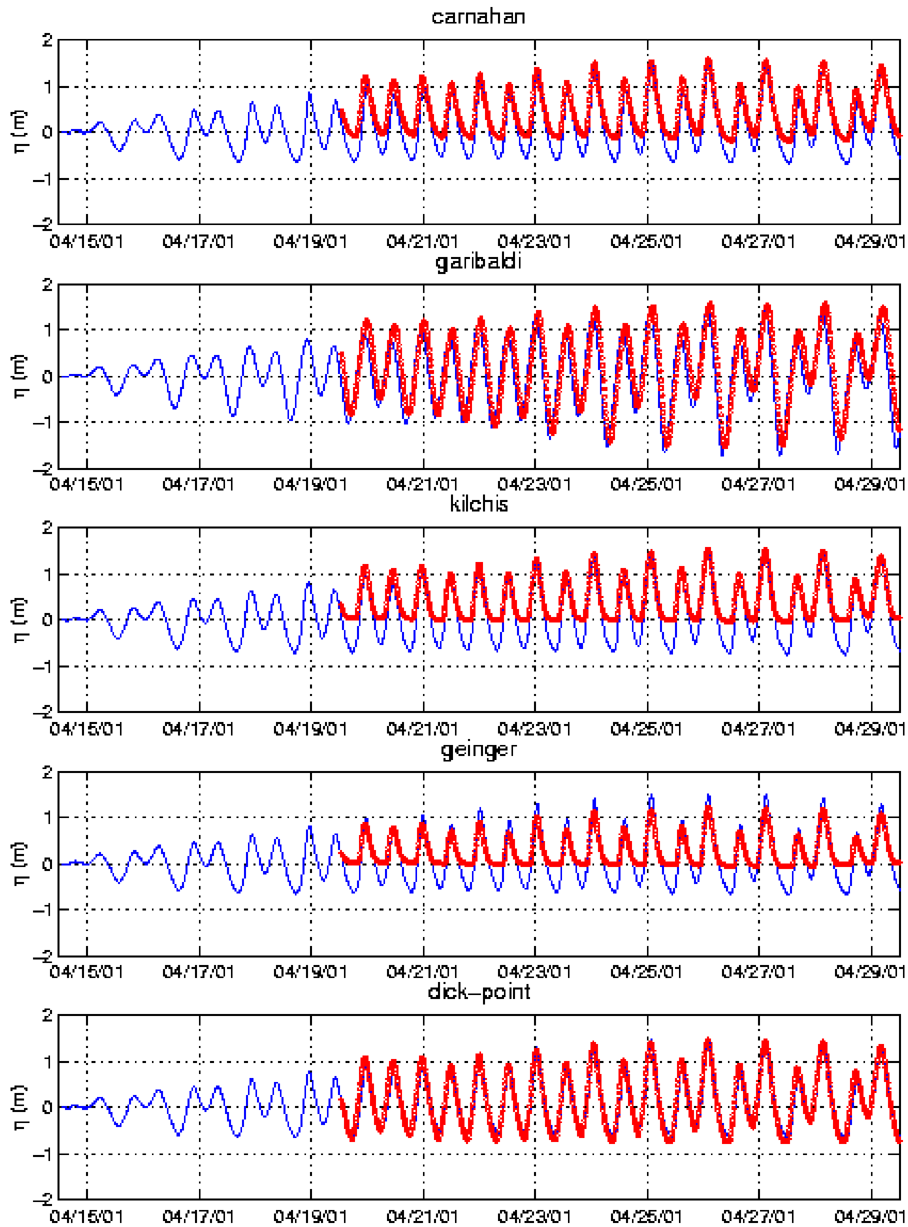

Figure 9: Model (Blue) to Data (Red) comparison of elevation (Tidal test case, spatially varying horizontal diffusion, Grid4)

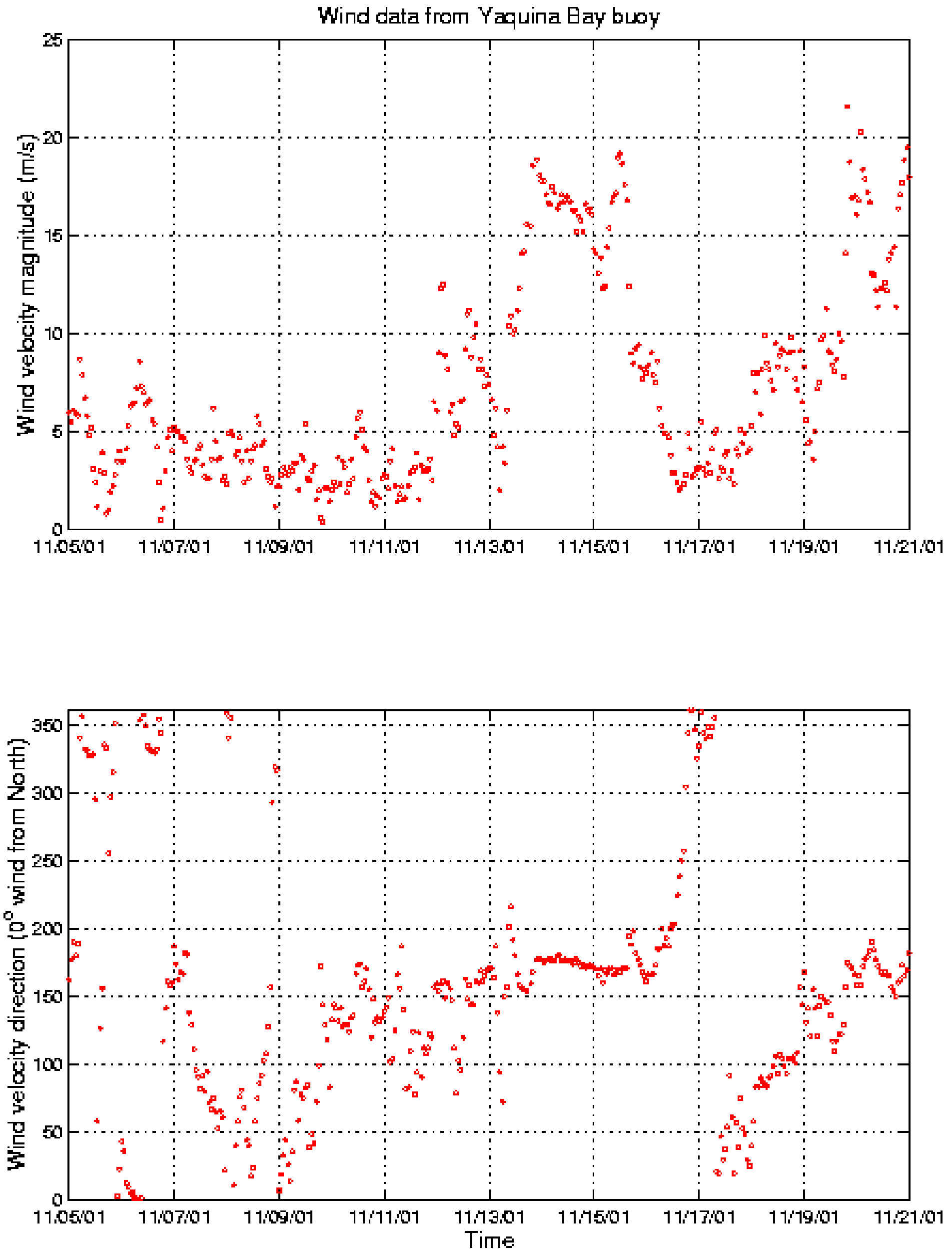

Figure 10: Offshore wind data from Yaquina Bay buoy. The buoy is approximately 67km due west and 118 km due south of the mouth of the Tillamook Bay estuary.

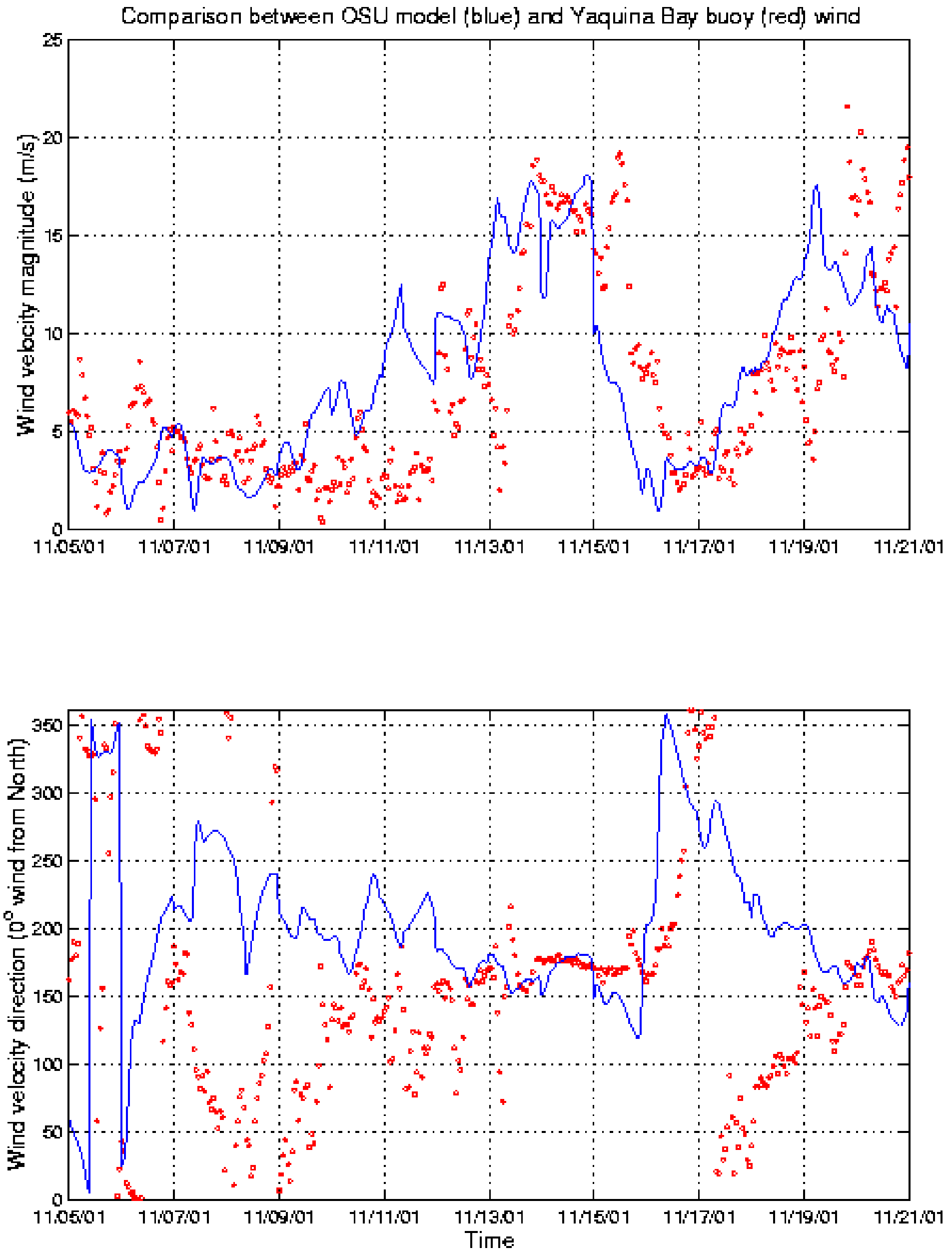

Figure 11: Comparison between OSU atmospheric model wind forecasts and Yaquina Bay buoy wind data.

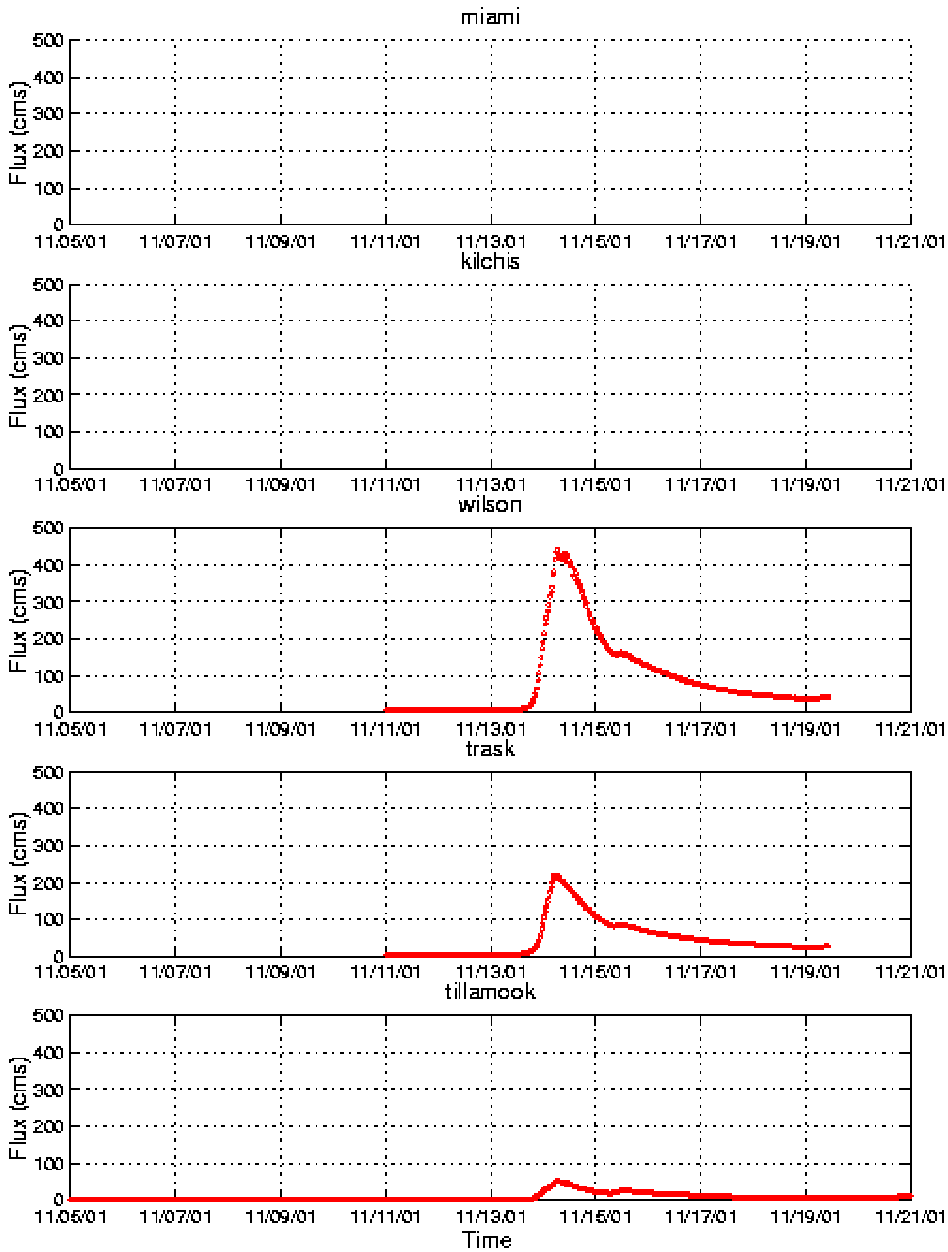

Figure 12: River discharge around the November 14th storm event. No discharge data was available for Miami and Kilchis rivers.

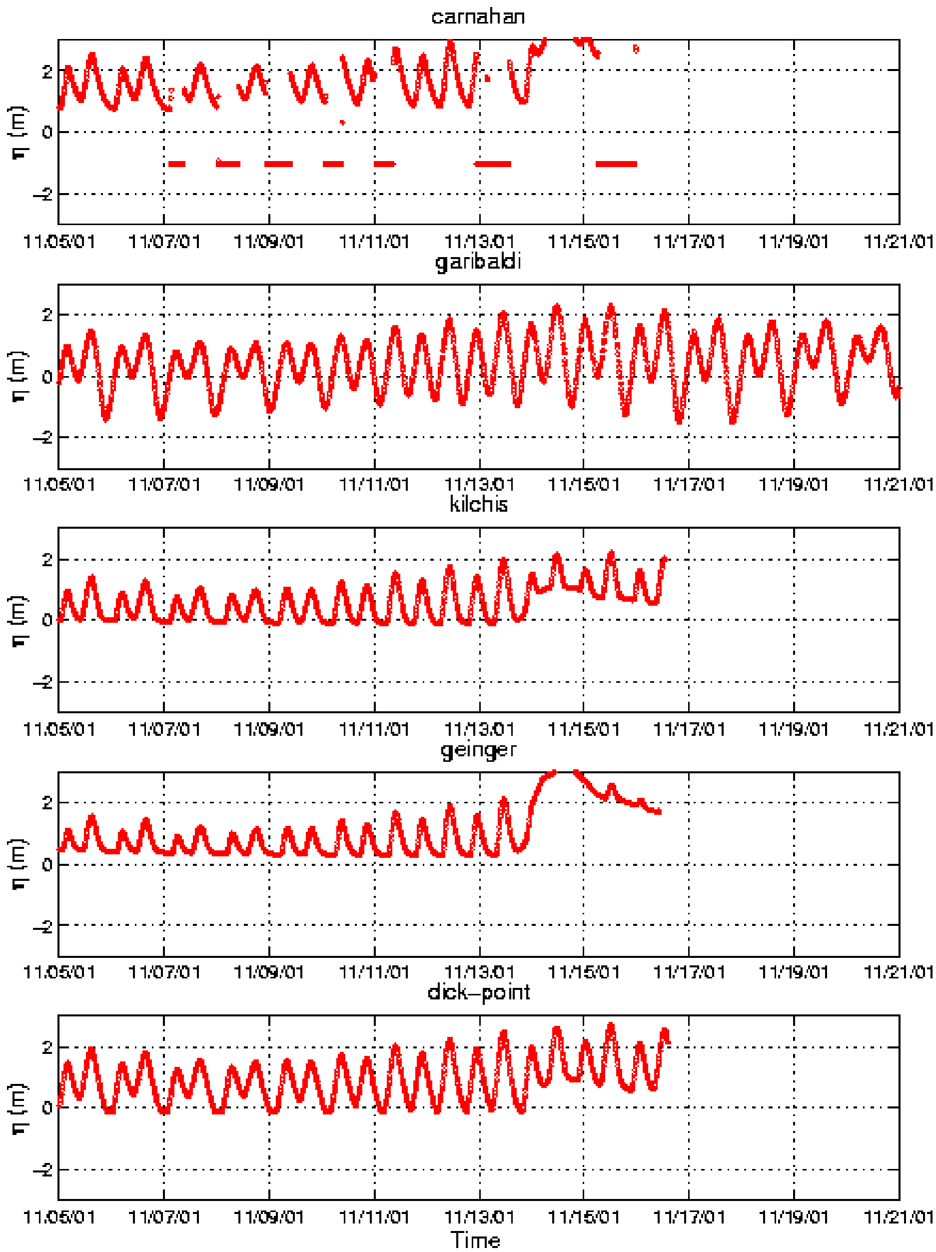

Figure 13: Gage elevation data during the November 14th storm. All the upstream gages stopped working by the end of the storm event.

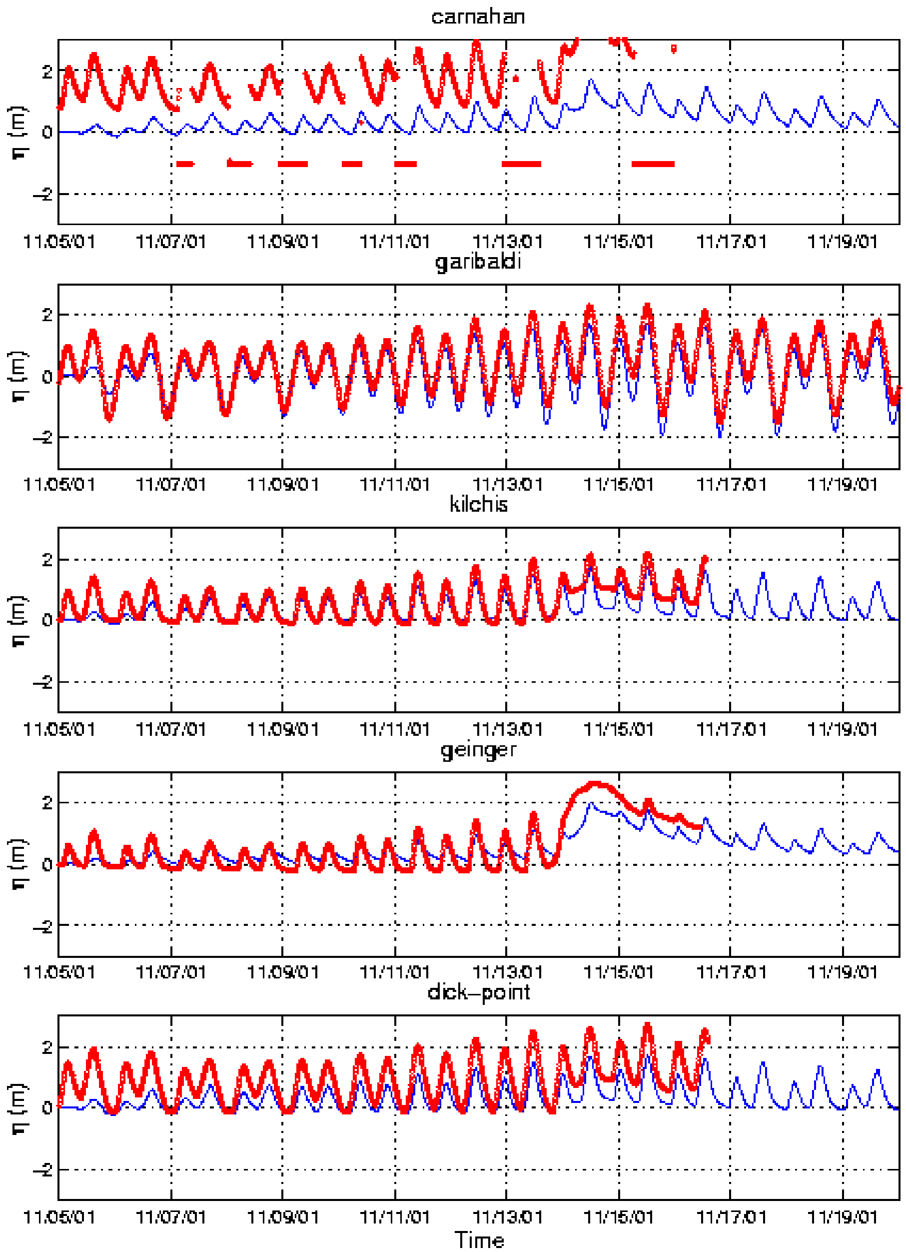

Figure 14: Model (Blue) to Data (Red) comparison of elevation (Nov 14th storm event, Grid 1)

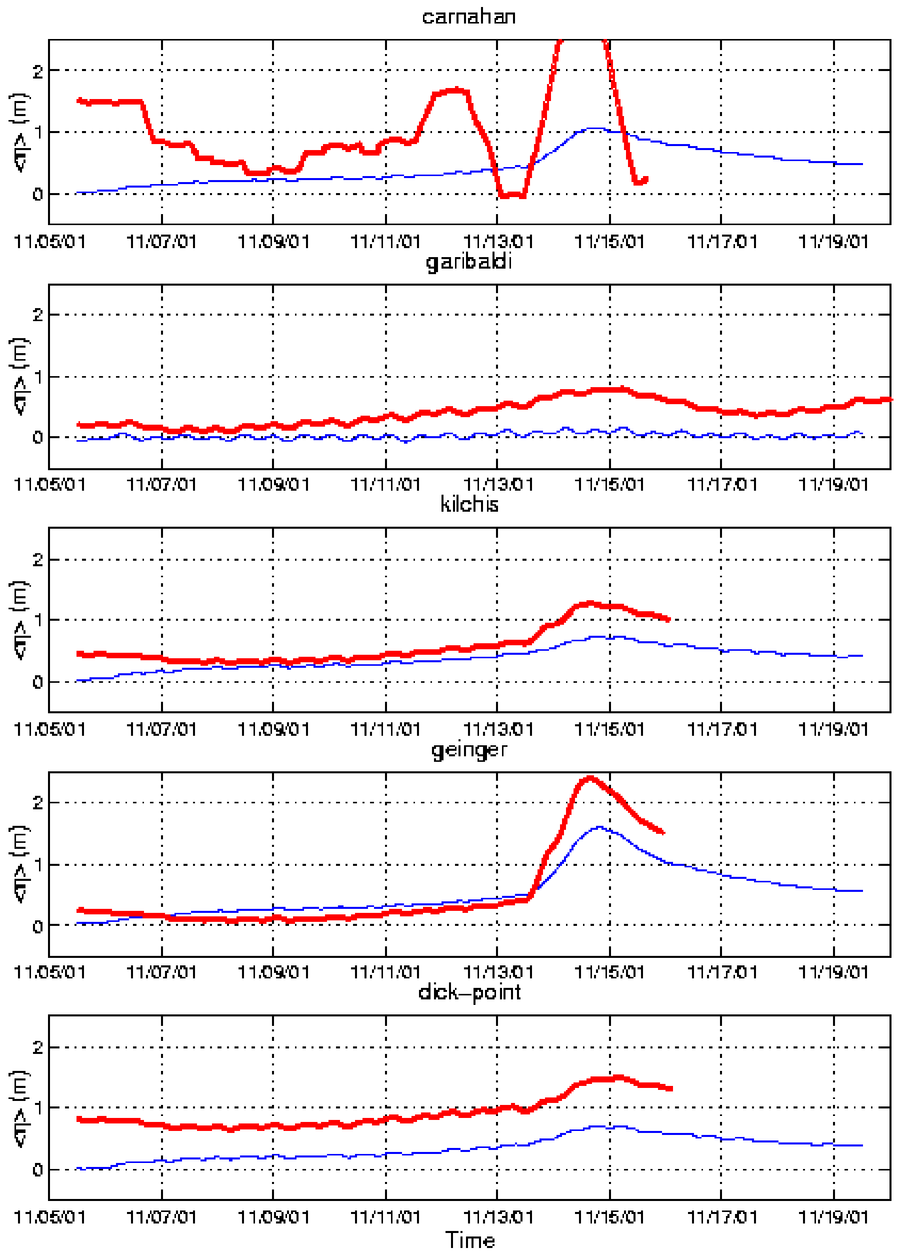

Figure 15: Model (Blue) to Data (Red) comparison of average elevation (Nov 14th storm event, Grid 1)

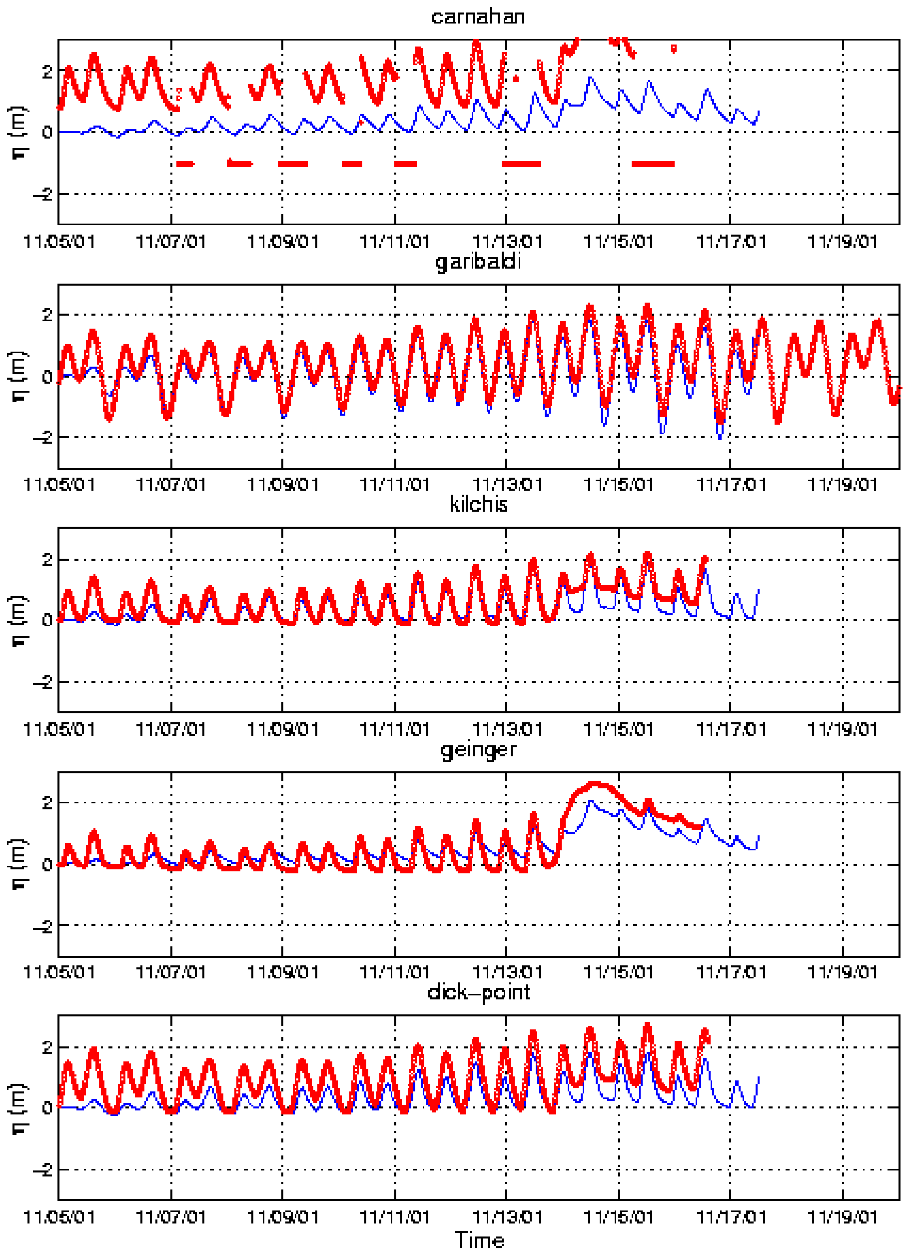

Figure 16: Model (Blue) to Data (Red) comparison of elevation (Nov 14th storm event, Grid 2)

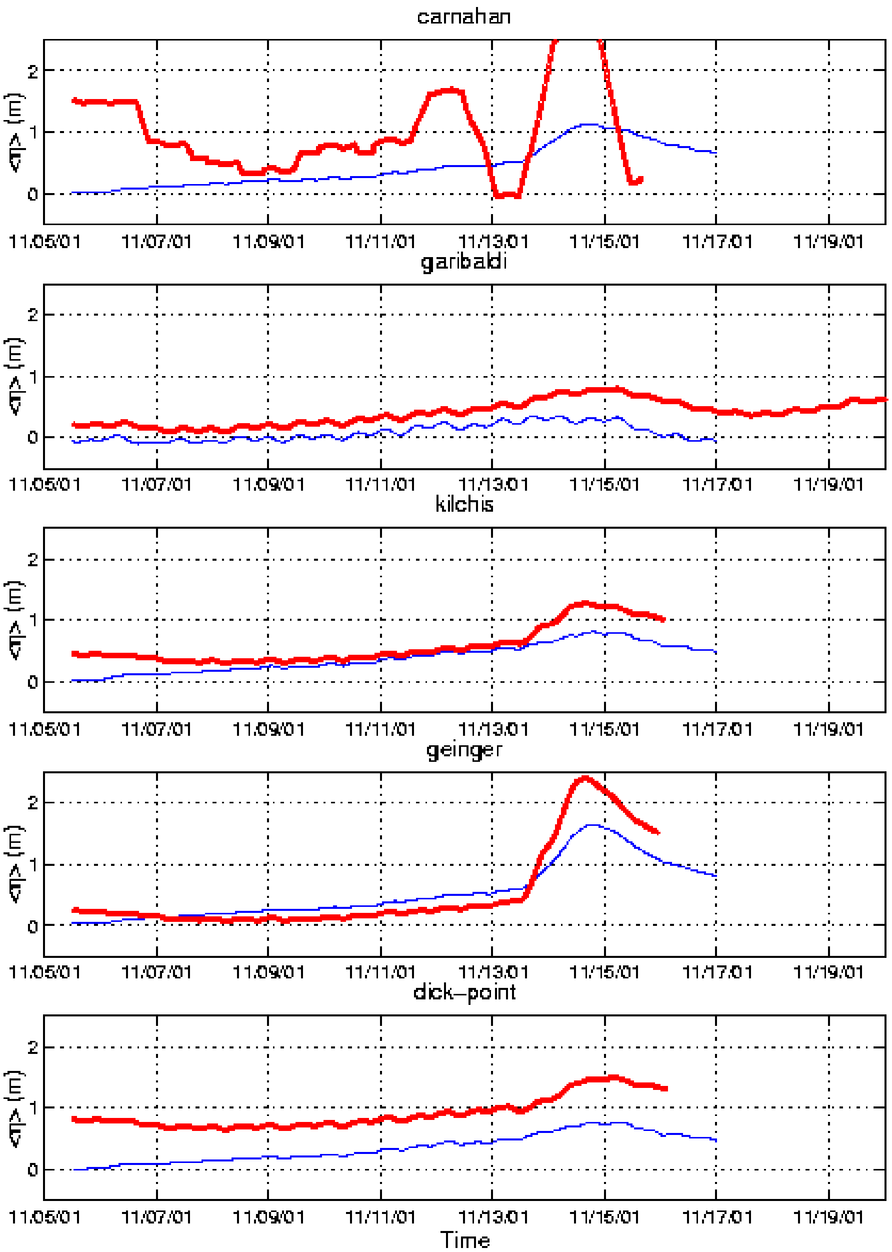

Figure 17: Model (Blue) to Data (Red) comparison of average elevation (Nov 14th storm event, Grid 2)

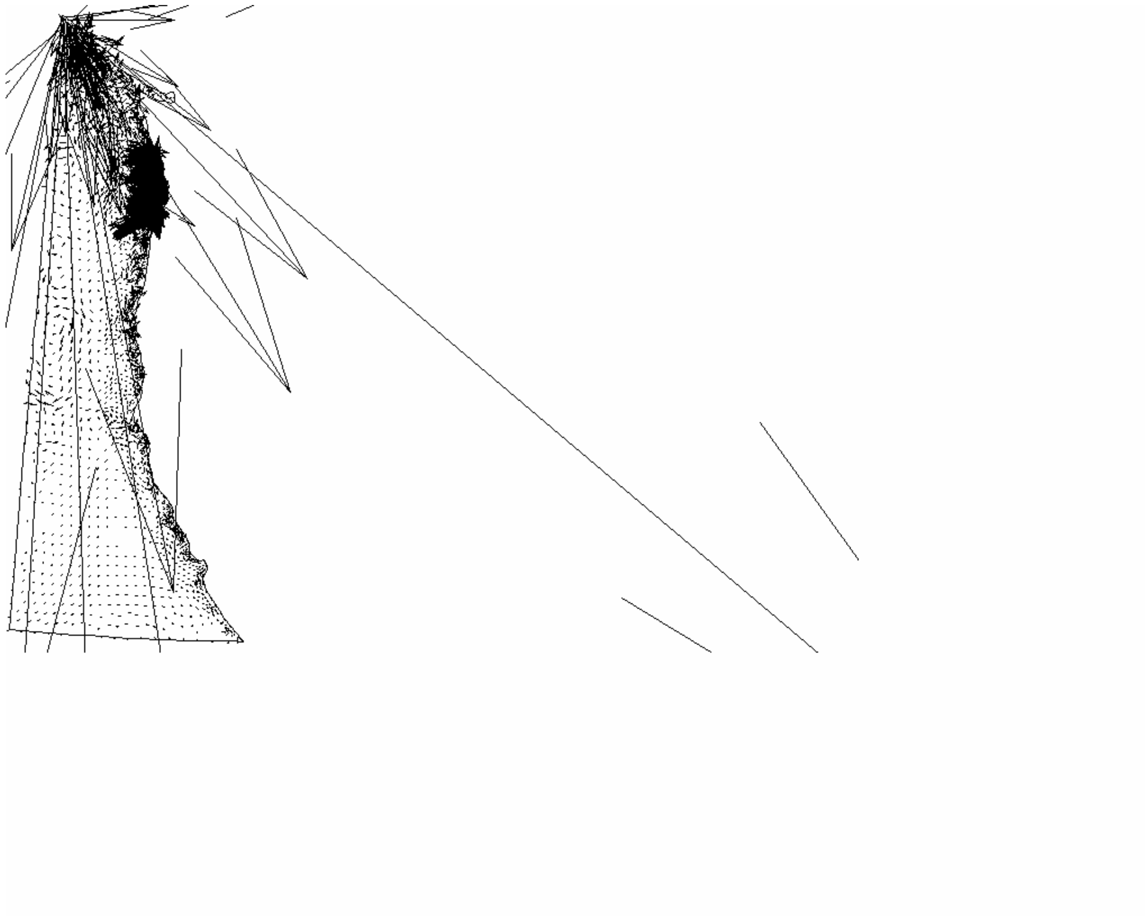

Figure 18: Snapshot of velocities corresponding to simulation in Figure 16. The model blows up at the northern offshore boundary after 12 days of simulation results.

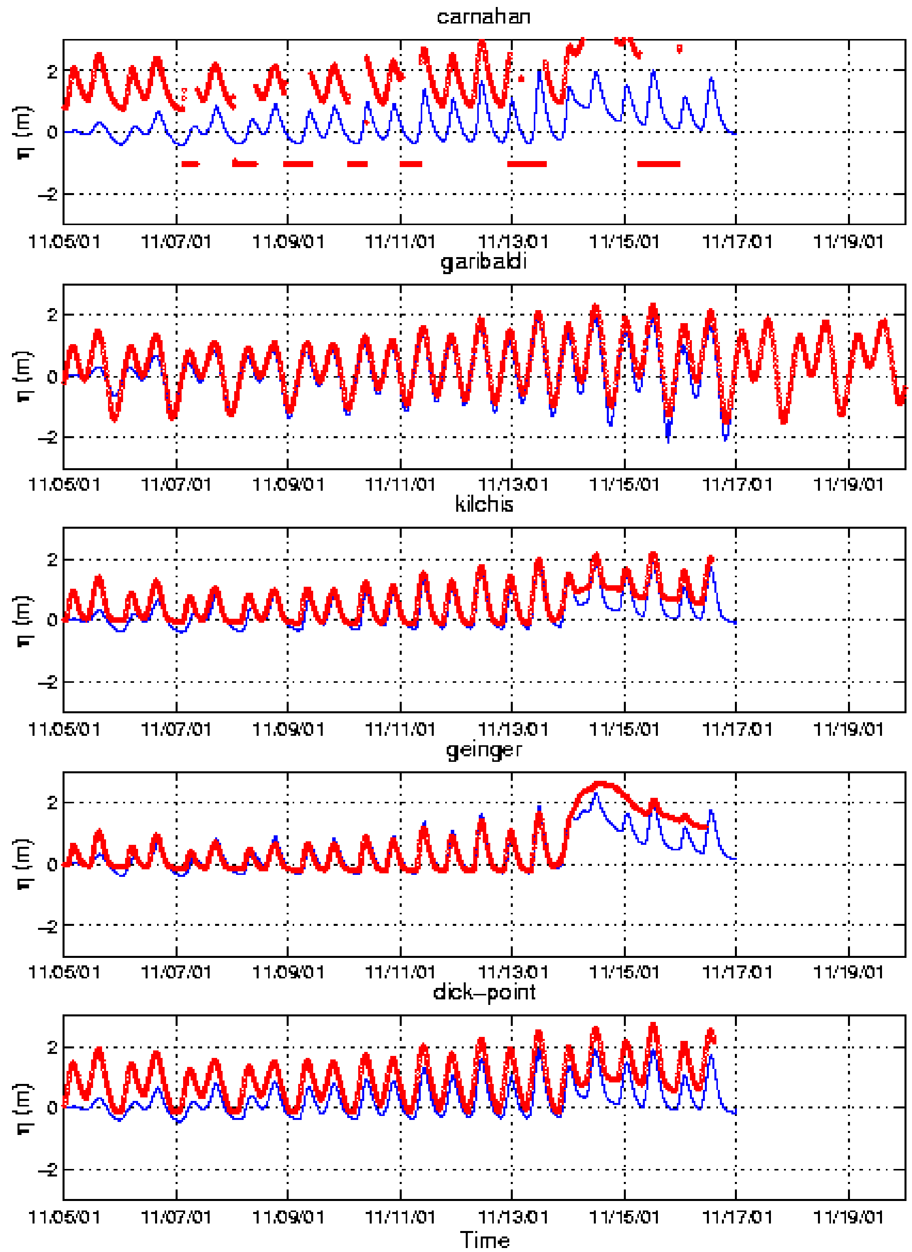

Figure 19: Model (Blue) to Data (Red) comparison of elevation (Nov 14th storm event, Grid 3)

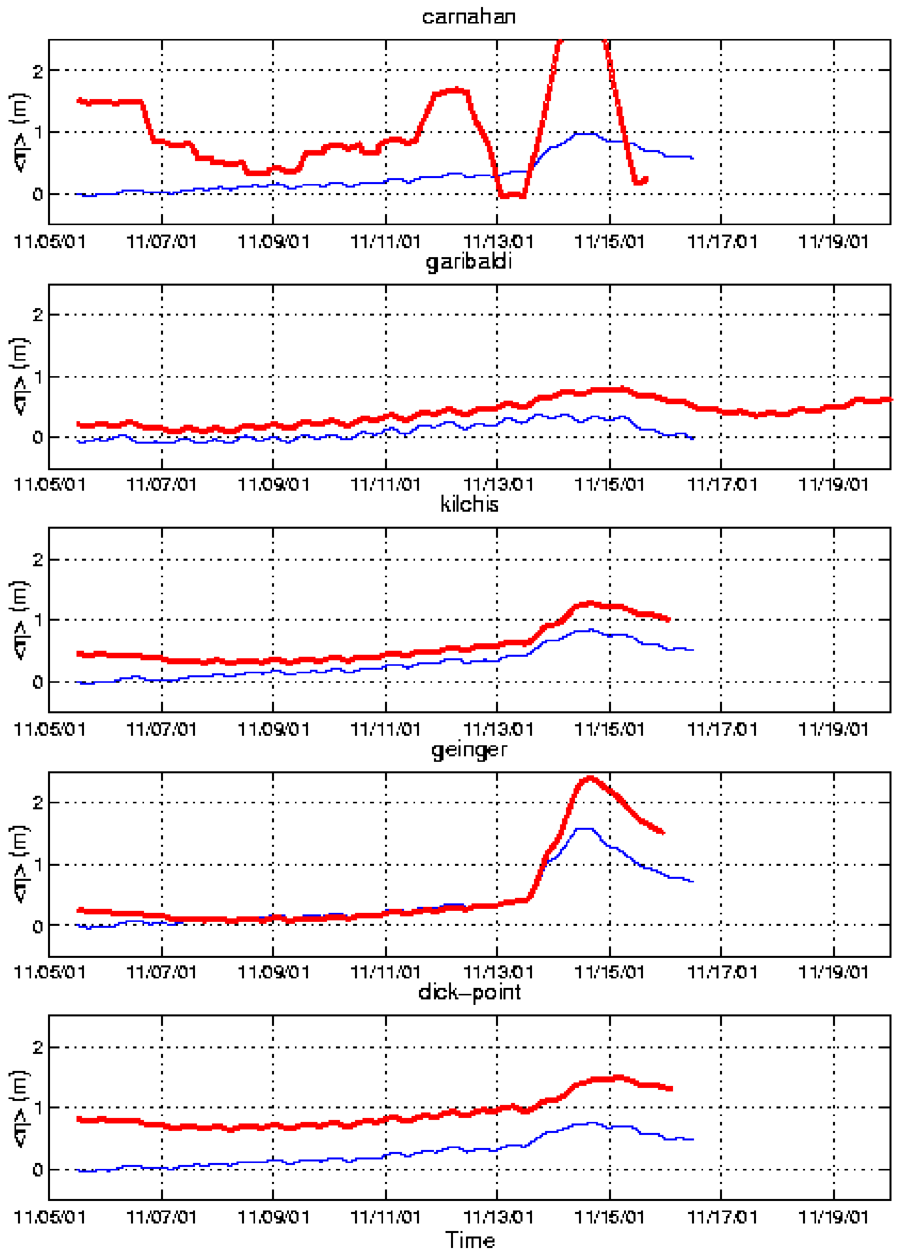

Figure 20: Model (Blue) to Data (Red) comparison of average elevation (Nov 14th storm event, Grid 3)

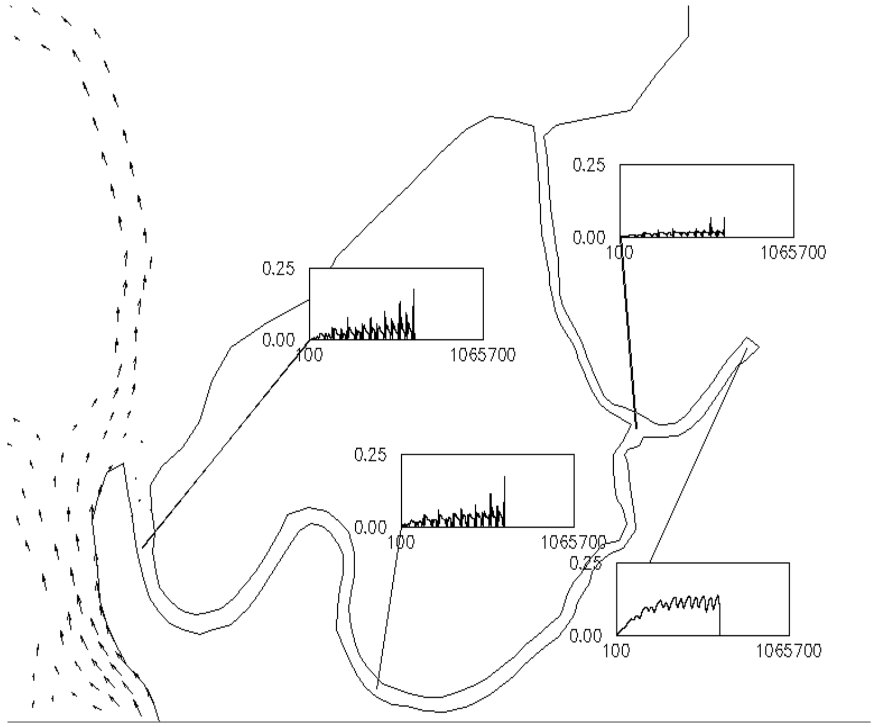

Figure 21: Velocity flow snapshot around the Kilchis river for the simulation shown in Figure 19. Time series of velocity magnitude in m/s at specific locations is shown in inset boxes. The time series plots show the noise in the velocity data and the subsequent drying of the river. The x-axis is in seconds since start of simulation.

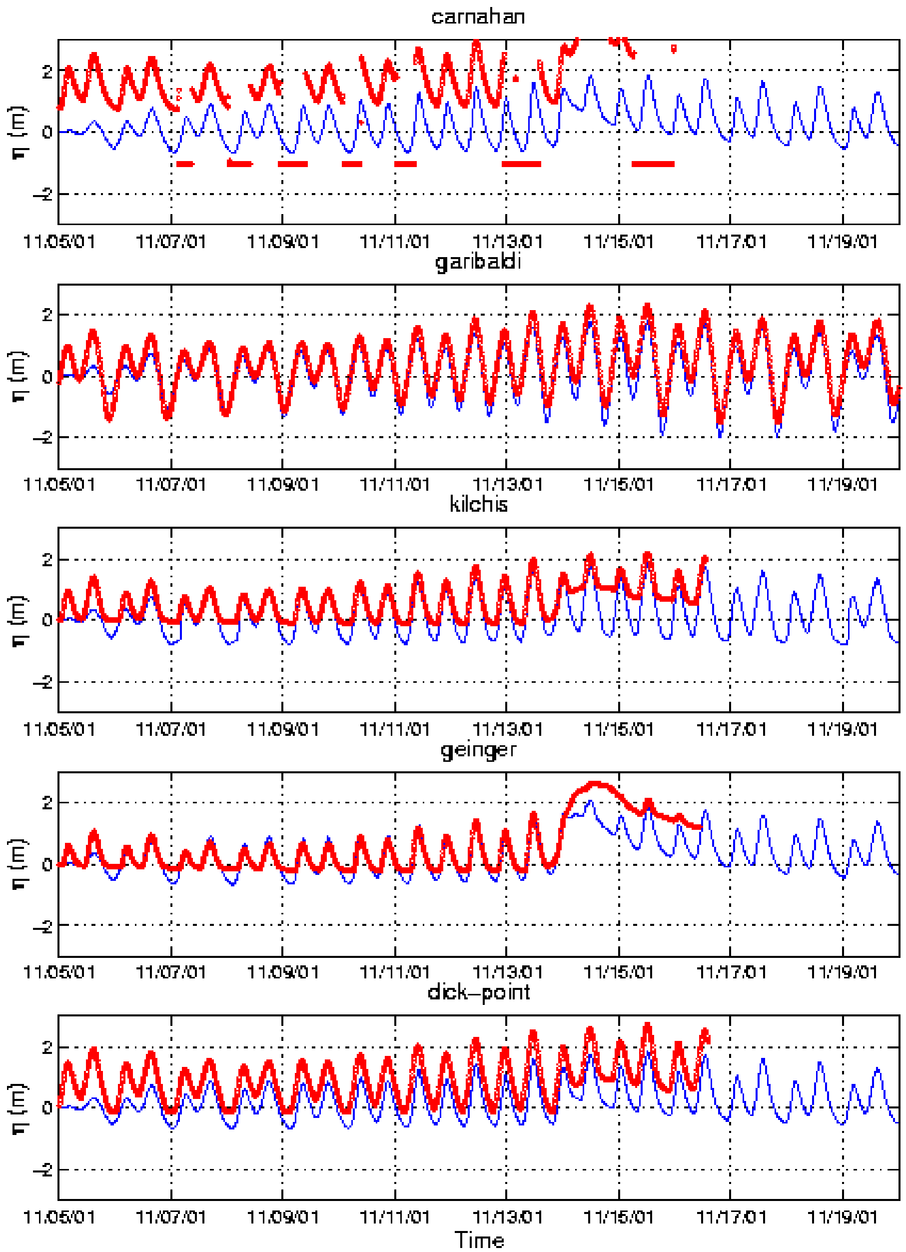

Figure 22: Model (Blue) to Data (Red) comparison of elevation (Nov 14th storm event, Grid 4)

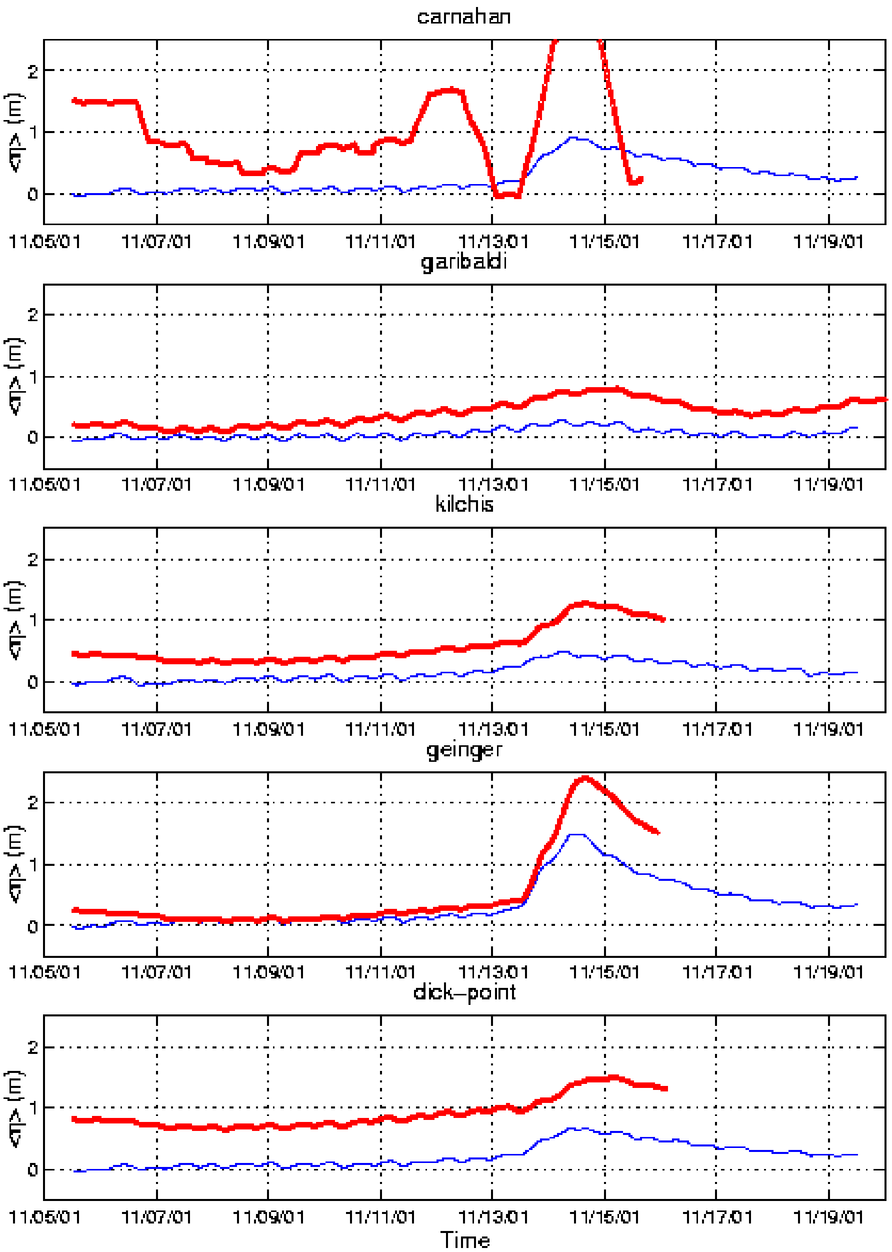

Figure 23: Model (Blue) to Data (Red) comparison of average elevation (Nov 14th storm event, Grid 4)

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General Investigation Feasibility Report

APPENDIX F

Correspondence

July 2004

For Detailed Meeting Minutes of the Feasibility Study Task Force from May 17, 2000 to April 21, 2004, please refer to:
http://usace.co.tillamook.or.us/default.html