The NTHMP Inundation Mapping Program

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Abstract. The U.S. National Tsunami Hazard Mitigation Program (NTHMP) was established in Fiscal Year 1997, and is now in its fifth year of operation. This report provides a review of NTHMP Inundation Mapping Program activities during the first 5 years, 1997–2001. Accomplishments include the establishment of a tsunami modeling infrastructure and the production of 19 inundation maps covering 88 coastal communities with an at-risk population estimated to be more than a million. In light of this success, the goal remains to provide every at-risk community with maps. The strategy for reaching this goal continues to evolve as a result of important lessons learned. A general plan and budget are presented for covering the remaining at-risk communities during the next 5-year period, 2002–2006.

The First Five Years: 1997–2001

The NTHMP Inundation Mapping Program is the first systematic, national effort to attempt a transfer of state-of-the-art tsunami inundation modeling technology from the research environment to the operational setting for the routine production of inundation maps. This section documents the 5-year history of this effort, including the major obstacles encountered, the evolution of program goals and strategies, the lessons learned in the process, and the accomplishments of the program during this period.

1. Background

From the beginning of this program, there has been continuing, unanimous recognition and agreement among NTHMP partners that inundation and evacuation maps are the fundamental basis of local tsunami hazard planning. Without a clear understanding of what areas are at risk and which areas are unlikely to be flooded, it is impossible to develop effective emergency response plans and education programs.

1.1 Initially proposed goals and strategy

With this in mind, the Tsunami Hazard Mitigation Implementation Plan (Tsunami Hazard Mitigation Federal/State Working Group, 1996) proposed the following goals and strategy for the 5-year period 1997–2001.

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1.1.1 Initial goals

- Provide all at-risk U.S. coastal communities with a preliminary inundation map within 3 years.
- Establish a maintenance program to update the maps to account for coastal developments and improved mapping technology.

1.1.2 Initial strategy

Based on the successful mapping program carried out earlier in Hawaii, it was proposed that NTHMP mapping goals could be achieved by relying primarily on a rapid, relatively low-cost 1-dimensional (1-D) model, rather than the more advanced, but relatively costly and time-consuming 2-dimensional (2-D) modeling technology. This original strategy thus focused heavily on maximizing the number of communities that could be covered, by proposing that the mapping effort

- Utilize the 1-D model developed by the University of Hawaii
- Train city and/or county engineers to use the 1-D model and produce maps
- Conduct training workshops: Year 1 in Washington and Oregon; Year 2 in Alaska and California; Year 3 in Hawaii
- Supplement 1-D modeling with 2-D modeling where needed
- Establish a tsunami inundation mapping center (TIMC) to support both 1-D modeling activities and the development, implementation and application of 2-D models
- Establish a maintenance program to update and improve the completed maps

1.2 Revised goal and strategy

The subsequent evolution of the original plan is documented in the NTHMP Steering Group Summary Reports, available at http://www.pmel.noaa.gov/tsunami-hazard/Summaries.html.

1.2.1 Obstacles to implementing initial strategy

By the end of December 1996, Steering Group reviews had identified two significant difficulties associated with Year 1 implementation of the original plan in Washington and Oregon:

1. City and/or County engineers were not available to be trained and produce maps, and
2. More advanced 2-D modeling technology was required for reliable mapping of many communities that were considered high priority.

To address these problems, a re-evaluation of the original plan was conducted, and a new goal and strategy were adopted.

1.2.2 Revised goal

- Provide inundation maps for high-priority at-risk communities, using best available modeling technology.

1.2.3 Revised strategy

It was decided to abandon 1-D modeling and utilize the more advanced 2-D modeling technology for all mapping. And, to optimize the effective use of the limited time and resources available, the following responsibilities were identified and agreed to for each step of the modeling and mapping process:

- State Agencies will identify the high-priority communities to be mapped
- Contractors will utilize 2-D models to produce Inundation Map products for high-priority areas
- State Agencies and local officials will produce evacuation maps, using inundation map products as guidance
- The Center for Tsunami Inundation Mapping Efforts (TIME) will assist the states and contractors with the modeling and mapping effort

It was recognized that adoption of the 2-D modeling technology would reduce the number of communities that could be mapped, but that the result would be inundation mapping products of indisputably improved detail, quality, and reliability.

2. What Was Promised?

Setting map production goals would, of course, require estimates of the time and cost involved. But any effort to model a particular community can be complex, and its success depends on a number of factors, including: the existence of unique physical characteristics especially difficult to model; the quality and coverage of bathymetric and topographic data; the development of a suitable merged bathymetric/topographic (bathy/topo) grid; the setup and execution of the grid/model software; and the visualization, special processing and analysis of large volumes of model output to provide useful final products. The ease or difficulty of modeling a particular area is thus difficult, if not impossible, to predict.

2.1 Time and cost estimates

Nonetheless, estimates were attempted. Research applications of 2-D inundation models have a long history, and a successful mapping effort had been carried out in Oregon using 2-D modeling technology. In addition, 1-D modeling had been used extensively to produce inundation maps in Hawaii. Based on the limited information available from these activities, a rough estimate of \$50K and 6 months per community was suggested to potential contractors for the work. However, these experienced members of the modeling community objected to the estimate, expressing the view that this could be viewed only as an optimistic lower limit for the most simple and straightforward case.

2.2 Production goal

In light of the uncertainty surrounding cost and time estimates, a general production goal was adopted.

- Map as many high-priority areas as possible with the limited time and resources available.

In this spirit, Washington, Oregon, and the TIME Center began the process of establishing priorities, and a competitive request for proposals was issued. High-priority coastal areas were identified by Washington and Oregon, and the Oregon Graduate Institute (OGI) was awarded two successive contracts to develop the inundation mapping products. In Years 2 and 3, the remaining three States also adopted this approach: California awarded two successive contracts to the University of Southern California (USC); Alaska contracted with the University of Alaska at Fairbanks (UAF); Hawaii awarded two contracts to the University of Hawaii (UH).

Typically, the production of inundation maps involved the following stages:

1. Model development and testing. This can be a major effort, but may be unnecessary if the contractor has been actively exercising a tsunami inundation model as part of a research or applied engineering project, for example.

2. Identification of priority communities. The state identifies communities based on population, previous tsunami history, etc., including preliminary estimates from TIME on the availability of bathymetric and topographic data for the areas of interest. An attempt is also made to assess both the probability and the consequences associated with a specific hazard.

3. Specification of computational grid coverage. The modeler analyzes the area to be mapped and communicates the coordinates and spatial resolution of the desired grid to TIME.

4. Grid development. First, TIME searches for and acquires the best available bathymetric and topographic data to produce the multiple imbedded finite difference grids (or the single finite element grid) that comprise the required computational grid for each specific community. As a practical matter, this has also meant that a significant digitizing effort must be undertaken to fill in data gaps. Second, these data are either forwarded to the modeler, who then constructs the grids (as has been the case for OGI modeling for Washington and Oregon) or TIME performs the actual merging of the bathy/topo data to form the required finite difference grids (as has been the case for modeling

in Alaska and California). It should be noted that Hawaii has been developing its computational grids independently, so far.

5. Source development. The state and the modeler, with some participation by TIME, decide on the specification of tsunami sources that represent "credible worst case scenarios" in terms of the initial conditions for the numerical model simulations.

6. Model simulations. The model is run with appropriate source conditions. Products are derived from the results to aid visualization and analysis—animations, time series, derivative quantities such as arrival times, maps of maximum runup and velocity, etc.

7. Quality control. This is a collaborative effort by state officials, the modeler, and TIME. The model results are examined for reasonableness, and compared with any historic observations or pre-historic information that might be available. This step produces inundation maps that are then made available to local emergency managers.

8. Final interpretation, analysis, and publication. Final maps are produced through modifications by professional judgments that reflect specific local knowledge and common sense decisions regarding inconsistencies or questionable features. This step results in a report and publication of the inundation map by the State.

Typically, a number of these stages can and do run concurrently, with iterative exchanges common between state officials, the modeler, and TIME. In particular, grid development and source development (stages 4 and 5) are usually conducted in parallel, and an iterative process involving model simulations and quality control (stages 6 and 7) is the norm.

3. What Was Accomplished?

Table 1 summarizes the inundation and evacuation mapping work that was completed, and Fig. 1 provides an example of each type of map.

3.1 Inundation maps

Nineteen inundation mapping efforts were completed for high-priority areas identified by the states. Oregon published five maps covering six communities, and Washington published one map covering 19 communities (Priest *et al.*, 1997b, 1998, 1999a, 1999b, 2000; Walsh *et al.*, 2000)

3.2 Evacuation maps

Six of the nineteen high priority areas were provided with evacuation maps that were developed at the community level by local, county, and state personnel using inundation maps as critical input to the process. The input and involvement of local communities is essential to the success of this effort.

Table 1: Mapping efforts completed by the NTHMP.

Areas	Inundation	Evacuation
ALASKA		
Northeast Kodiak Is.	√	
CALIFORNIA		
Santa Barbara	√	
San Francisco–San Mateo	√	
Los Angeles–S. Monica	√	
Northern San Diego	√	
Southern San Diego	√	
HAWAII		
W. Honolulu, Oahu	√	
Kona Coast, Hawaii	Coarse Grid	
OREGON		
Astoria	√	√
Warrenton	√	√
Seaside–Gearhardt	√	√
Newport (Yaquina Bay)	√	
Gold Beach (Rogue River)	√	√
Coos Bay	√	
WASHINGTON		
Pacific County	√	√
Gray's Harbor County	√	√
Clallam County	√	
Jefferson County	√	
Puget Sound	Coarse Grid	

3.3 Infrastructure development

Arguably the most important accomplishment of this program was the development of the necessary infrastructure to transfer best available science from research settings to operational applications. Academic scientists that were given the opportunity to apply their tsunami modeling expertise to real-world problems responded to this challenge with enthusiasm. Prior to the NTHMP there were no modeling groups that conducted R&D focused on exploiting state-of-the-art modeling technology to produce tsunami inundation maps. The NTHMP was the essential catalyst for the initiation and continuation of such R&D activities at:

- Four academic institutions (UAF, USC, UH, OGI)
- Eight state agencies (Alaska Department of Emergency Services, Alaska Department of Natural Resources, California Office of Emergency Services, Hawaii Civil Defense Division, Oregon Department of Geology & Mineral Industries, Oregon Emergency Management, Washington Emergency Management Division, Washington Division of Geology & Earth Resources)
- The Federal TIME Center.

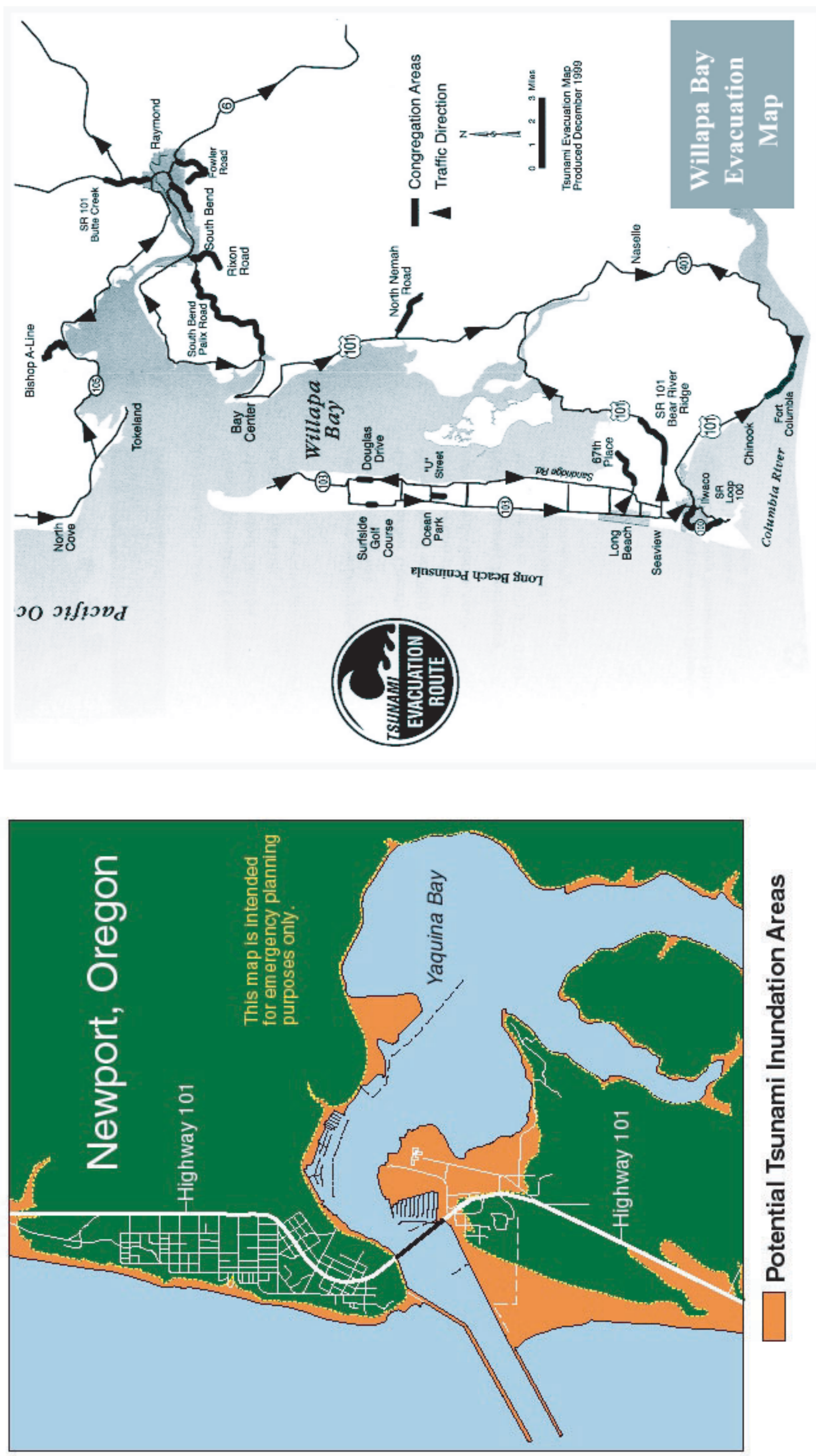

Figure 1: Inundation map for Newport, Oregon (left panel), and evacuation map for Willapa Bay, Washington (right panel).

4. What Was the Impact?

4.1 Quantitative impact

Quantitatively, the 19 inundation maps produced by this program impacted 88 coastal communities with an estimated at-risk population of more than a million persons (Table 2). In Oregon and Washington, evacuation maps were also developed by local and state officials for 23 of the communities covered in these two states, using the inundation maps as fundamental guidance.

Table 2: Communities and populations impacted by NTHMP inundation maps. Population at-risk estimates do not include those covered by coarse-grid maps of the Kona Coast, Hawaii, and Puget Sound, Washington.

	State					
	AK	**CA**	**HI**	**OR**	**WA**	**Totals**
Maps	1	5	2	6	5	**19**
Communities	5	42	9	7	25	**88**
Population At-Risk	9,608	857,915	66,916	41,743	44,383	**1,020,565**

Note that the at-risk population estimates in Table 2, and all others presented in this report, must be considered very preliminary, since they were obtained using the first, primitive version of a methodology under active development, using GIS technology and Census 2000 data. A brief description of the methodology, including current deficiencies and planned improvements, is provided in Appendix A.

4.2 Qualitative impact

The impact of a tsunami inundation map on Emergency Management (EM) officials and citizens alike cannot be overestimated—it is a clarifying, galvanizing catalyst for action. The Mapping Program in general, and the tsunami inundation maps in particular, have had a major positive impact in the following areas.

4.2.1 Improved collaboration of R&D and EM communities

Because the academic scientists and emergency managers are well-respected and influential members of their respective communities, their vigorous collaboration on hazard mitigation issues has had an important positive impact on the relationship of the tsunami R&D and EM communities. This is a direct result of the successful NTHMP effort to improve this country's tsunami modeling and mapping infrastructure.

4.2.2 Improved planning

Once a map is completed and available for study, previously vague concerns and abstract issues are suddenly and immediately clarified and rendered concrete. It is at this moment that effective, community-specific planning has truly begun—individual hazards can be identified and mitigation measures can be developed and implemented that are specific to that hazard. A map is thus the fundamental starting point for any effective planning and mitigation program, aiding the evaluation of critical issues such as population and infrastructure vulnerability, and the identification of feasible evacuation routes.

4.2.3 Improved education and preparedness

The maps are an absolutely essential educational tool and, to judge the bottom-line impact of these maps, one has to consider their effect on the final users—citizens residing in small and large coastal communities at risk to tsunamis. Once completed, public workshops and informational forums are held to present the maps to citizens of these communities, and to provide an opportunity for discussion of the result with Local, State, and Federal Emergency Managers and the scientists that developed the maps. Again and again, the powerful impact of these maps was clear—the awareness of a citizen, previously vague and uncertain, dramatically intensified and, in many cases, prompted the individual to become an active participant in the mitigation program.

4.2.4 Improved survival

Lives will undoubtedly be saved because of the dramatic impact these maps have made on communities. Improvements in emergency planning and preparation, and a more aware and educated population will translate into many fewer fatalities when the next destructive tsunami attacks a U.S. coast.

5. Analysis—Lessons Learned

Much of what follows is discussed in more detail in a study conducted by the TIME Center (González and Titov, 2000).

5.1 States differ in needs and mapping strategies

The approach to mapping in each state has similarities and differences. In all states, the priorities and the technical approach to developing appropriate scenarios depends heavily on the knowledge and expertise of local and regional tsunami modelers, geoscientific professionals, and emergency managers.

But differences naturally arise because of substantial state-to-state variability in such things as the physical environment, population distribution, history of disasters, and the management and technical infrastructure; these necessarily require different strategies for implementing a tsunami inundation mapping program.

Oregon's mapping effort began in mid-1997. This state started with substantial experience in tsunami inundation map production and had a mapping infrastructure already in place, with leadership provided by DOGAMI and expert modeling personnel at OGI. The OGI model is an advanced circulation model modified for tsunami inundation, known as ADCIRC (Priest *et al.*, 1997a), which uses a finite element (FE) grid with variable spatial resolution, appropriately coarse or fine, as required. Coarse-grid model simulations had been performed before the start of NTHMP, and evacuation maps had been developed for many communities. Oregon's focus is now on the application of additional model simulations to produce more detailed and accurate map products; the development of fine-resolution computational grids, and thus the acquisition of adequate, site-specific bathymetry and topography data, are therefore required if this effort is to be successful. Population and community density are also relatively low in this state, so that each mapping effort includes a relatively small number of communities.

Washington's mapping effort also began in mid-1997 and capitalized on the Oregon experience by utilizing OGI as the tsunami modeling contractor. The physical setting in this state is unique. In addition to a coastal population at risk from CSZ events, Washington must also consider at-risk residents that live on the Straits of Juan de Fuca coastline and the islands of the eastern strait, as well as the large coastal and island population threatened by locally generated tsunamis in Puget Sound. As in Oregon, strong geoscientific leadership is provided by the Washington Division of Geology and Earth Resources, which works closely with the Washington State Military Department Emergency Management Division. Recent numerical simulations in Puget Sound have utilized the TSUNAM2 finite difference model, developed in Japan (Imamura, 1996).

Alaska's program was first funded in Fiscal Year 1998. Tsunami modeling research talent was available, but had been inactive for some time, due to lack of funding. No operational mapping infrastructure was in place then, including the basic requirement for an implemented, tested, and well-exercised tsunami model that could be immediately utilized in a systematic mapping effort. Geoscientific expertise was readily available, however, with leadership provided by the Alaska State seismologist, strong technical mapping support provided by the Alaska Department of Natural Resources, and close collaboration with the Alaska Division of Emergency Services. The University of Alaska Fairbanks has successfully developed, tested, and now applies a tsunami model that utilizes imbedded finite difference (FD) grids to provide appropriately coarse and fine spatial resolution where needed. A serious obstacle to map production is the difficulty of developing adequate bathy/topo grids for the modeling. Because Alaska is very tectonically active and because there are differences in the sources and ages of data, differences in reference levels are difficult or impossible to resolve. This makes accurate merger of bathy/topo data at the shoreline problematic. Many high-priority areas simply lack adequate data and, as a consequence, have been passed over for mapping. Population density and community density are also low in this State, so that regional mapping efforts cover a relatively low number of communities.

California's mapping effort also began in FY1998. An active tsunami research group was in place at the University of Southern California, using the Method Of Splitting Tsunami (MOST) tsunami model (Titov and Synolakis, 1997), characterized by imbedded FD grid technology. The California Office of Emergency Services provides leadership, setting priorities and guiding the direction of the program. Geoscientific expertise is sought from academia and state agencies on an ad-hoc, case-by-case basis. California has the highest population and community density, so that each mapping effort covers a relatively large number of residents at risk.

Hawaii's effort did not begin until FY1999. This state has a long history of dealing with tsunami disasters, and has developed inundation maps for most communities, utilizing 1-D modeling technology. Because of this, Hawaii spent only a small fraction, $35K, of its budget on mapping activities, deciding to take a broader approach and supporting R&D on other, related issues: forecasting the impact of distantly generated tsunamis through the inversion of tide gauge data, an investigation of the hazard due to locally generated tsunamis—especially landslide sources due to volcanic eruptions—and instrumentation to provide early detection and warning of local tsunamis. The program is led by the Earthquake Program of the Civil Defense Division, and draws on local geoscientific and tsunami research expertise in academia. The tsunami models utilized are also of the imbedded FD grid type, TSUNAM2, and more recently the COMCOT (COrnell Multigrid COupled Tsunami) model (Liu *et al.*, 1995).

5.2 The structure of State Mapping Teams is critical

Because of the strong inter-disciplinary nature of this work and the emphasis on state priorities, it is imperative that State Mapping Teams be comprised of at least two state components: 1) State Emergency Management, which must identify and set priorities for the effort, and 2) State Geologic Survey or its equivalent, to work closely with state EM in identifying hi-priority, state-specific geo-hazards and developing credible tsunami generation scenarios. The third essential component must be 3) a strong modeling activity that is focused on the production of maps and other useful hazard mitigation products.

5.3 Initial cost and time estimates were low

Table 3 summarizes the funding history of the 5-year mapping program, including estimates of in-kind support from each state and NOAA. The value of bathymetric data contributed by NOAA's National Ocean Service (NOS) is based on the minimum cost of conducting a typical bathymetric survey; depending on the areal coverage, complexity of the region, and a number of other factors, the cost of a single survey varies from $150K to $500K. Similar estimates were not available for the corresponding topographic data. Overall, in-kind support was more than double the direct support received by the NTHMP.

Table 4 combines the mapping information in Table 2 and the NTHMP funding history of Table 3 to estimate unit costs and time involved in producing the inundation maps. It is clear that the initial cost and time estimates were overly optimistic—the 2-D modeling effort took more time and was

Table 3: NTHMP funding history, 1997–2001 (thousands of dollars).

	State					
	AK	**CA**	**HI**	**OR**	**WA**	**Total**
NTHMP Support						
State	194.2	194.2	194.2	184.2	184.2	**951.0**
TIME	220.2	220.2	90.0	210.3	210.3	**951.0**
Total	**414.4**	**414.4**	**284.2**	**394.5**	**394.5**	**1,902.0**
In-kind Support						
State	206.3	142.4	50.0	400.0	95.0	**893.7**
PMEL	48.4	48.4	48.4	48.4	48.4	**242.0**
NOS Bathymetry	150.0	750.0	300.0	900.0	750.0	**2,850.0**
Total	**404.7**	**940.8**	**398.4**	**1,348.4**	**893.4**	**3,985.7**
TOTAL	**819.1**	**1,355.2**	**682.6**	**1,742.9**	**1,287.9**	**5,887.7**

more expensive than predicted. The average cost of a single inundation mapping effort was about $100K, and the average duration of the work was about 1 year. This includes the relatively high cost and time for the work in Alaska, which had to develop and test its tsunami modeling capability, and where adequate bathymetry and topography was extremely difficult to obtain. If Alaska is excluded from these estimates, then the average cost was $79.4K per map, $17.2K per community, $1.41 per individual at risk, and 10.0 months to complete an individual mapping effort.

The effects of population and community density are apparent and most obvious in the case of California, the most heavily populated state, which had lowest cost per community and individual at-risk. Alaska, with the lowest population density, is associated with the highest cost; however, a significant portion of this higher cost must also be due to the higher costs associated with model and bathy/topo grid development. The relatively low costs in Hawaii can be expected to rise, since the current effort included about half of Honolulu, the largest population center in the state.

5.4 Computational grid development is a major source of delay

The task of producing merged bathy/topo grids was more difficult than expected. Time-consuming digitizing efforts were required to fill in gaps in the available bathymetric and/or topographic data, and the methodology for merging bathymetric and topographic data into a single grid is not yet mature. Specific technical problems that complicate the grid development task are inadequate coverage, poor quality of older data, and geodetic datum issues that complicate the merging of different datasets. A number of high-priority coastal areas were not mapped because adequate bathymetry and/or topographic data did not exist.

Table 4: Unit cost and time estimates for production of inundation maps, excluding in-kind support. Costs are in thousands of dollars, except that the cost/person is given in dollars.

	State					
	AK	**CA**	**[a]HI**	**OR**	**WA**	**Average**
Cost/Map	414.5	82.9	112.5	65.7	78.9	**97.0**
Cost/Community	82.9	9.9	25.0	56.4	15.8	**20.9**
Cost/Person (Dollars)	$43.14	$0.48	$3.36	$9.45	$8.89	**$1.81**
Years to Complete	3.5	3.5	2.5	4.5	4.5	—
Months/Map	42.0	8.4	15.0	9.0	10.8	**11.7**

[a]Hawaii also funded non-mapping activities, and these estimates are therefore adjusted to reflect direct funding of $35K from NTHMP and $100K from NASA, for a total of $135K in direct support of inundation mapping.

5.5 Source specification is a major technical issue

Up to now, this program has concentrated on developing credible seismic sources to provide initial conditions for tsunami modeling. But prediction of individual, specific seismic events is problematic, and probabilistic methods that are under development may be more appropriate. Furthermore, it has become clear in the last few years that the program must develop a methodology to include sub-aqueous and sub-aerial landslide sources, which can also be important tsunami generating mechanisms.

5.6 Coarse-grid model computations can provide useful preliminary guidance

The current models in use employ relatively coarse grids offshore (0.5–2 km) and fine-resolution grids (25–100 m) to cover specific communities at risk. Finite element models accomplish this with a continuously variable grid scheme, while finite difference models employ imbedded grids. It is well known that the accuracy of inundation model computations degrades as the spatial resolution of the grid is made more coarse. But it appears that, while coarse-grid results may not be accurate in an absolute sense, they do seem to provide useful information in a relative sense, i.e., on *spatial patterns* of inundation. In principle, then, larger regions can be covered with somewhat degraded spatial resolution and accuracy. Although highly preliminary, such maps can help identify coastal areas at relatively high or low risk, and thus provide useful guidance to state geoscientists and emergency managers in the production of evacuation maps. But, again, interpretation of such results is especially critical, and must be performed with particular care.

The Next Five Years: 2002–2006

The following sections build on the lessons learned over the past 5 years to assess the magnitude of the work remaining, and to develop a general plan and budget for the next 5-year period.

Table 5: Inundation map production summary. Note that pre-NTHMP information is provided in the first column for completeness, but not included in the NTHMP total column.

	Pre-NTHMP	NTHMP				
	Completed	Completed	In Progress	Planned	Remaining	Total
ALASKA						
Maps		1	1	20	[30]	52
Communities		5	13	40	89	147
Pop. At-Risk		9,608	7,192	60,247	45,103	122,150
CALIFORNIA						
Maps	2	5	1	1	[11]	18
Communities	7	42	8	8	97	155
Pop. At-Risk	28,052	857,915	37,433	89,539	963,926	1,948,813
[a]**HAWAII**						
Maps	66	2	4	2	[13]	21
Communities	69	9	13	4	37	63
Pop. At-Risk	348,524	66,916	133,199	6,287	176,878	383,280
OREGON						
Maps	[b]58	6	1	6	[15]	28
Communities	31	7	1	11	12	31
Pop. At-Risk	95,094	41,743	2,220	23,371	27,760	95,094
WASHINGTON						
Maps		5	1	5	[8]	19
Communities		25	3	46	30	104
Pop. At-Risk		44,383	11,056	241,297	601,500	898,236
TOTALS						
Maps	124	19	8	34	[77]	138
Communities	100	88	38	109	265	500
Pop. At-Risk	443,618	1,020,565	191,100	420,741	1,815,167	3,447,573

[a]Not listed for Hawaii are two additional maps in progress for the Hilo and Kahului area funded by NASA's Solid Earth and Natural Hazards Program.

[b]Many of these Oregon maps cover populated regions that lack Census 2000 designated communities.

6. Assessment of the Work Remaining

Figures 2–6 graphically summarize the completed, in-progress, and planned mapping efforts in each state, as well as preliminary estimates of the at-risk population. Shaded areas correspond to the boundaries of officially designated communities; the at-risk population is only that portion of the community that resides within 1 km of the coast.

Table 5 summarizes the number of maps completed, in progress, and planned, and the number of communities and population covered by each map. It also lists the number of at-risk communities and the population remaining to be mapped. Finally, an estimate of the number of maps that must be produced to cover every community at risk is also provided in square brackets. The number of "remaining maps" was estimated by measuring the

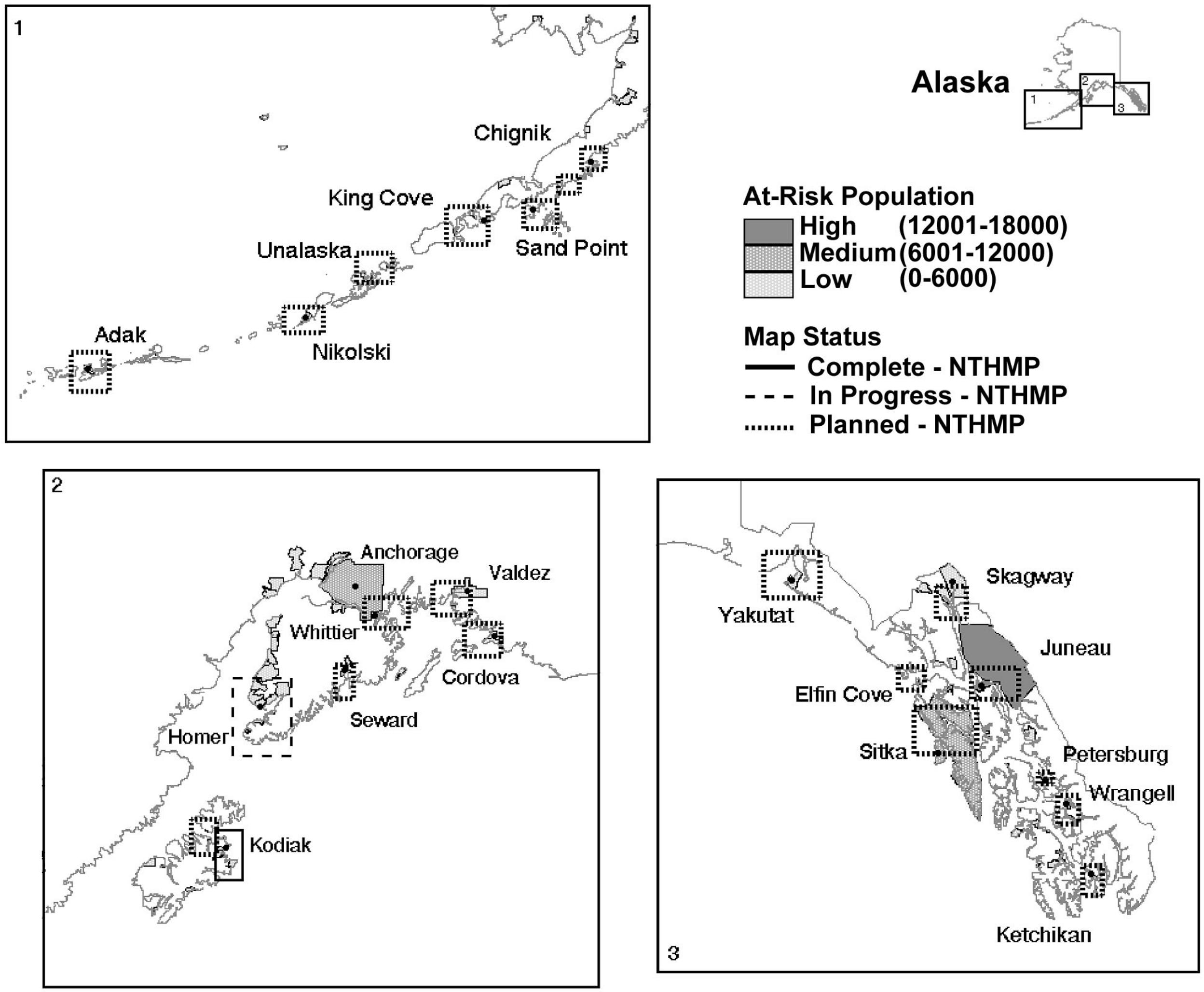

Figure 2: Summary of completed, in progress, and planned inundation maps, and estimates of at-risk population for Alaska. Estimates of at-risk population are very preliminary, based simply on residence within 1 km of the coast, and subject to various sources of error; see Appendix A for a brief discussion of the methodology.

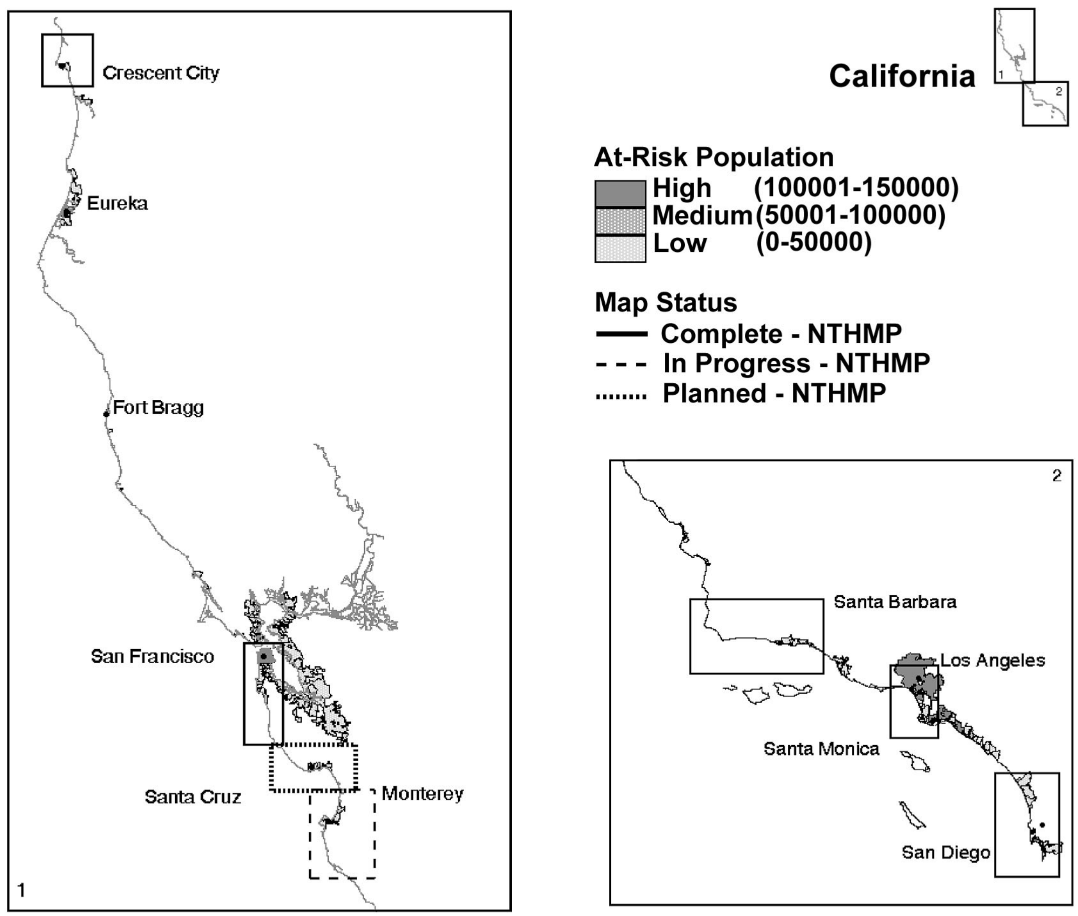

Figure 3: Summary of completed, in progress, and planned inundation maps, and estimates of at-risk population for California. Estimates of at-risk population are very preliminary, based simply on residence within 1 km of the coast, and subject to various sources of error; see Appendix A for a brief discussion of the methodology.

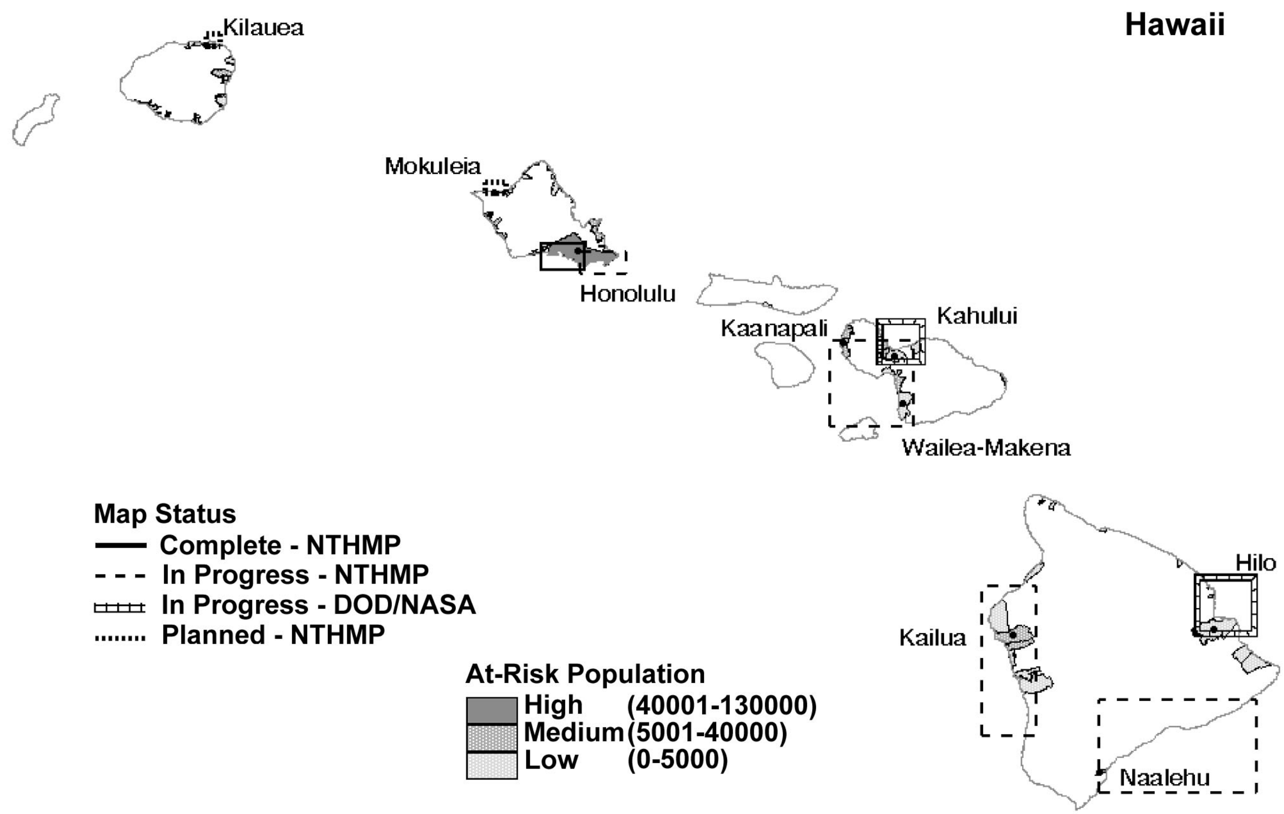

Figure 4: Summary of completed, in progress, and planned inundation maps, and estimates of at-risk population for Hawaii. Hilo and Kahului inundation mapping are currently in progress, supported by NASA's Solid Earth and Natural Hazards Program. Estimates of at-risk population are very preliminary, based simply on residence within 1 km of the coast, and subject to various sources of error; see Appendix A for a brief discussion of the methodology.

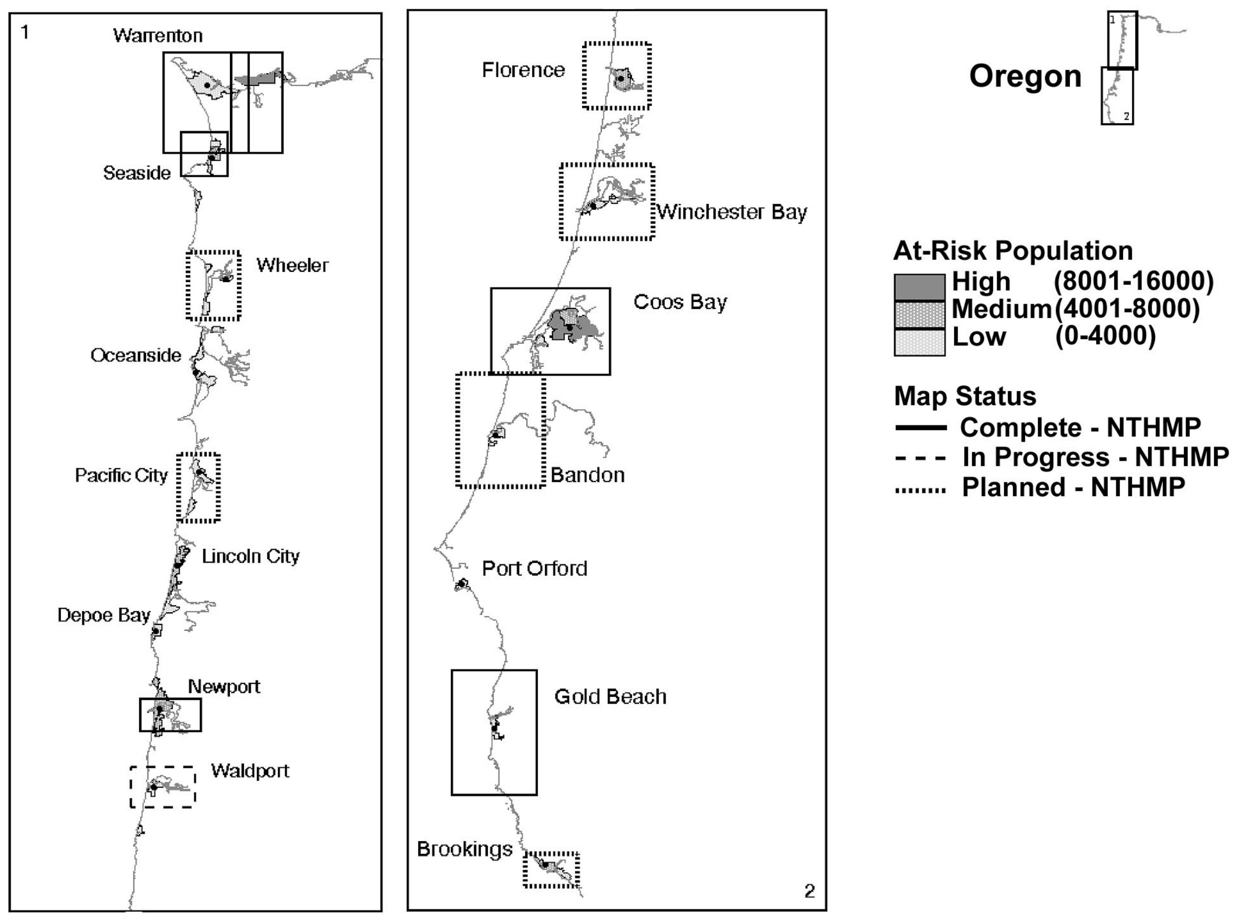

Figure 5: Summary of completed, in progress, and planned inundation maps, and estimates of at-risk population for Oregon. Estimates of at-risk population are very preliminary, based simply on residence within 1 km of the coast, and subject to various sources of error; see Appendix A for a brief discussion of the methodology.

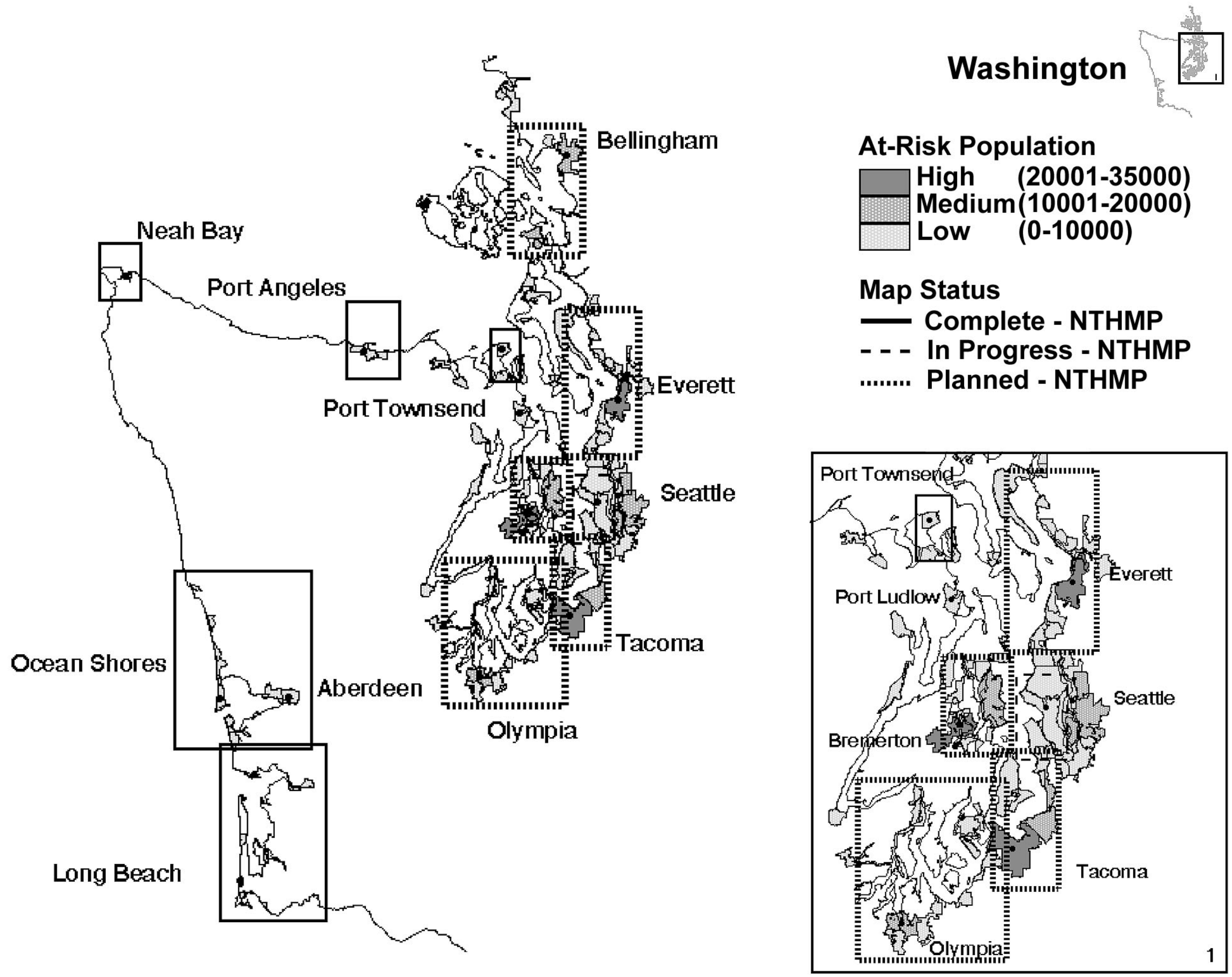

Figure 6: Summary of completed, in progress, and planned inundation maps, and estimates of at-risk population for Washington. Estimates of at-risk population are very preliminary, based simply on residence within 1 km of the coast, and subject to various sources of error; see Appendix A for a brief discussion of the methodology.

total length of coastline that remained unmapped and using the fact that a typical map covers a coastal region of about 100 km. These are, of course, only rough estimates—the actual dimensions of a grid developed for each specific effort will vary, depending on the details of each particular region. Nonetheless, the estimates provide a useful assessment of the magnitude of the work remaining.

It would take more than 20 years for five State Mapping Teams to produce all 111 planned and remaining maps needed to cover 374 at-risk communities, if each group maintained the current production rate of about 1 map per year. This is clearly not acceptable, and the NTHMP must therefore develop a different mapping strategy.

7. A Strategy to Increase Map Production

The lessons learned regarding the technical, organizational, and cost/time issues of map production provide valuable planning guidance. In particular, an effective strategy for the next 5 years should include the following components

7.1 Develop coarse-grid methodology

In principle, one way to increase the areal coverage of each map is to sacrifice spatial detail and absolute accuracy by using coarse-grids. Preliminary inundation and evacuation maps might then be developed with these results. The preliminary maps might then guide States in identifying and prioritizing at-risk communities for subsequent, more accurate mapping with fine-grid computations.

This is currently done, but on an ad-hoc basis in which interpretation of the results is heavily dependent on professional judgement. More research to develop a systematic methodology is needed on this complex issue. For example, other disciplines have developed sub-grid parameterization methods that might be fruitfully applied to improve the absolute accuracy of tsunami inundation coarse-grid computations.

Finally, it should be noted that coarse-grid 2-D computations are preferred over 1-D modeling for the following reasons. A 1-D modeling effort should include multiple 1-D computations for a region, so the use of a 1-D model does not eliminate the need for good bathymetry and topography data in that region. The amount of work involved in collecting these data, running the models, providing quality control, and interpreting the result will be similar for either the 1-D or 2-D modeling effort. Finally, the physics of the 2-D model are superior to that of the 1-D formulation. Most obviously, 1-D computations deal only with shoaling and do not include the effects of refraction, which can be substantial; the physics of refraction is, of course, included in 2-D models.

7.2 Strengthen inter-agency partnerships

Bathymetric surveys are conducted by NOAA's National Ocean Service (NOS) and topographic data are collected by the U.S. Geologic Survey (USGS). Both are involved in LIDAR bathy/topo data collection efforts. Stronger collaboration is needed with these and other such activities to speed the development of adequate bathy/topo computational grids that are essential to map production. A good first step—attendance at NTHMP Steering Group meetings by representatives of these and other relevant activities.

7.3 Encourage and facilitate relevant R&D

Members of the tsunami research community conduct R&D on issues that bear directly on NTHMP goals—good examples of such research are probabilistic methods for inundation mapping, the analysis and interpretation of paleotsunami deposits, and investigations of Cascadia Subduction Zone geotectonics. By virtue of its status as a National Program, the NTHMP is in a position to influence the direction of tsunami R&D and the funding priorities of other programs administered by Federal and state agencies.

7.4 Increase the frequency and amount of funding to each state

Currently, only two of the five states receive funding each year, on a rotating basis, because of inadequate funding. This may have been appropriate during the first 5-year period, when a mapping infrastructure was being developed. However, an infrastructure is now in place and it is essential that each state receive realistic funding to support the expert personnel of the State Mapping Teams needed to conduct an effective, full-time, continuing mapping program.

8. Goals and budget

The general goals of the NTHMP Mapping Program for the next 5-year period, 2002–2006, and the required budget for 2002 are as follows (the 2003–2006 budgets should be adjusted for inflation).

1. Complete maps for the remaining U.S. communities at risk, using a combination of coarse-grid computations for preliminary maps and fine-grid 2-D modeling for higher quality maps in high-priority areas. It is essential that all five State Mapping Teams receive adequate funding for continuous mapping programs that model inundation, produce evacuation maps, and publish the resulting hazard mitigation products. This intensified effort by the five States will require a funding level of $750K/year.

2. Establish a systematic map improvement and maintenance program, with organizational and technical leadership provided by the TIME Center. This effort will include the establishment of a Facility for the

Analysis and Comparison of Tsunami Simulations (FACTS), a WWW-based virtual R&D environment that will link tsunami modelers, other scientists, and emergency managers. The FACTS network will facilitate shared access to critical data and the development and implementation of improved tsunami hazard mitigation products. FACTS will allow, for example, quick inventories of bathy/topo data by State Mapping Teams and viewing of simulations by State Emergency Managers. This is the first step in the establishment of a Tsunami Community Modeling Activity with an organizational structure that will facilitate the systematic development, implementation, and application of improved modeling technology to hazard mitigation. To improve inundation map products, a number of technical/scientific/emergency management issues must be addressed in close collaboration with the tsunami R&D and EM communities, including:

- coarse-grid mapping methodology and guidelines
- water velocity modeling
- forces on structures
- probabilistic methods for inundation mapping
- "death and destruction" indices and "fragility curves"
- GIS applications of tsunami mapping products

This expanded effort will require a TIME funding level of $300K/year.

3. Develop the necessary bathymetry and topography databases needed for the creation of adequate merged bathy/topo computational grids that are essential to the modeling activity. This activity is critical to the success of the program and will require funding for data acquisition and database development of $250K/year.

9. Conclusion

Because most lives lost to tsunamis are due to locally generated events for which there is little or no warning time, because planning and education are the most effective way to save lives, and because the single most important and fundamental planning tool is a community-specific inundation map, the modeling infrastructure developed by the NTHMP must be expanded and improved. The momentum achieved by the NTHMP Mapping Program in the first 5 years must be sustained, and the job of providing inundation maps and the associated hazard mitigation program to threatened coastal communities must be continued and completed.

Acknowledgments. The success of the NTHMP Mapping Program is due to the dedicated efforts of the emergency managers, geoscientists, and academic scientists in all five Pacific States that participated in this enterprise.

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Appendix A. Estimates of At-Risk Populations

This Appendix provides a short description of the methodology used to develop estimates of at-risk population and detailed state-by-state tables that include entries for individual communities. Space limitations precluded the publication of these tables here, but they may be viewed at the TIME Center website at http://www.pmel.noaa.gov/tsunami/time/.

Overview

At-risk communities include all U.S. Census designated and incorporated places within 1 km from the coast. The data is based on 2000 Census block data gathered by the U.S. Census Bureau and provided by the software firm GeoLytics©.

The U.S. Census Bureau provided the following definitions:

- Census Blocks—Census Blocks are the smallest geographic area for which the Census Bureau collects and tabulates decennial census data. Census Blocks are formed by streets, roads, railroads, streams, and other bodies of water, other visible physical and cultural features, and the legal boundaries shown on Census Bureau maps.
- Census Designated Place (CDP)—closely settled, named, unincorporated communities that contain a mixture of residential, commercial, and retail areas similar to those found in incorporated places of similar sizes. There are no minimum or maximum population thresholds for recognition as a CDP. The Census Bureau works with local participants to delineate boundaries for CDPs.
- Incorporated Places—have political/statistical descriptions of city, town, borough, or village and are legally incorporated under the laws of its respective state.

Each table contains the following:

1. Community Name
2. Population of the community categorized by Total, Adult, and Child
3. At-Risk Population Estimates (population of areas within 1 km of the coast)
4. Population Density per square mile
5. Status of inundation maps for each community. The status abbreviations are as follow:

C-<*State*>	Completed pre-NTHMP
C-NTHMP	Completed by NTHMP
IP-NTHMP	In progress by NTHMP
P-NTHMP	Planned
R-NTHMP	Remaining

Procedure

ArcView 3.2 was used to calculate census data within a specific community. Shapefiles of each state's communities (as explained above) were downloaded from the U.S. Census Bureau website. Shapefiles containing census block data were created for each state using GeoLytics© Software. Coastline shapefiles were gathered from various sources.

An algorithm was developed to obtain at-risk populations for each community. The algorithm was built using ArcView system scripts and the X Tools extension. The following procedure was used:

- Communities within 1 km of the coast were selected using the Select by Theme script on the community and coastline shapefiles.
- Total populations were calculated for each community using the X Tools Identity algorithm on the community and block data shapefiles.
- A 1-km buffer was created from the coastline shapefile using the Buffer script.
- At-risk populations were calculated for each community using the X Tools Intersect Themes algorithm on the total community populations and buffer shapefiles.
- Resulting population data was exported into a tabular format.
- A quality control check was performed using original U.S. Census Bureau population data tables.

Deficiencies

Certain factors are unaccounted for in the current algorithm, and can cause under- or over-estimates of the at-risk population. Only officially identified communities are considered, so a population is not counted if they are not resident in such a community. Some populations are counted even though they may reside at a height above mean sea level or a distance upriver that makes tsunami inundation unlikely; in this report, some manual editing was performed to reduce this source of error. Tourism, weekday/weekend, and day/night effects can cause potentially large variations in the at-risk population at seasonal, weekly, and daily timescales, and these are not accounted for.

Planned improvements

Further development of the algorithm will:

- exclude population at a given height above mean sea level
- exclude population considered safe due to limited tsunami penetration upriver or into a bay
- include population not residing in officially recognized communities

- include population based on inundation and/or evacuation maps
- include day-night changes in population
- include seasonal changes in population due to tourism

Improved estimates will be posted on the TIME website as they become available.

References

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GeoLytics© —http://www.geolytics.com