Chapter 6

Tsunami Warning Decision Support

Once an earthquake has been detected and its magnitude and location analyzed, tsunami warning centers use criteria and, where available, models to determine if an initial tsunami warning should be issued. Tsunami warning centers require additional capabilities to refine the forecast beyond the initial warning. This chapter focuses on the tsunami warning system decision support programs that are used in watch-stander decision making:

- **Criteria** for issuing warnings based upon science and historical events.
- **Situational awareness** software that helps watch-standers detect events in real time.
- **Computer models** of tsunami wave height based upon science, historical events, and earth observations.

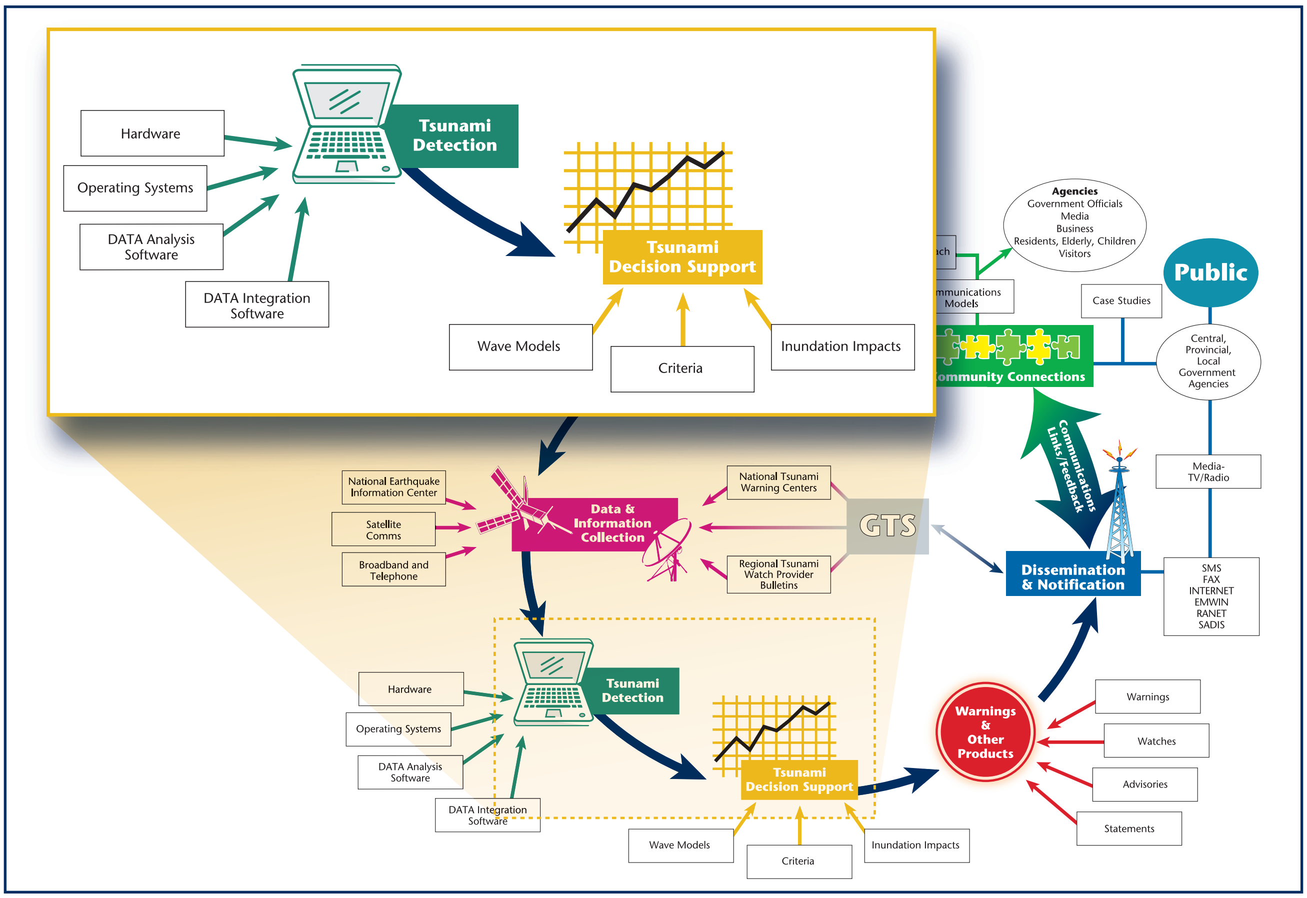

Figure 6-1. Where Decision Support Fits into the End-to-End Tsunami Warning System Chain

- **Assessment of impacts** of events based upon inundation models, preparedness, land use and mitigation programs, etc.
- **Training** for operational watch standers.
- **Research and development** to improve center operations and products.

The infrastructure required for decision support programs, including the hardware, operating systems, communications, and maintenance programs, are discussed in Chapter 5, Tsunami Detection. This chapter should be read by persons who need to understand the types of programs that support operational decision making, and how these programs are evolving.

How Does Tsunami Decision Support Fit into an End-to-End Tsunami Warning System?

As discussed in Chapter 5, National Tsunami Warning Centers (NTWC) and Regional Tsunami Watch Providers (RTWP) function on a day-to-day basis much as a seismological observatory does. A tsunami warning center should do two things as fast as possible: locate any moderate or larger sized earthquake, and assess its magnitude. Once that is accomplished, the center can begin to assess any potential tsunami threat to the regions in its area of responsibility (AOR).

The rapid detection and characterization of tsunami-generating earthquakes by computer applications programs provide the first indication of a potential tsunami in an end-to-end tsunami warning system. Initial seismic-based warnings are subsequently refined by the detection of tsunami-generated changes in sea level, measured by tide gages and buoys. Computer applications programs are used to analyze sea level data to generate forecasts of tsunami wave height and inundation for specific coastal areas. The refinement of initial seismic-based warnings by good computer models can greatly increase the credibility of the warnings by decreasing false alarms.

What Is in this Chapter?

This chapter contains sections that discuss the following topics:

- **Bulletin threshold criteria** used by some NTWCs and RTWPs
- Description of **watch stander situational awareness software** used at West Coast/Alaska Tsunami Warning Center (WC/ATWC)
- **Tsunami wave height models**
- **Computer inundation** models for assessing local impacts
- **Watch stander training requirements**
- **Research and development** to support operations and product improvement

What Are the Most Important Points to Remember about Tsunami Decision Support Requirements for NTWCs and RTWPs?

- The rapid detection of tsunami-generating earthquakes by computer applications programs provides the first indication of a potential tsunami.
- Situational awareness software is crucial to watch-stander efforts to respond as quickly as possible to seismic events.
- Computer applications programs are used to analyze sea level data to generate forecasts of tsunami wave height and inundation for specific coastal areas.
- Training programs and applied research help centers improve their performance.

Bulletin Threshold Criteria

Tsunami bulletins are initially issued solely on the basis of seismic data. Three key earthquake parameters that can be determined quickly from seismic waveform data for the evaluation of an earthquake's tsunamigenic potential are:

- **Location** - whether the earthquake is located under or very near the sea
- **Depth** - whether the earthquake is located close enough to the earth's surface to have caused a significant displacement of that surface
- **Magnitude** - the size of the earthquake

Bulletins are issued as soon as the earthquake's tsunami potential has been analyzed. The first messages are based on earthquake magnitude and location. The type of message issued generally depends on predetermined criteria or thresholds.

After the initial bulletin has been issued, a tsunami warning center must monitor recorded tsunami effects through tide gages and tsunameters (such as the Deep Ocean Assessment and Reporting of Tsunami [DART™] system) to confirm the existence or nonexistence of a tsunami and its degree of severity. In coordination with other NTWCs and RTWPs, the NTWC should issue a cancellation, extension, or final bulletin as appropriate.

Tsunami history and pre-event modeling are taken into account along with observed tsunami amplitudes when determining the extent of danger for the AOR. A center may refrain from issuing a warning or may issue the warning for only selected areas if tsunami history (and modeling, if available) indicates there is no danger, or danger only to selected areas.

Bulletin Thresholds

Bulletin thresholds may vary somewhat due to local circumstances. Tsunami warning centers should strive, however, to adhere as closely as possible to the generally accepted values recommended by the Intergovernmental Oceanographic Commission's Indian Ocean Tsunami Warning System (IOC/IOTWS – II, January 2006) and used by most, if not all, NTWCs and RTWPs. These are given in Table 6-1. Definitions used in the table are:

- **Earthquake Magnitude**: The moment magnitude, Mw (Table 3-3), is more accurate for large earthquakes than the more common Richter magnitude. It is recommended that the moment magnitude to use for initial bulletins be Mwp, based on the first arriving seismic P waves. Subsequent estimates of Mw may be made by methods based on later-arriving seismic waves.
- **Local Tsunami**: A local tsunami is one with destructive or life threatening effects usually limited to within 100 kilometers (km) of the epicenter.
- **Regional Tsunami**: A regional tsunami is one with destructive or life threatening effects usually limited to within 1000 km of the epicenter.
- **Ocean-wide Tsunami**: An ocean-wide tsunami is one with destructive or life threatening effects that can extend across an entire ocean basin.

Table 6-1. Product Thresholds Based on Earthquake Strength

Earthquake Depth	Earthquake Location	Earthquake Magnitude Mw or Mwp	Description of Tsunami Potential	Bulletin Type
< 100 km	Under or very near the sea	≥ 7.9	Potential for a destructive ocean-wide tsunami	Tsunami Watch /Warning
		7.6 to 7.8	Potential for a destructive regional tsunami	Tsunami Watch /Warning
		7.0 to 7.5	Potential for a destructive local tsunami	Tsunami Watch /Warning
		6.5 to 7.0 or inland	Very small potential for a destructive local tsunami	Tsunami Information Bulletin
	Inland	≥ 6.5	No tsunami potential	Tsunami Information Bulletin
≥ 100 km		≥ 6.5	No tsunami potential	Tsunami Information Bulletin

For events that could trigger a tsunami that poses danger across an ocean basin, the area within 3 hours tsunami travel-time of the epicenter will be placed in a tsunami warning status, with the area within a 3- to 6-hour travel-time zone placed in a watch status. For smaller events only expected to be dangerous locally, warnings will be fixed to a certain distance from the source with no watch, as the tsunami is not expected to be dangerous elsewhere.

Japanese Meteorological Agency Approach

Figure 6-2, from the JMA website, graphically illustrates the basic decision process, including criteria based upon initial earthquake magnitude, that most NTWCs and RTWPs use when an earthquake occurs.

Interim Tsunami Advisory Information Service.

The upgrade of the regional sea level network for tsunami monitoring will enable the Centres to issue Tsunami Warning messages in the future.

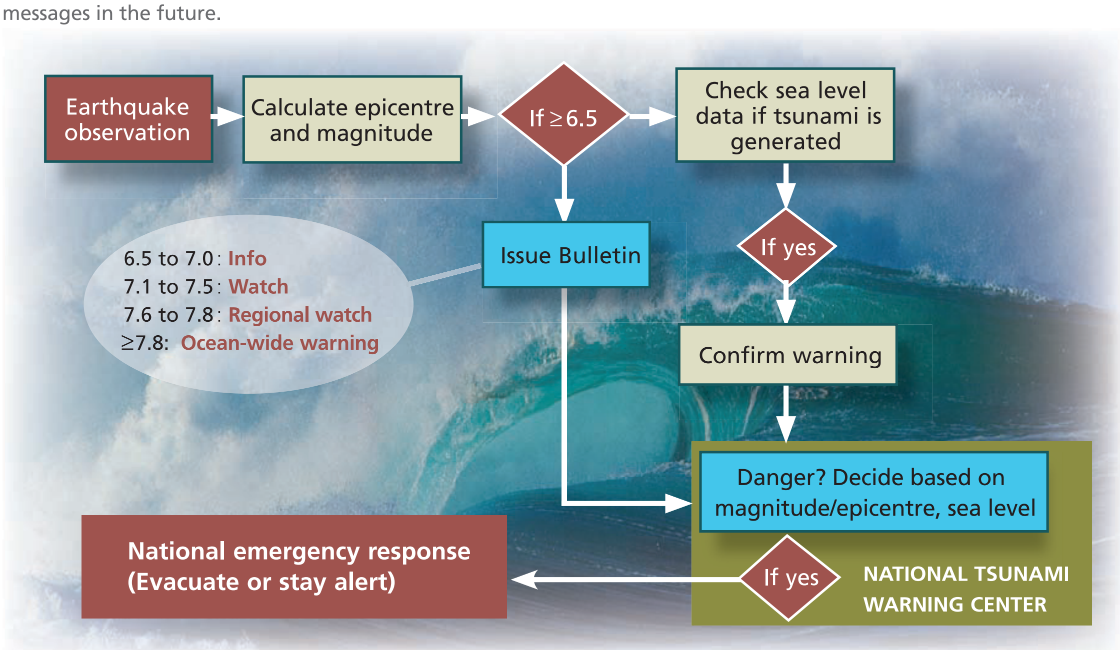

Figure 6-2. Basic Warning Center Response Procedures
(Source: JMA, **http://www.jma.go.jp/en/tsunami/***)*

Thailand National Disaster Warning Center Approach

Based upon the Thailand NDWC's *Concept of Operations* (Draft Version 3.3, March 2006), prepared by the Pacific Disaster Center, Thailand has slightly different standard operating procedures for the tsunami warning decision. Once NDWC receives notification of seismic activity or of an earthquake of greater than Magnitude 7.0 Richter, from either domestic or international hazard information providers, the supervisor (duty officer) consults with the experts of the command center. The experts verify the information, use computer-based simulations to estimate the tsunami wave's arrival to coastal areas, and generate and analyze scenarios to assess the potential risk. Information from various geophysical sources is collected, compared, and analyzed to verify earthquake information, ensure redundancy, and understand the maximum level of risk (illustrated in Figure 6-3).

Magnitude (Richter)	Distance (Km) 0–24	25–48	49–112	113–200	201–400	401–720
3.0–3.9	Advisory	Advisory	Advisory	———	———	———
4.0–4.9	Warning Low Risk	Advisory	Advisory	Advisory	Advisory	———
5.0–5.9	Disaster	Warning High Risk	Advisory	Advisory	Advisory	Advisory
6.0–6.9	Disaster	Disaster	Warning High Risk	Warning Low Risk	Advisory	Advisory
7.0-7.9	Disaster	Disaster	Disaster	Disaster	Warning High Risk	Warning Low Risk
8.0–8.9	Disaster	Disaster	Disaster	Disaster	Disaster	Warning High Risk
> 8.9	Disaster	Disaster	Disaster	Disaster	Disaster	Disaster

Figure 6-3. Summary Table Showing "Levels of Risk" and the Distance of an Earthquake's Effective Radius from Coastal Areas of Thailand
(Source: NDWC)

Once an earthquake of Magnitude 7.0 or greater is confirmed, the NDWC immediately informs all relevant agencies. Command Output Officers are also informed to "stand by" and prepare to activate the warning towers. The NDWC immediately communicates with officers at the Similan Island to closely monitor sea level changes, which will indicate the presence of an approaching tsunami. Within 20 minutes of receiving the notification, NDWC compiles, analyzes, and assesses the probable impact, based on the hazard warning criteria shown in Figure 6-3.

In addition, NDWC has developed criteria to assess the possibility of a tsunami being generated based on the depth of the earthquake or its hypocenter (which is used to further refine the risk level), as shown in Figure 6-4.

Approach Used at a Center with Multiple Criteria

The thresholds listed in Table 6-1 cannot always be followed due to local circumstances. Figure 6-5 shows the thresholds used by the WC/ATWC for the west and east coasts of the United States, and the Caribbean Sea. These differences are substantial but necessary to meet unique circumstances in each of the areas served by this RTWP. Such differences place a large burden on operational watch standers as they must keep track of several different criteria during a single event. If there are multiple events occurring simultaneously, or nearly simultaneously, this complicates the use of criteria thresholds to issue a tsunami bulletin.

Magnitude	Depth of Hypocenter	
	less than 100 km	**more than 100 km**
5.0–6.4	**Low possibility to generate Tsunami Advisory**	Low possibility to generate Tsunami **Advisory**
6.5–6.9	Possibility to generate Tsunami **Alert/Watching**	Low possibility to generate Tsunami **Advisory**
7.0–7.7	Possibility to generate Tsunami **Alert/Watching**	Possibility to generate Tsunami **Alert/Watching**
> 7.8	Very high possibility to generate Tsunami **Warning**	Possibility to generate Tsunami **Alert/Watching**

Figure 6-4. Likelihood of Tsunami Generation Considering the Hypocenter's Location *(Source: NDWC)*

WC/ATWC-Pacific

Area / Mag	AK, BC, WA, OR, CA	Bering Sea Deep	Arctic O., and Bering Shallow	Not in AOR
4–6.4	TIS*** SEAK71 or SEUS71	TIS*** SEAK71	TIS*** SEAK71	
6.5–7	TIS WEPA43 and WEAK53	TIS WEPA43 and WEAK53	TIS WEPA43 and WEAK53 with appropriate Evaluation	TIS WEPA43 and WEAK53
7.1–7.5	Warning * 350Km WEPA41 and WEAK51	Warning * Pribilof/ Aleutian Is. WEPA41 and WEAK51		
7.6–7.8	Warning* 1000Km WEPA41/51			Advisory/ Watch/ Warning WEPA41 and WEAK51
7.9–10	**Warning 3W/3W WEPA41/ WEAK51**			

WC/ATWC-Atlantic

Area / Mag	East Coast US & Canada	East Coast Inland <400 Mile	Gulf Mex Gulf St. L	Puerto Rico/ US VI	Not AOR Western Caribbean	Not AOR Eastern Caribbean	Not AOR Atlantic
4	TIS*** SEXX60		TIS SEXX60	TIS SEXX60			
5					TIS SEXX60	TIS SEXX60	
6	TIS WEXX22 and WEXX32	TIS WEXX22 and WEXX32	TIS WEXX22 and WEXX32	TIS WEXX22 and WEXX32	TIS WEXX22 and WEXX32	TIS WEXX22 and WEXX32 Warning * Puerto Rico/ US VI WEXX20/30	
6.5				Warning * Puerto Rico/ US VI WEXX20 and WEXX30			TIS WEXX22 and WEXX32
6.8–7.5	Warning * 350Km WEXX20 and WEXX30		Warning * Gulf only WEXX20 and WEXX30				
7.6–7.8	Warning* 1000Km WEXX20/30						
7.9–10	**Warning 3W/3W WEXX20/ WEXX30**				Warning * Puerto Rico/ US VI WEXX20/30		TIS/Warn-ing Spec. area WEXX22/32 and WEXX20/30

Notes: *TIS* *Tsunami Information Statement*
TIB *Tsunami Information Bulletin*

Figure 6-5. Bulletin Thresholds Used by the WC/ATWC

Important Points to Remember about Bulletin Thresholds Based Solely on Earthquake Information

- Bulletins are issued as soon as the earthquake's tsunami potential has been analyzed.
- Tsunami history and pre-event modeling are taken into account along with observed tsunami amplitudes in determining the extent of danger for the AOR.
- All tsunami warning centers should use the internationally agreed-upon suite of message products to avoid confusion, especially amongst the tourist population.
- Centers should strive to adhere as closely as possible to the generally accepted bulletin threshold values recommended by IOC/IOTWS.
- An RTWP may require different criteria for different portions of its AOR.

Watch Stander Situational Awareness Support

EarlyBird and EarthVu, two software packages developed at WC/ATWC, are excellent examples of an operational suite of tools that assist watch standers in maintaining situational awareness. Situational awareness is the capacity of the watch stander to detect seismic events in real time.

EarlyBird

WC/ATWC's EarlyBird seismic data processing system is used for both real-time and post-processing of seismic data. EarlyBird is a combination of standard USGS Earthworm modules, WC/ATWC-developed Earthworm modules, and stand-alone seismic processing software.

EarlyBird automatically locates and sizes, using Mb, Ml, Ms, Mw, and Mwp, (Table 3-3) worldwide, regional, and local earthquakes. Graphical interfaces for the Earthworm modules have been created to allow interactive additions and changes to automatically computed parameters during initial earthquake processing, or after the fact. Real-time data can be monitored and interacted with directly through Earthworm modules. Data logged to disk by the system can be analyzed immediately after logging through stand-alone analysis programs. The automatically computed seismic parameters are interfaced with the tsunami message generation software and the EarthVu GIS.

Seismic data arrives at the WC/ATWC by four basic paths: digital broadband data via leased circuits, digital broadband data transmitted via the CrestNet, digital broadband data transmitted over the internet, and digital data transmitted via a Very Small Aperture Terminal (VSAT) satellite ground station system. Data are exported to other centers using the CrestNet or internet.

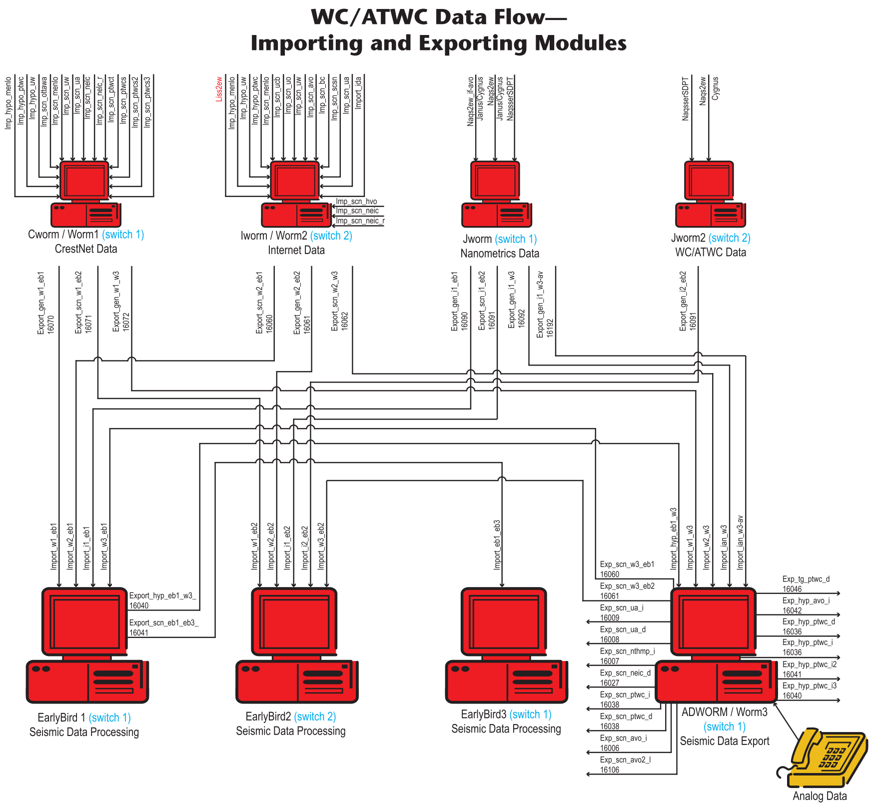

Figure 6-6. Connections Between Import/Export and Processing Systems at WC/ATWC

A separate PC is used to acquire data from each path and to export data and hypocenters to other centers. Connections between import/export and processing systems are shown in Figure 6-6. Switches, routers, PCs, and data paths are configured to eliminate any single points of failure.

A network consisting of eight Windows XP-based PCs comprises the EarlyBird seismic processing system. Five PCs, as described above, import and export data using standard Earthworm modules. Two of the remaining PCs are the main and backup seismic data processors. Both constantly monitor earthquake activity on approximately 250 seismic channels. The last PC is a training/development PC that mirrors the main EarlyBird system.

The data processing flow within EarlyBird 1 is shown in Figure 6-7. Earthworm rings are shared memory locations. The windows icons indicate modules that accommodate user interaction and review. Module Pick_wcatwc analyzes the signal to determine the onset of an earthquake. Once a pick has been made, the signal is further analyzed to determine Mb, Ml, and Mwp magnitude parameters. Alarms are triggered when parameters have been exceeded (location and size). When a large earthquake occurs (M>5), long period and broadband data are processed to refine the magnitude estimate. Each of the modules is described in greater detail below.

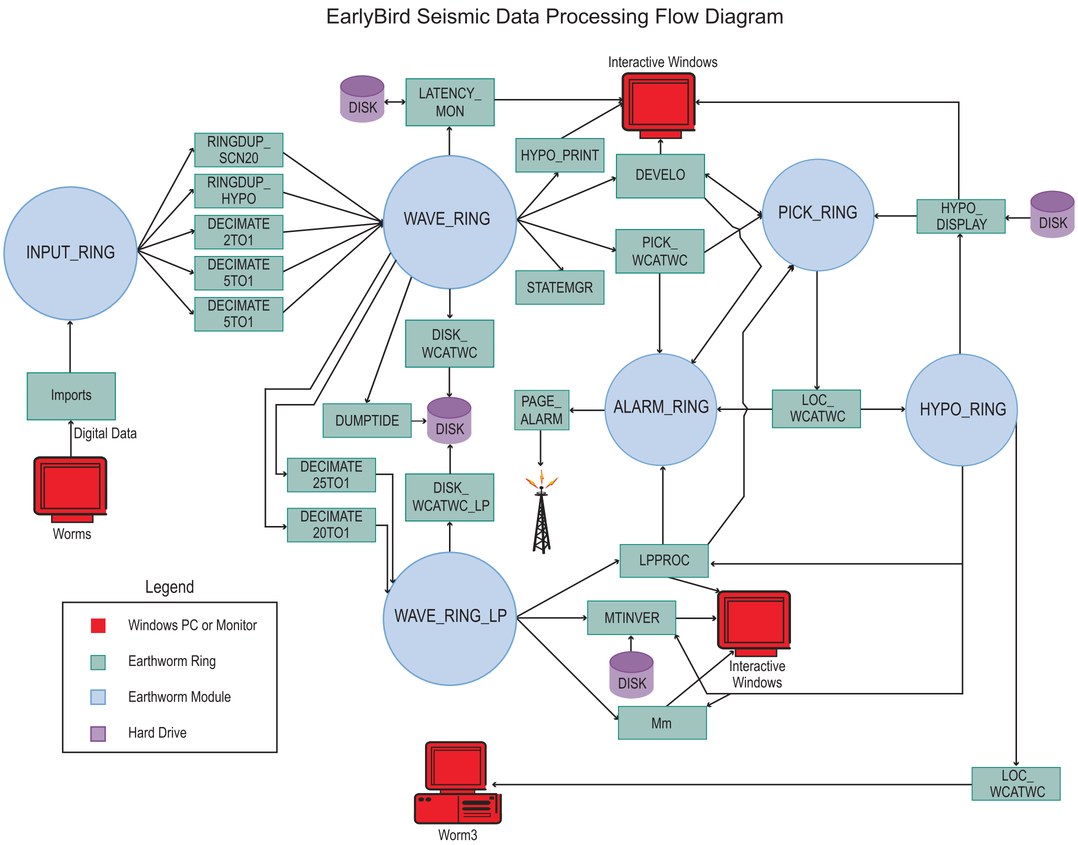

Figure 6-7. Data Processing Flow Within the WC/ATWC Earlybird Software

Earlybird uses the following standard Earthworm modules:

- adsend - digitize analog data
- copystatus - copy errors/heartbeats from one ring to another decimate - filter and reduce the sample rate of data for export and processing
- export_generic/scn - send hypocenter and trace data to other centers
- import_generic - gather hypocenter and trace data from other centers
- import_ida - receive data from the Incorporated Research Institutions for Seismology (IRIS) International Deployment of Accelerometers (IDA) network into Earthworm
- liss2ew - receive data from the IRIS Albuquerque Seismic Laboratory (ASL) network into Earthworm
- ringdup_scn/generic - copy messages from one ring to another
- statmgr - monitor modules attached to a ring
- startstop - start and restart all modules when necessary

Several locally developed Earthworm modules are:

- atplayer - imulate real-time events with older data
- develo - display real-time, short period seismic data in develocorder type view
- disk_wcatwc - log trace data to disk
- dumptide - log certain channels to disk (tide gage data)
- hypo_display - display computed hypocenter parameters and adjust P data
- hypo_print - log hypocenters to disk and EarthVu
- latency_mon - track data outages and latencies for all channels
- loc_wcatwc - associator/locator module
- lpproc - display real-time, long period seismic data and process data for Ms
- mm - process surface wave data for Mm (Mw)
- mtinver - process data for moment tensor
- page_alarm - send alarm messages through various interfaces
- pick_wcatwc - P-picking/magnitude determination algorithm

Four stand-alone, non-Earthworm-based programs are also part of the EarlyBird system:

- ANALYZE - program reads, analyzes and displays seismic data previously logged to disk, and archive data to CD-ROM
- LOCATE - watch stander can interactively locate detected earthquakes, trigger Long Period processing in lpproc, or the watch stander can run the ANALYZE program to determine Ms and Mw, and display location and P data to a PC screen
- MESSAGE2 - program creates tsunami warning and other messages
- SUMMARY - program displays earthquake summary and procedures to monitor

The stand-alone programs are designed to operate completely independently; that is, one does not have to be running for the others to operate. Data are shared between the programs through disk files, and sometimes semaphores. The Earthworm system is modular. If one module breaks, the others should not be affected. The Earthworm module statmgr monitors the modules and will restart them if necessary. The Earthworm startstop module starts and stops the Earthworm modules, and gives the status of each.

All of the programs, including the Earthworm-based components of EarlyBird, run on a PC with a graphics adapter that splits the screen into twelve monitors. The programs ANALYZE, LOCATE, and SUMMARY each display a window covering one monitor. Earthworm modules lpproc, develo, hypo_display, mm, mtinver, and latency_mon also have graphical displays that utilize a monitor. MESSAGE2 brings up a dialog box when activated in LOCATE. The EarthVu system uses the other four monitors. The EarlyBird system can be run on a single-monitor PC, but data will not be as clear as on a twelve-monitor system.

EarthVu

EarthVu is geographic display software developed at the WC/ATWC. Its main functions are to:

- Display epicenters on various scale maps
- Overlay pertinent information such as historic tsunamis and earthquakes, volcanoes, elevation contours, roads, pipelines, tsunami watch/warning areas, etc.
- Provide a graphical platform for computing tsunami models
- Display results of previously computed models for calibration during tsunami warnings
- Compute and display tsunami travel times
- Interface with earthquake and tsunami databases
- Create maps to link to tsunami messages issued by the center

Tip

EarthVu has four modes and runs in parallel with EarlyBird.

EarthVu runs in parallel with the Early Bird seismic processing system and normally uses four computer monitors. EarthVu is sent **automatic** and **interactively computed** earthquake locations. As these locations are acquired, appropriate maps are shown on the monitors.

EarthVu can be run in one of four modes:

1) Display large-scale maps and overlays

2) Interface for tsunami travel time maps

3) Display small scale maps

4) Display regional maps showing the last 7 days' events

Overlays

Several overlays are available in EarthVu:

- Major Cities
- Tsunamis - all known Pacific basin tsunamis, from NOAA National Geographic Data Center (NGDC)
- Earthquakes - all known quakes with magnitude >5, 1900-present, from USGS National Earthquake Information Center (NEIC)
- Volcanoes - from Global Volcanism Program
- Seismometers - seismometer data processed at WC/ATWC
- Tide Gages - tide gage sites recorded at WC/ATWC
- Watch/Warning Areas - present tsunami watch/warning status

- Lat/Lon Grids - meridians and parallels at specifiable intervals
- Cities - from U.S. Department of Defense (DOD) Digital Chart of the World
- Contours - from DOD Digital Chart of the World
- Geographic Names - from DOD Digital Chart of the World
- Airports, roads, pipelines, power lines, trails, railroads - from DOD Digital Chart of the World

Other interactive options available in EarthVu are: display detailed data on a tsunami, volcano, tide gage, or seismometer with a mouse click; re-draw a map with color coded elevations/bathymetries; turn on/off voice option (says location as displayed); call historic databases; and specify an area of the map to expand in the small-scale map program.

Historic tsunami and earthquake data are queried with program HISTORY, which is called from EarthVu. HISTORY retrieves information from the databases by date, location, and magnitude. The output can be in summary form or in great detail, and is written to the screen and/or printer. The earthquake database is from the USGS/NEIC. It contains all earthquakes between 1900 and the present over magnitude 5 (more than 70,000 quakes). The tsunami database is taken mostly from NOAA/NGDC studies (such as Lander et al., 1993; Lander, 1996). It contains more than 1,000 Pacific basin tsunamis dating back to 47 BC. The same information accessed by program HISTORY is also used by EarthVu and the other programs when displaying tsunamis and earthquake data on maps.

Tsunami Travel Times and Models

Tsunami travel time and tsunami model computations can also be performed and displayed through the EarthVu interface. Tsunami travel time results are displayed on an EarthVu map. EarthVu acts as a graphic interface where model areas are specified and results are displayed. EarthVu also displays pre-computed model results and provides a method to scale the results based on recorded tsunamis during a warning. Far-field tsunami amplitude forecasts can be made using the Model/Results option in the EarthVu program. These forecasts are based on pre-computed tsunami models scaled by observed sea level data. Over 300 pre-computed models are available. For WC/ATWC, maximum amplitudes (zero-to-peak in meters) are saved at 99 places along the coasts of Alaska, British Columbia, Washington, Oregon, California, Hawaii, and at all DART buoys. Models are run with grid increments of 5 feet over the deep ocean, 1 foot over the shelf, and, where necessary to describe local shoreline configuration. Nonlinear, shallow-water equations are used with friction effects over the finer grids included. Inundation is not taken into account. The basic technique is described by Kowalik and Whitmore (1991, *Science of Tsunami Hazards*). The methodology of utilizing pre-computed models during tsunami warnings is described by Whitmore and Sokolowski (1996, *Science of Tsunami Hazards*).

Important Points to Remember about Using WC/ATWC's EarthVu and EarlyBird Software to Maintain Situational Awareness

- EarthVu runs in parallel with the EarlyBird seismic processing system and normally uses four computer monitors.
- EarlyBird automatically locates and sizes (using Mb, Ml, Ms, Mw, and Mwp) world-wide, regional, and local earthquakes.
- EarthVu can be run in one of four modes and several GIS overlays are available for the watch stander to use.
- Tsunami travel time and tsunami model computations can be performed and displayed through the EarthVu interface.
- EarthVu also displays precomputed model results and provides a method to scale the results based on recorded (by tide gages and DART buoys) tsunamis during a warning.

Tsunami Wave Height and Inundation Computer Models

The current focus at established tsunami warning centers is to develop a fast, accurate operational tsunami forecast system that provides an optimal interpretation of the available earthquake and sea-level data, and quantifies the potential tsunami impact on coastal communities. Such a system is critical to decision-makers at tsunami warning centers, who must rapidly assess the hazard to coastal communities. The stakes are high: A missed warning could result in devastating fatalities, while needless evacuations are dangerous, expensive, and erode confidence in the warning system. Tsunami forecasting technology under development at NOAA and JMA is based on the well-tested approach used in most hazard forecast systems—i.e., the integration of real-time measurement and modeling technologies.

Model-based interpretation of the tsunami, such as those by the Method of Splitting Tsunamis (MOST) model developed at NOAA's Pacific Marine Environmental Laboratory (PMEL), occurs in two stages. First, a pre-computed database of deep-ocean model simulations is exploited to formally invert the real-time tsunameter (DART buoy) data stream and produce a linear best-fit solution in deep water; this step is completed within a few minutes of data acquisition. Second, the deep-water values just offshore are used to initiate real-time execution of nonlinear inundation models to provide community-specific forecasts of tsunami inundation; this step is completed in less than 10 minutes.

The MOST Model

The evolution of earthquake-generated tsunami waves has three distinctive stages: generation, propagation, and runup. The MOST numerical model (NOAA Technical

Memorandum ERL PMEL-112, 1997) computes all three stages, providing a complete tsunami simulation capability.

Tip

The MOST model uses a precomputed database of deep-ocean tsunami simulations.

Generation

The generation stage of tsunami evolution includes the formation of the initial disturbance of the ocean surface due to the earthquake-triggered deformation of the seafloor. This initial water surface disturbance evolves into a long gravity wave radiating from the earthquake source. Modeling of the initial stage of tsunami generation is therefore closely linked to studies of earthquake source mechanisms.

The tsunami generation process is based on a fault plane model of the earthquake source (Gusiakov, 1978; Okada, 1985), which assumes an incompressible liquid layer on an underlying elastic half-space to characterize the ocean and the Earth's crust. The implementation of this elastic fault plane model (Titov, 1997) utilizes a formula for static sea-floor deformation to calculate the initial conditions required for subsequent computations of tsunami propagation and inundation.

Propagation

A tsunami can propagate long distances before it strikes a shoreline hundreds or thousands of kilometers from the earthquake source. To accurately model tsunami propagation over such large distances, the Earth's curvature should be taken into account. Other factors, such as Coriolis forces and dispersion, may also be important.

Dispersion changes the wave shape due to slightly different propagation speeds of waves with different frequencies. This effect can be taken into account even without the explicit use of dispersive terms in the governing equations; Shuto (1991) suggested that this process could be simulated by exploiting the numerical dispersion inherent in finite-difference algorithms. This method accounts for dispersive effects, but allows the use of non-dispersive linear or nonlinear equations for wave propagation modeling. The MOST propagation model uses a numerical dispersion scheme and the nonlinear shallow-water wave equations in spherical coordinates, with Coriolis terms (Murty, 1984):

$$h_t + \frac{(uh)_\lambda + (vh\cos\phi)_\phi}{R\cos\phi} = 0$$

$$u_t + \frac{uu_\lambda}{R\cos\phi} + \frac{vu_\phi}{R} + \frac{gh_\lambda}{R\cos\phi} = \frac{gd_\lambda}{R\cos\phi} + fv$$

$$v_t + \frac{uv_\lambda}{R\cos\phi} + \frac{vv_\phi}{R} + \frac{gh_\phi}{R} = \frac{gd_\phi}{R} - fu$$

where λ is longitude, ϕ is latitude, $h = h(\lambda,\phi,t) + d(\lambda,\phi,t)$ is the amplitude, $d(\lambda,\phi,t)$ is the undisturbed water depth, $u(\lambda,\phi,t)$, $v(\lambda,\phi,t)$ are the depth-averaged velocities in the longitude and latitude directions, respectively, g is the gravity accelration, f is the Coriolis parameter ($f = 2\omega\sin\phi$), and R is the Earth radius. In the MOST model, these equations are solved numerically using a splitting method similar to that described by Titov (1997).

Inundation

Runup of a tsunami onto dry land is probably the most underdeveloped part of any tsunami simulation model, primarily because of a serious lack of two major types of data: high-quality field measurements for testing of the models, and fine-resolution bathymetry/topography data. The first major obstacle to improving simulations of the inundation process, i.e., the lack of high-quality experimental and field measurements of runup, has been especially severe. Recently, this problem has been somewhat alleviated by a series of large-scale runup experiments conducted at the Coastal Engineering Research Center (CERC) of the U.S. Army Corps of Engineers (Briggs *et al.* 1995) and by several post-tsunami surveys that provided high-quality field data (Yeh *et al.*, 1993; Synolakis *et al.*, 1995; Imamura *et al.*, 1995; Yeh *et al.*, 1995; Borrero *et al.*, 1997).

The second serious obstacle to accurate inundation model simulations is the requirement for high-resolution bathymetry and topography data in critical near-shore areas; in most cases, 10- to 50-meter horizontal resolution of gridded bathymetry and topography data are essential. Such high-resolution data are not easily obtained. Where adequate bathymetric and topographic data are available, the MOST model inundation computations are sufficiently accurate to develop useful hazard mitigation tools and guidance products such as inundation maps.

Asteroid-Generated Tsunami Model

A model of an asteroid-generated tsunami was developed by Robert Weiss, Kai Wünnemann, and Heinrich Bahlburg (2006) in Geophysical Journal International. This numerical model estimates the generation, propagation, and runup of tsunamis caused by oceanic impacts.

Hypervelocity impacts of asteroids in marine environments produce tsunami waves independent of the water depth and the diameter of the projectile, although the characteristics of induced waves are affected by these parameters. The authors present a model, consisting of the well-known impact model and a nonlinear wave propagation model, to study the generation and subsequent spread-out of the initial wave pattern caused by the strike of an asteroid or comet in the ocean. The numerical simulation of oceanic impacts requires some changes and extensions to the original impact model code. The handling of different materials (water and solid rocks) is particularly crucial due to the cratering process.

For the simulation of the propagation of tsunami waves generated by the impact process, they use a newly developed wave propagation model, which is based on the nonlinear shallow water theory with boundary conditions derived from the impact model. The runup of the tsunami wave on the coastline is handled as a special case of reflection and is realized by the well-established MOST code. Besides the model description, the authors illustrate the capability of the modeling scheme by the simulation of the strike of an asteroid 800 meters in diameter on a 5000-meter-deep ocean at 10.2 kilometers per second, the subsequent propagation of the induced tsunami waves over an artificial bathymetry, and the runup of the wave on the coast.

Other Inundation Models

Several other inundation models are being developed in addition to the inundation component of the MOST model. For example, The FLO-2D® model by FLO-2D Software, Inc., can be used to create detailed overland inundation mapping for ocean storm surge or tsunami hazards and is particularly effective in urban areas where buildings, obstructions, streets and channels can affect the flood wave progression. The modeling detail provided by FLO-2D® exceeds that of other hydrodynamic models, and the results include predicted flow depths, velocities, discharge hydrographs, dynamic and static pressure, specific energy, and area of inundation. The specific input data required for a FLO-2D® ocean storm surge model is wave height or water surface elevation as a function of time (time-stage data pairs) for the coastal grid elements.

Important Points to Remember about Tsunami Modeling

- NTWCs and RTWPs should strive to implement a fast, accurate, operational tsunami forecast system that provides an optimal interpretation of the available earthquake and sea-level data, and quantifies the potential tsunami impact on coastal communities.
- The evolution of earthquake-generated tsunami waves has three distinctive stages: generation, propagation, and runup. The NOAA MOST numerical model computes all three stages, providing a complete tsunami simulation capability.
- Runup of a tsunami onto dry land is probably the most underdeveloped part of current tsunami simulation models, primarily because of a lack of two major types of data: high-quality field measurements for testing of the models, and fine-resolution bathymetry/topography data.
- Models for asteroid-generated tsunamis are also available in addition to models for earthquake-generated tsunamis
- Other inundation models exist in addition to the MOST inundation model

Watch Stander Training

A scientist in the position of watch stander must possess the professional judgment necessary to gather and evaluate appropriate information for accuracy and completeness, and to implement the correct response in a timely manner for the protection of lives and property. He/she must be able to make observations, calculations, and interpretations, using all available geophysical, oceanographic, and geographic data, obtained by diverse methods of communications, to locate an earthquake, determine its magnitude, evaluate its potential for tsunami generation, evaluate appropriate tsunami data for degree of potential threat, and issue, with follow-up, a tsunami watch, a tsunami warning, or other information messages as necessary.

Tip

A tsunami warning center should have both geophysicists and oceanographers on staff.

The ability to take appropriate actions is based on an expert knowledge of theoretical and applied geophysics, volcanology, sedimentology, regional tectonics, geography, and oceanography of both the source region as well as potential impact areas. These skills and this knowledge are not all acquired during study in a single academic discipline; **a long period of on-the-job training is required for geophysicists and oceanographers to perform at an optimum level**.

A center should have a mix of geophysicists and oceanographers on staff. Further, the center should have a rigorous on-station training program that provides periodic training on the end-to-end procedures for obtaining and processing data and issuing test bulletins. One effective way to do this is to utilize historic data from past events. Some NTWCs and RTWPs have developed computer simulation programs (notably the WC/ATWC's EarlyBird system) to facilitate this type of training. These simulators can provide watch standers with many years of experience in a short period of time.

In addition to providing experience for watch standers, periodic operational end-to-end training also exercises the communications paths that a center uses to collect data and disseminate bulletins. This is very important as these communications channels are crucial to proper performance in actual events, which are relatively infrequent.

Important Points to Remember about Watch Stander Training

- A scientist in the position of watch stander must possess excellent professional judgment.
- A long period of on-the-job training is required for geophysicists and oceanographers to perform at an optimum level.
- Periodic operational end-to-end training provides experience for watch standers and also exercises the communications paths that a center uses to collect data and disseminate bulletins.

Research and Development

Applied research and program development activities at RTWPs and NTWCs generally fall into three broad categories:

- Science: Applied oceanographic and seismic research that leads to better models of parameters like hypocenter location, earthquake tsunami generation characteristics, tsunami wave speed and amplitude, inundation maps, etc. The emerging "what if" technology falls in this category.
- Processing: Development of computer methods for speeding the processing of seismic and sea level data, disseminating products to new technologies, and programs that assist watch standers in maintaining situational awareness.
- Social science: Developing education programs, warning messages, and other communications that produce the desired reactions by constituents.

Each RTWP and NTWC can function acceptably without a rigorous research and development program. A center can rely on improvements and new techniques developed at other NTWCs, RTWPs, and academic and government research institutions. However, a center can often better address its own unique local problems. Additionally, a local research and development program creates an atmosphere of progress within a tsunami warning center. A mix of oceanographers, seismologists, computer programmers, and networking/communications experts is optimal as it gives the center the skills needed to address research and development in all three of the above categories.

Tip

A tsunami warning center's local research and development program can often best address local problems.

In additional to building a multi-disciplinary staff, tsunami warning centers are urged to establish and exercise strong links with academic institutions and other professional research groups such as the Asian Disaster Preparedness Center (ADPC) and the Pacific Disaster Center (PDC). These links often lead to advances in procedures and help the center remain on the cutting edge of new technology and techniques. Collaborative ties can be established at nearby or co-located institutions, or by staff who are alumni, or through contacts made at meetings and workshops.

Experimental Products

The four basic international products (warning, watch, advisory, and statement) may not meet all the needs of an RTWP or a NTWC. For example, an RTWP may need to develop or modify a specialized product to meet the needs of one or more of the NTWCs it serves. A NTWC may need to develop or modify a specialized product to meet unique conditions or requirements of one or more of its customers. Similarly, RTWPs and NTWCs may contemplate providing a new, or changing an existing service. In all these cases the warning center should establish and follow an *a priori* process that has been thought through and discussed with the center's customer base well before the change process begins. Such an approach will help the center avoid many of the pitfalls associated with making changes.

A new or changed product or service begins as a concept, which is developed into a proposal. Once the proposal has been articulated but before development begins, the tsunami warning center should ensure that implementing the new or changed product or service would be acting in a fair and evenhanded manner with respect to all stakeholders, and accomplished in a manner that maximizes fairness and openness. Figure 6-8 describes the process to follow in developing and implementing a new or enhanced product or service. Products and services in this process can be national or local in scope. The six guiding principles outlined below should be followed when considering whether a new product or service or change to an existing product or service can be made.

New or Enhanced Products/Services Process

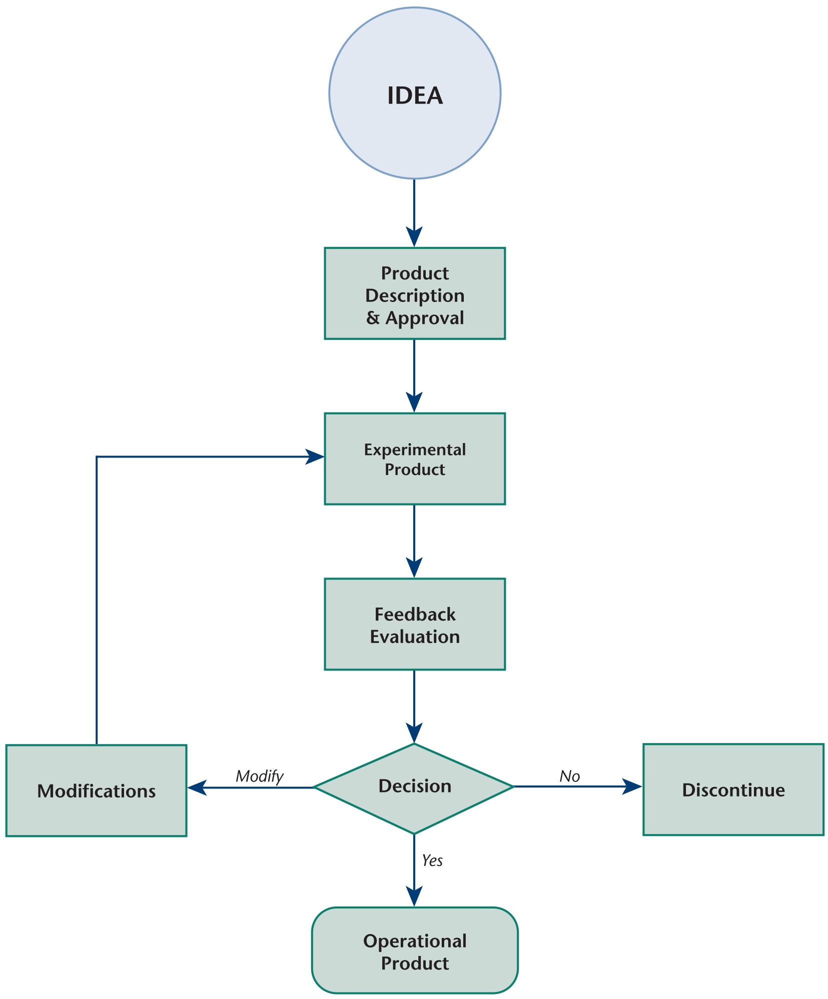

Figure 6-8. Steps to Implementing an Experimental Product (from National Weather Service Instruction 10-102 May 18, 2006)

Six guiding principles when considering beginning or changing an existing product or service:

1. **Mission connection** - The product or service must be connected to the center's mission.
2. **Life and property first** - Protection of life and property must be placed first in the allocation of resources and the development and dissemination of products and services.
3. **No surprises** - All users, including those in the private sector, must be provided adequate notice and opportunity for input into decisions regarding the development and dissemination of products and services.
4. **The stakeholders own the data** - Open and unrestricted dissemination of publicly funded information is good policy and may be the law.
5. **Equity** - All dealings with various constituents must be equitable and not show favoritism to particular partners, particularly those in the academic and commercial sectors. A service to a segment of the user community should not be provided that cannot be provided to all similar types of users.
6. **Maintain and explain the routine** - When faced with requests for specifically tailored services, make sure the user fully understands the products which the center "routinely" provides.

Product Improvement Program

The objective of tsunami modeling research is to develop numerical models for faster and more reliable forecasts of tsunamis propagating through the ocean and striking coastal communities. Forecast modeling software products specifically designed to support the tsunami warning center's forecasting operations are invaluable. In addition to this, inundation modeling designed to assist coastal communities in their efforts to assess the risk and mitigate the potential of tsunami hazard are also invaluable.

Tsunami Wave Forecast Modeling

The main objective of a forecast model is to provide an estimate of wave arrival time, wave height, and inundation area immediately after a tsunami event. Tsunami forecast models are run in real time while a tsunami is propagating in the open ocean. Consequently they are designed to perform under very stringent time limitations.

Given the time constraints of this type of study, the process of computing the three stages of tsunami modeling, namely, wave generation, propagation, and inundation, is usually expedited by generating a database of pre-computed scenarios. The pre-computed database contains information about tsunami propagation in the open ocean from a multitude of potential sources. When a tsunami event occurs, an initial source is selected from the pre-computed database. In the initial stages of the tsunami, this selection is based only on the available seismic information for the earthquake event.

As the wave propagates across the ocean and successively reaches the sea level gages and DART systems, these report the recorded sea level information back to the tsunami warning centers, which, in turn, process the information and produce a new and more refined estimate of the tsunami source. The result is an increasingly accurate forecast of the tsunami that can be used to issue watches, warnings, or recommend evacuations.

When an event similar to one of the pre-computed scenarios occurs, the available propagation information is used to compute the last stage of the study, wave inundation.

Inundation Modeling

An inundation modeling study attempts to recreate the tsunami generation in deep or coastal waters, wave propagation to the impact zone, and inundation along the study area. High-resolution bathymetric and topographic grids are used in this type of study to reproduce the correct wave dynamics during the inundation computations. The high-quality bathymetric and topographic data sets needed for development of inundation maps require maintenance and upgrades as better data become available and coastal changes occur.

Inundation studies can be conducted taking a probabilistic approach in which multiple tsunami scenarios are considered, and an assessment of the vulnerability of the coast to tsunami hazard is evaluated, or they may focus on the effect of a particular "worst-case scenario" and assess the impact of such a particularly high-impact event on the areas under investigation.

The results of a tsunami inundation study should include information about the maximum wave height and maximum current speed as a function of location; maximum inundation line; and time series of wave height at different locations, indicating wave arrival time. This information can be used by emergency managers and urban planners primarily to establish evacuation routes and the locations of vital infrastructure. Additionally, emergency managers and other officials are in urgent need of operational tools that will provide accurate tsunami forecasts as guidance for rapid, critical decisions in which lives and property are at stake. The more timely and precise the warnings are, the more effective the actions that local emergency managers can take and the more lives and property can be saved.

Combined, measurement and modeling techniques can provide reliable tsunami forecasts. To forecast inundation from early tsunami waves, seismic parameter estimates and tsunami measurements are used to sift through a pre-computed generation/propagation forecast database and select an appropriate (linear) combination of scenarios that most closely matches the observational data. This produces estimates of tsunami characteristics in deep water, which can then be used as initial conditions for a site-specific (nonlinear) inundation algorithm. A statistical methodology has been developed to forecast the maximum height of later tsunami waves that can threaten rescue and recovery operations. The results are made available through a user-friendly interface to aid hazard assessment and decision making by emergency managers.

The MOST model performed computations of generation/propagation scenarios for the forecast database. The nonlinear high-resolution model will provide the inundation forecasts. This methodology is the foundation of the next-generation forecast tools for tsunami warning and mitigation that are being developed in close collaboration with tsunami warning centers and academia. These new tools will provide site- and event-specific forecast of tsunami amplitudes to assist emergency managers during tsunami warning and mitigation procedures.

Important Points to Remember about Research and Development Programs at NTWCs and RTWPs

- Applied research and program development activities at RTWPs and NTWCs generally fall into three broad categories: geophysical science, processing, and social science.
- A tsunami warning center's research and development program creates an atmosphere of progress.
- Collaboration with other institutions helps a center remain on the cutting edge of new technology and techniques.
- A new product should pass a rigorous testing program before becoming operational.