

**Remote Sensing of Surficial Process Responses To Extreme Meteorological Events**

**Final Report**

*Final  
Report  
2017  
045312*

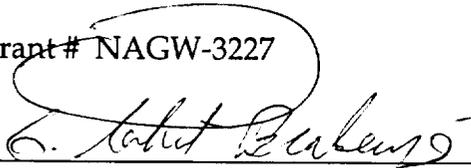
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## SUMMARY

Changes in the frequency and magnitude of extreme meteorological events are associated with changing environmental means. Such events are important in human affairs, and can also be investigated by orbital remote sensing. During the course of this project, we applied ERS-1, ERS-2, Radarsat, and an airborne sensor (AIRSAR-TOPSAR) to measure flood extents, flood water surface profiles, and flood depths. We established a World Wide Web site (the Dartmouth Flood Observatory) for publishing remote sensing-based maps of contemporary floods worldwide; this is also an online "active archive" that presently constitutes the only global compilation of extreme flood events. We prepared an article for EOS concerning SAR imaging of the Mississippi Valley flood; an article for the International Journal of Remote Sensing on measurement of a river flood wave using ERS-2, began work on an article (since completed and published) on the Flood Observatory for a Geoscience Information Society Proceedings volume, and presented lectures at several Geol. Soc. of America Natl. Meetings, an Assoc. of Amer. Geographers Natl. Meeting, and a Binghamton Geomorphology Symposium (all on SAR remote sensing of the Mississippi Valley flood). We expanded in-house modeling capabilities by installing the latest version of the Army Corps of Engineers RMA two-dimensional hydraulics software and BYU Engineering Graphics Lab's Surface Water Modeling System (finite elements based pre- and post-processors for RMA work) and also added watershed modeling software. We are presently comparing the results of the 2-d flow models with SAR image data. The grant also supported several important upgrades of pc-based remote sensing infrastructure at Dartmouth. During work on this grant, we collaborated with several workers at the U.S. Army Corps of Engineers, Remote Sensing/GIS laboratory (for flood inundation mapping and modeling; particularly of the Illinois River using the AIRSAR/TOPSAR/ERS-2 combined data), with Dr. Karen Prestegard at the University of Maryland (geomorphological responses to the extreme 1993 flood along the Raccoon drainage in central Iowa), and with Mr Tim Scrom of the Albany National Weather Service River Forecast Center (initial planning for the use of Radarsat and ERS-2 for flood warning). The work thus initiated with this proposal is continuing.

## PROJECT HISTORY

During the Great Flood of the Upper Mississippi Valley in 1993, the utility of orbital SAR remote sensing for obtaining basic data about such hydrologic events became clear. Brakenridge and a colleague (Jim Knox, University of Wisconsin) obtained an emergency travel award from the National Geographic Society to facilitate low altitude flyover of the flooded Upper Valley near the time of ERS-1 image acquisition; NASA HQ supported processing and delivery of the ERS scenes to us as well as other interested investigators. We were able to combine our visual and photographic observations of the flooding with the ERS scenes; at this time this was a new application for the ERS project. A New

England television news team interviewed the Dartmouth team, and both the ERS data and NASA support of this work was thereby widely publicized (newspapers in the region also ran stories with included color photographs). ESA has since featured the work in their "New Views of the Earth: Applications achievements of ERS-1" publication (ESA SP-1176/11, 1996; see Figure 1 in the Appendix)

In analysis of the images, we combined the SAR imaging of the flood water with topographic data, plotted downvalley profiles of the water surface from the intersection of the flood water edges with the land surface, and, with other colleagues, co-authored a contribution for the American Geophysical Union's EOS publication (Brakenridge and others, 1993). In this article, we outline how useful satellite imagery could be for flood studies at this moderate-to-high resolution spatial scale. We also described an unexpected result: time synchronous elevated water stages on the valley's west side compared with those on its east. We suggested that the elevated stages were due to a classic backwater curve effect on a major tributary (the Des Moines River) and noted that combined remote sensing/topography constitutes unique data for the hydraulic analysis of river floods. The paper alerted both the remote sensing and the hydrology scientific communities to a previously underappreciated capability of remote sensing applied to river floods.

At about the same time, a successful proposal was made to ESA to gain access to additional SAR images of other flood events. We obtained ESA's DESCW software, which allowed us to track planned ERS satellite acquisitions. This in turn allowed us to order SAR images of recent flood events if chance imaging of such floods had occurred. Due to the satellite's busy operating schedule, this was common and we have now accumulated 80+ full resolution ERS-1 or ERS-2 images of major flood events world-wide. Further analysis of these data is ongoing, and is included within a new NASA-funded EOS-IDS investigation.

Our science goals evolved as we worked with the data. We strove for a balance between practical applications, which would stress rapid map production of inundated lands, and demonstrations of new analytical approaches. Thus, in some cases, image delivery to Dartmouth was prompt, and we were able to work with other interested national and international institutions involved in flood disaster response and recovery. For example, the Great Southern Scandinavia flood of winter, 1995, was well imaged by ERS-1, and we produced change detection-based flood inundation color composites and classifications that were shipped to a Norwegian laboratory (Jordforsk) involved in flooded land mapping (Figures 2 and 3 in the Appendix ). In other cases, image delivery was delayed by several months or even years; we are still currently receiving ERS data for areas such as Viet Nam that were flooded several years ago and where these data were obtained at local ground stations

and put into a long queue for processing. Our analysis of these data is thus still incomplete.

Where time series of images include river reaches observed before and after levee breaching or overtopping, the TABS hydraulic modeling software allows predicting the effect of such levee changes; in principle, image series and computer models can be compared quite closely. We joined with a colleague (Karen Prestegaard of the University of Maryland) to study the dynamics and effects of the 1993 flood within the Raccoon drainage (central Iowa) by combining her field data and our analysis of the SAR coverage, and with modeling helping to bridge these two kinds of data. A graduate student thesis is in progress in Maryland on this topic.

Related work continued to be performed on two separate activities: testing computer techniques for digital topography generation, and testing mathematical landscape models that focus overland flow and predict the locations of flood damage. Early in the project we started exploring the generation of digital topography with Shuttle Large Format Camera and MOMS-2 orbital stereoscopic images; we examined their capability for providing the local topography needed for SAR image analysis and related flood hydraulics modeling. DEMs were generated from the Shuttle data but numerous problems with translating the large film size into digital image files useful within a PC environment were encountered (the entire image must be used if the image source is an optical camera and film; at suitable scanning resolutions, single image file sizes reach above 500 megabytes). Similarly, we obtained MOMS data from DARA and generated some digital topography; the plans were to accomplish some initial work using the shuttle MOMS data in anticipation of the PRIRODA-based MOMS providing more abundant such data. However, MOMS use is currently problematical due to recent collision damage suffered by MIR, and our work in modeling is using the recently released GTOPO digital topography instead. Instead of continuing with these approaches, we are currently requesting ASTER stereo data for selected river valleys where we already have SAR imagery of large flood events.

In regard to the Large Format Camera-based work, NASA HQ responded to our renewal proposal by noting that the Syria DEM/SPOT work we proposed (and began) was the least highly rated of the proposal contents and that we should budget our effort accordingly. We have decided instead to focus work in northern New England, in which watershed DEMs and predictive models of the locations of flood damage can to be assessed. A renewal proposal noted that the forested terrain is difficult for remote sensing, however, after a long delay, RSI is about to ship a three scene interferometric data set of a portion of this region, and we are ready to process the single look complex product using PCI software purchased last year. This completes our combined air photo/SPOT/Landsat/ERS SAR collection for this local field area. Discussions were also begun this final project year with a NOAA river forecast office in

Albany, NY concerning a pilot test of rapid turn-around Radarsat data for actual flood warning.

## DISCUSSION OF SAMPLE FLOOD REMOTE SENSING RESULTS

### SAR Floodwater Classification

SAR imaging of overbank river flooding requires that water surfaces be discriminated from dry or wet land surfaces. With C-band SAR, a strong backscatter contrast commonly occurs in agricultural areas (and thus most floodplain lands), because even moderately wind- or current-roughened water still returns less signal than croplands or bare soil (e.g. examine Figure 1, which covers a large area of floodplain lands planted mainly in corn).

Where forests still exist along the floodplain, such discrimination becomes more difficult. For the southern Norway flood of June, 1995, we found it necessary to use at least two time steps: an exact repeat (so from same orbital position) "before" image precisely co-registered to the flood image. This provides the opportunity for multi-temporal classification of water pixels based on the backscatter change (Figures 2 and 3). Because of this experience, we are skeptical that single image work in forested terrain (such as in the SE U.S. following hurricane incursions) can produce reliable results: it is exceptionally difficult to map inundation along even partially forested floodplains without such time series. The problem of similar signal return from dry and wet forested floodplain land is reduced if L-band SAR is instead used (see below); a combined L and C band approach may be optimal.

### Hydraulic Modeling Validated by Remote Sensing

HEC-2 modeling techniques are a well-established approach toward modeling flood flows and thus estimating flood risk along river valleys. They rely on accurate flow cross-sectional information, including floodplain topography. With such information, and a steady flow flood discharge, the water stage can be calculated at each cross section site.

Among the suite of ERS-1 images obtained for us by ASF in the wake of the Upper Mississippi Valley flood, we recognized that one tributary valley should have been experiencing the passage of the flood crest when the SAR image was obtained. We selected this valley for stage measurements based on the SAR image and using the methodology outline in the EOS paper. (Figure 4). We then used HEC-2 to model a constant discharge flood flow along the valley in order to predict the effects of valley morphology on river stage (Figure 5). Any observed local stage elevation above this modeled surface would, therefore, have some other cause than river channel and valley cross-sectional morphology, and could reflect the higher discharge caused by the flood peak. In this manner, we compared the measured (non-constant discharge) and modeled (constant

discharge) flood surfaces. A region of elevated stage does in fact occur at the interpolated position of the flood crest as indicated by two gaging stations up and downstream (Figure 5). This result, which constitutes the first remote sensing-based observation of a river flood wave, was accepted by the *International Journal of Remote Sensing* and should finally be published in 1998.

### The Web Site and Dartmouth Flood Observatory Catalog

As this project began, Web sites were beginning to become much more widely used as a method for scientific communication. With the encouragement of NASA HQ, considerable effort was expended to develop a local site relating to our research and that could provide several needed functions: a) organized cataloging of extreme events on a global basis; b) dissemination of flood remote sensing results, particularly rapid turn-around of such results when this is possible, and c) on-line analytical tools for both detecting and analyzing extreme flood events. Dartmouth College agreed to host the site, and its usefulness will soon be even more enhanced by the College's successful competition for NSF funding for upgraded high speed ("Internet 2") connections. A research assistant (Brian Tracy) and a faculty colleague (Dan Karnes) assisted in setting the site up at: <http://www.dartmouth.edu/artsci/geog/floods/>.

Most of the figures here included were downloaded directly from this site: it has become an integral part of our work. Included is an expanding global catalog of flood events, that has, unfortunately, so far changed in format from one year to the next. We believe that the current version (shown in abbreviated form in Figure 6) is stable and that we can maintain similar catalogs each year at reasonable % effort levels. The older catalogs will be reformatted into the 1997 version. We found that the use of text summaries of each event, drawn from copyrighted news stories as well as from government sources, was labor-intensive and, if "published" on the Internet could constitute copyright infringement. We also determined that it was firm "numbers" regarding the events that were most useful in analyzing flood causation, frequencies and magnitudes, and geographic patterns. Such numbers include areas inundated, hydroclimate classification, geographic location, and magnitude estimates; they also include socioeconomic information such as fatalities, number of people displaced, and estimated dollar losses. However, users of our site have indicated that our simply compiling such events and assigning a catalog identification number, and providing a "region affected" vector polygon in GIS format, is itself valuable: no worldwide register of such events existed prior to development of the Dartmouth catalogs.

There is clearly much more than can be done. Comparisons of global flood event maps from one year to the next show changes in the geographic pattern of these rare, extreme events (Figure 7). They are a useful complement to, for example, analysis of tropical storm tracks, or to the monthly DMSP-derived precipitation anomalies (in the future, this may apply as well to more detailed

tropical rainfall results from NASA remote sensing). The site is expanding to include many other useful functions for flood remote sensing: an array of Internet-based "flood detection tools" that help to alert us and other users to new flood reports; a cloud cover assessment page which facilitates optical satellite-based flood observation by providing best-available real time weather satellite images; and a flood analysis page in which we are assembling the meteorological data that can be interpreted for first order flood causation inferences. All of this work positioned us to successfully compete for an EOS-IDS project start in 1997; this new project will help us to routinely map extreme flood inundation limits, and to use EOS sensors such as MODIS for flood detection in sparsely inhabited regions.

A short sampling of Internet WWW sites that presently contain links to the Dartmouth Flood Observatory follows. It includes national and international government, educational, and commercial institutions. Some of these sites also link directly to our image data:

#### Colleges and Universities: Teaching

<http://www.carleton.edu/curricular/GEOL/resource/remgis.webresc/using.remote.data.html>

Carleton College Remote Sensing/GIS Educational Resources

<http://www.emporia.edu/S/www/earthsci/student/garmon/flood.htm>  
Emporia State University Flood Hazards Bibliography

[http://www.wsu.edu:8080/~geology/geol101/rivers/rivers\\_links.html](http://www.wsu.edu:8080/~geology/geol101/rivers/rivers_links.html)  
University of Kentucky Geology 101 Curriculum

<http://earthsense.atmos.uah.edu/flood.html>  
Earthsense: Hydrology and Remote Sensing Education  
Project for the K-12 Earth Science Education Community

[http://www2.ncsu.edu/ncsu/pams/meas/courses/481/481\\_bookmarks.html](http://www2.ncsu.edu/ncsu/pams/meas/courses/481/481_bookmarks.html)  
North Carolina State University MEA 481 course curriculum

#### Colleges and Universities: Research

<http://tgl.geology.muohio.edu/gbook/gresources.html>  
Miami University, Web Resources for Geologists

<http://aleph.ac.upc.es/~carles/geografia/temas.html>  
University of Barcelona Flooding List

<http://www.dir.ucar.edu/esig/socasp/zine/5.html>  
A UCAR weather site

<http://www.geog.le.ac.uk/cti/flood.html>  
Subject Based Centre of the Higher Education Council of England, Scotland, and  
Wales

<http://maligne.civil.ualberta.ca/water/misc/floodlinks.html>  
University of Alberta School of Civil Engineering

<http://poe.ipac.caltech.edu:8080/hazards/>  
JPL Natural Hazards Research

<http://www.geo.cornell.edu/geology/eos/EOSBM.html>  
Cornell University Global Change Research Links

### Government Agencies

<http://www.ncr.usace.army.mil/navdata/flood.htm>  
Rock Island District, U.S. Army Corps of Engineers, Flood Information

<http://www.evansville.net/~amyers/flood.html>  
Evansville Community Web site with special page devoted to 1997 Ohio River  
Flood

<http://www.catt.rmit.edu.au/emergency/es-www/es-www-em.html>  
Australian Emergency Management Links

<http://www.state.me.us/mema/web.htm>  
State of Maine Emergency Management Agency

[http://water.dnr.state.sc.us/climate/sercc/us\\_servers.html](http://water.dnr.state.sc.us/climate/sercc/us_servers.html)  
Southeast Regional Climate Center

<http://ltpwww.gsfc.nasa.gov/ndrd/ndrd1.html>  
Natural Disaster Reference Database

[http://www.reliefweb.int/mapc/afr\\_horn/index.html](http://www.reliefweb.int/mapc/afr_horn/index.html)  
Relief site maintained by the UN Department of Humanitarian Affairs

### For Profit Companies

<http://www.dvtech.com/pages/pages/TecRisk.htm>  
Developmental Technologies Inc. Technology Page

<http://www.disastercenter.com/flood.htm>  
The Disaster Center

## Not For Profit Organizations

<http://www.amerrescue.org/floods.htm>  
American Rescue Team International

<http://hydrolab.arsusda.gov/~jritchie/>  
International Association of Hydrological Sciences

<http://www.utexas.edu/depts/grg/ustudent/frontiers/fall95/heath/heath.html>  
Association of American Geographers Water Resources Speciality Group

## Quick Response Inundation Mapping

We developed various image-map formats and processing methods aimed at practical utility for disaster relief, recovery, and mitigation efforts. Such maps also provide basic records of a flood long after the disaster, and can usefully be compared, in the U.S., to the FEMA-established 1% exceedance probability floodplains. As of this writing (January, 1998), some Dartmouth Flood Observatory's satellite image-maps of flooding are currently being used in an international relief effort in Somalia: see "Relief-web" location: [http://www.reliefweb.int/mapc/afr\\_horn/index.html](http://www.reliefweb.int/mapc/afr_horn/index.html). Our capabilities to generate such images are directly based on equipment and work initiated under the present project.

For visualization, image drapes over topography can be useful (Figure 8). For mapping, and easy import into GIS, geocoded maps with superimposed UTM or other graticules are needed (Figure 9). The first example shows the Napa River during the Great Central Valley Flood of 1995; the resolution is much reduced in this version but the coding of topography by color, when added to the three dimensional perspective view created by the drape, promotes visualization of the areas affected by flooding. In regard to both such drapes, and the planimetric maps, the color-encoded topography also symbolizes the presence of an otherwise hidden topographic data layer: production of detailed water surface profiles can proceed by extracting topographic values for those pixels along the water edge.

In the case of the Illinois Valley flood (e.g. Figure 9), an AIRSAR flyover was arranged, with the assistance of NASA HQ, and nearly matched that of an ERS-1 pass. We thus have matching orbital C and aerial multifrequency imaging SAR and interferometric topography (Figures 10a-c). The figures show only a sampling of these data and they also illustrate a challenge for practical applications. Namely, how may distribution of co-registered topography and remote sensing flood imaging proceed. If such could be manipulated by the end user, the utility would be improved, because this "snapshot" is just one of many

views and software operator can obtain as they, in effect, accomplish an overflight. Currently, inexpensive, PC or Mac-based off-the-shelf software allow flyover viewing of such co-registered data, and some www sites (such as at JPL for AIRSAR/TOPSAR) allow some www-based image manipulation before downloading. Note also in Figure 10c the ease of visibility of an artificial levee. SAR data are famous for their speckled, grainy appearance and the difficulties they pose non-specialist interpreters. However, draping SAR over topography appears to much improve ease of interpretation for such practical applications as levee damage assessment or flooded land boundary discrimination. A remaining problem with INSAR topography is noise (Figure 10c), but further processing with spatial filters can remove most such artifacts. We continue to work on this particular ERS/AIRSAR data set, because of the many areas of flooded forests; we hope to develop a combined L/C band classification approach for discrimination of flooded forested lands and combine this with water profile results. A paper is in preparation.

## **Appendix: Selected Illustrations From This Project's Research**

Figure 1. From "New Views of the Earth: Applications achievements of ERS-1" (*in* ESA SP-1176/11, 1996).

In 1993, the Midwest region of the United States experienced a wet autumn and an unusually heavy winter snowfall. In addition, in 1993, Wisconsin, Iowa and Illinois experienced the wettest June-July period since records began in 1885. Measurable rainfall fell within Iowa for 33 consecutive days and unusually heavy rains occurred in July, a month that is more commonly characterised by regional moisture deficits. As a result, major flooding events occurred along the Mississippi valley over a period of several months, causing major loss of life and extensive damage to property and utilities. Parts of the region were declared a disaster area and a presidential declaration of emergency operations were required.

Figure 1 illustrates the use of Synthetic Aperture Radar (SAR) data to map the course of flooding along the Illinois River Valley, where numerous river control structures are maintained. Twelve SAR scenes of the Mississippi basin were acquired between 7 July and 1 August 1993. These were combined with US Geological Survey 1:24 000 scale topographic maps at Dartmouth College to determine the level of flooding over the basin. A map depicting the levels of flooding was then delivered to the US Army Corps of Engineers to facilitate strategic decisions on rescue priorities and response measures. The figure illustrates a flood inundation map delivered to the US Army based on 12 SAR data acquired close to the peak level of flooding. The black and grey areas indicate flooded land.

*Courtesy of G.R. Brakenridge, Dartmouth College, Hanover, USA*

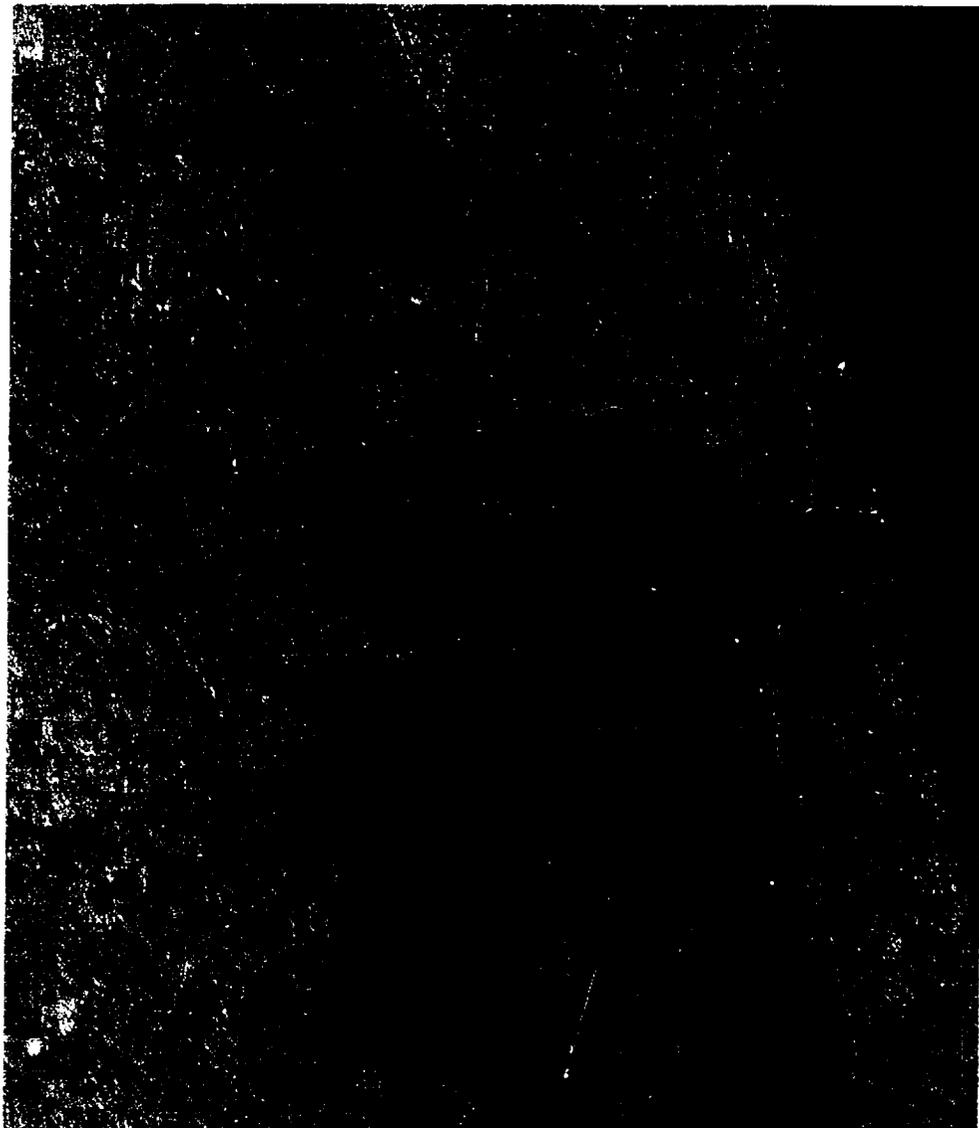
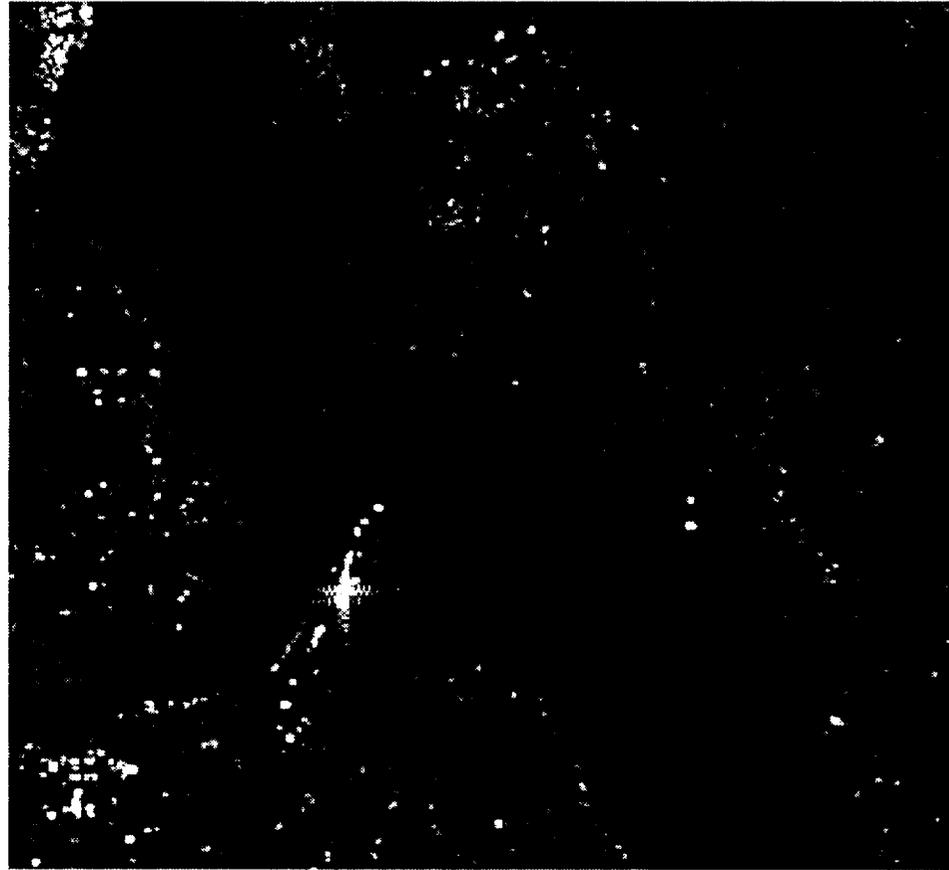


Figure 2. Crop from large color composite image map produced for Jordforsk of the 1995 Great Flood in Norway.



C-band synthetic aperture radar  
Composite of two images:  
April 30, 1995 and June 4, 1995  
From: ERS-1 satellite

Dartmouth Flood Observatory  
Department of Geography  
Dartmouth College  
Hanover, NH 03755 USA

2 km

Research supported by:  
NASA Mission to Planet Earth,  
Oceans, Solid Earth, and Natural Hazards,  
in cooperation with Jordforsk  
SAR image data © European Space Agency, 1995

Figure 3. Crop from large flood classification image map produced for Jordforsk of the 1995 Great Flood in Norway. Blue areas (black if this is a black and white illustration) show classified inundated lands on June 4.



C-band synthetic aperture radar  
Classification of two images:  
April 30, 1995 and June 4, 1995  
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in cooperation with Jordforsk  
SAR image data © European Space Agency, 1995

Figure 4. Stage measurements along the Pecatonica River 0950 local time, July 7, 1993.



Fig. 5. Flood profiles from step backwater-modeled and SAR-measured water surface elevations. A steady discharge of  $350 \text{ m}^3 \text{ sec}^{-1}$  (the instantaneous peak discharge at Darlington on July 6, 1993) was used in the step backwater (HEC-2) model. The flood wave is shown between measurement sites 11 and 16.

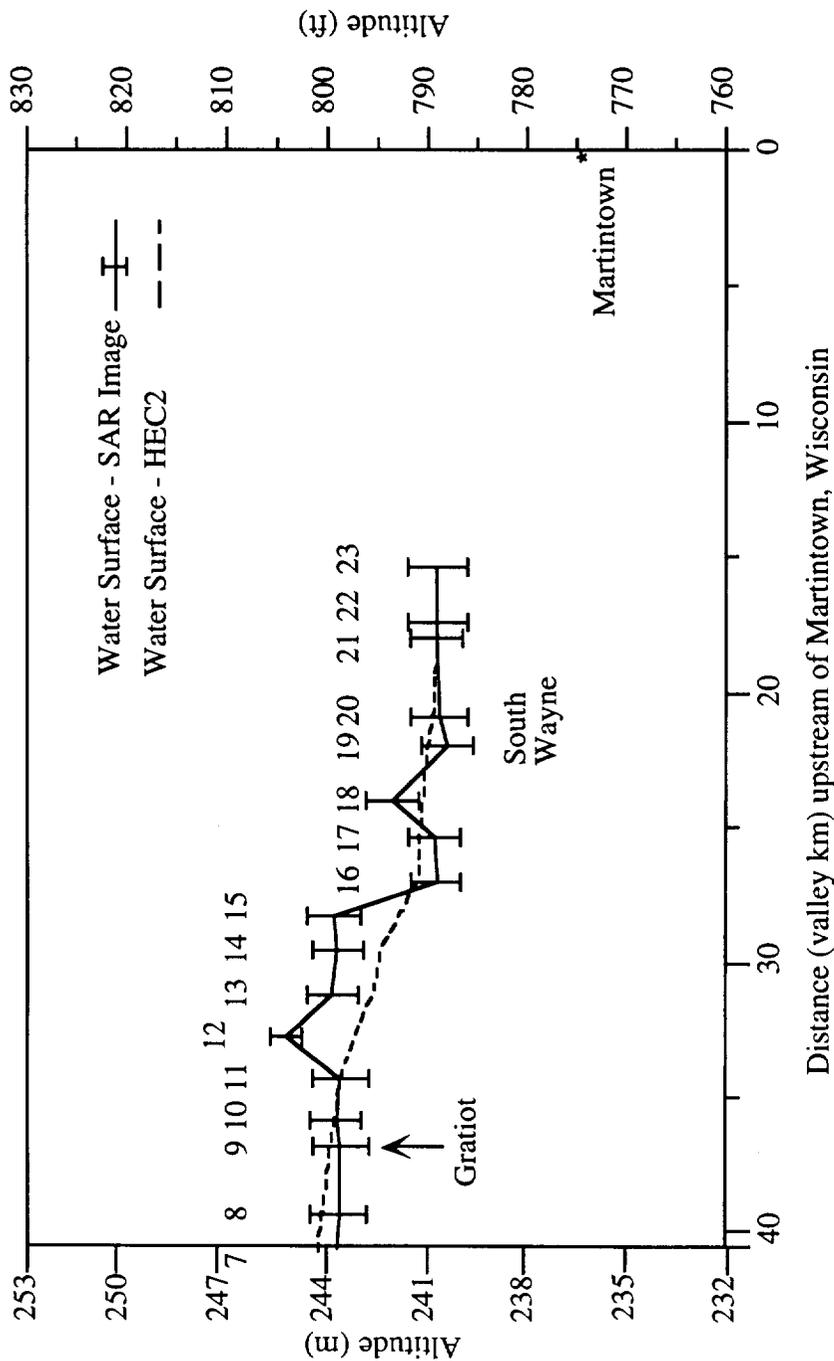


Figure 6. Abbreviated version of the 1997 Dartmouth Flood Observatory catalog. Using Netscape, table was downloaded from the Web site as text file and read into a widely available spreadsheet program. A MapInfo format version includes geographic coordinates and, in some cases, vector delineation of inundation boundaries.

Catalog Number	Region	Subregions	Date began	Date ended	Fatalities	Displaced	Hydroclimate
DFO-1997-96	Tanzania Congo and other nations	Central Tabora Tanzania Congo River at Kisangani	12/20/97	12/31/97	nd	20000	Tpz
DFO-1997-95	NW Albania	Lezhe	12/20/97	12/23/97	nd	nd	CpSe
DFO-1997-94	S Spain and Portugal	Badajoz Extremadura Andalusia Guadiana River Alenejo Algarve Ourique Pomerol	11/5/97	11/6/97	32	nd	TsuCs
DFO-1997-93	S Viet Nam-Linda	13 provinces and Thailand Ratchaburi Petchaburi Kanchanaburi	11/2/97	11/3/97	313	30000	
DFO-1997-92	Azores and S Portugal	Sao Miguel Ribeira Quente Madeira Lisbon Setubal Evora Portalegre	10/30/97	10/31/97	29	50	TsuCs
DFO-1997-91	S Mexico	Chiapas Yajalon Sabanilla Petalcingo	10/27/97	10/31/97	8	1200	Tpz
DFO-1997-90	S Somalia	Tiyeglow Jubba Bardera Shebele rivers NW Somalia NE Kenya Tana River Ethiopia	10/25/97	11/17/97	1830	230000	
DFO-1997-89	S Greece and W. Turkey	Patras Athens Istanbul Izmir Bursa	10/25/97	10/25/97	nd	nd	TsuCs
DFO-1997-88	S Brazil	Rio Grande do Sul Santa Catarina Parana Itaqu Uruguay River	10/15/97	10/22/97	nd	20000	Tpz
DFO-1997-87	N Columbia	Carmen de Bolivar Bolivar Province	10/14/97	10/16/97	2	15000	Tpz

DFO-1997-86	S Brazil	Uniao da Vitoria S Parana Iguacu River NE Argentina S Paraguay	10/05/97	10/15/97	nd	3600 Tsu
DFO-1997-85	SW Mexico- Pauline	S Oaxaca SW Guerrero Puerto Escondido Santiago Acapulco	10/8/97	10/9/97	400	nd Tso/Tpz
DFO-1997-84	S Spain	Alicante Almeria Valencia provinces	9/30/97	10/1/97	5	400 TsuCs
DFO-1997-83	C Viet Nam- Fritz	Danang Quang Ngai Quang Nam provinces Huong River Hue City	9/25/97	9/28/97	10	nd Tpz
DFO-1997-82	Morocco	El Hajeb Taza Khenifra Marrakesh Meknes Imouzzar- Handar Rommani Atlas Mountains	9/28/97	9/29/97	nd	nd TsuCs
DFO-1997-81	W Mexico-Olaf	Oaxaca Chiapas	9/28/97	9/29/97	12	nd Tso
DFO-1997-80	W Mexico and SW U.S.-Nora	Baja California Tijuana to Mexicali Yuma	9/25/97	9/27/97	nd	240 Tso
DFO-1997-79	Sri Lanka	Landslides in Dehiowita Avisawela Yatiantota Kelani river	9/14/97	9/17/97	nd	5000 Tpz
DFO-1997-78	NE Thailand	Four northeastern provinces	9/10/97	9/17/97	14	hundreds Tszo of thousands
DFO-1997-77	E Afghanistan	Mehtar Lam	9/7/97	9/8/97	30	600 Cs*
DFO-1997-76	Pakistan	Punjab Lahore Rawalpindi Jhelum Chenab Sutlej	8/24/97	8/28/97	140	21000
DFO-1997-75	S China-Zita	Guangdong Guangxi	8/24/97	8/25/97	nd	54000 TsuCpSs*
DFO-1997-74	Morocco	Taroudant Hoceima Benslimane Settat	8/24/97	8/26/97	15	nd TsuCs

DFO-1997-73	S Thailand	10 southern provinces Chumphon Ranong Surat Thani Trang	8/22/97	8/28/97	42	200000 Tpz (?)
DFO-1997-72	Chile	northern portions	8/15/97	8/19/97	10	nd Tsu
DFO-1997-71	Hong Kong-Zita	nd	8/22/97	8/23/97	nd	nd Tszo
DFO-1997-70	Burma	Pegu Division Mon State Salween Sittaung Jaing Irawaddy Chindwin rivers	8/10/97	8/20/97	100	thousands Tszo
DFO-1997-69	N and W Sudan	Berber Province	8/18/97	8/20/97	nd	5200 Tpu
DFO-1997-68	SE China-Winnie	Jinhua City Wenling Anhui Province	8/18/97	8/20/97	56	708000 TsuCpSs*
DFO-1997-67	Philippines-Winnie	Manila Pampanga Province	8/15/97	8/19/97	16	60000 Tpz
DFO-1997-66	N India	Himalayas Himachi Radesh Chiragon Sutlej at Wangtu Andhara	8/12/97	8/13/97	110	nd Tszo
DFO-1997-65	N Taiwan-Winnie	NE Taiwan Taipei	8/18/97	8/18/97	31	nd Tszo
DFO-1997-64	India	nd	8/10/97	8/12/97	110	nd Tszo
DFO-1997-63	N Arizona	Antelope Canyon Havasupai Indian Reservation	8/10/97	8/12/97	10	350 Tsu
DFO-1997-62	Hong Kong	Tai Po	8/13/97	8/15/97	nd	4000 Tszo
DFO-1997-61	NE India	Bihar West Bengal Rajasthan	8/1/97	8/9/97	24	nd Tszo
DFO-1997-60	S China-Victor	Guangdong Hong Kong	8/2/97	8/7/97	65	nd Tszo
DFO-1997-59	N Colorado	Ft Collins Spring Creek	7/29/97	7/30/97	5	nd CpSe*
DFO-1997-58	Bangladesh	Chittagong and Cox's Bazar	8/1/97	8/4/97	4	tens of Tszo thousands
DFO-1997-57	Romania	foothills south of Carpathian Mountains Caras Severin Prahova Dimbovita counties	7/25/97	8/5/97	6	8000 CpSe*

DFO-1997-54	E. Germany	Oderbruch basin east of Berlin Frankfurt an der Oder in the Ziltendorf basin Oder River	7/15/97	8/9/97	nd	5000
DFO-1997-53	Bangladesh	nd	7/11/97	7/12/97	100	thousands Tszo
DFO-1997-48	Poland	Klodzko Opole Raciborz Wroclaw Slubice Oder River	7/15/97	8/9/97	54	162500 CpSe*
DFO-1997-47	E. Czech Republic	nd	7/6/97	7/24/97	48	40000 CpSe*
DFO-1997-45	N Sweden	Pitea	7/27/97	7/29/97	0	20 CSs**
DFO-1997-44	S. China	Jiangxi Zhejiang SW Guizhou Guangdong Guangxi	7/6/97	8/1/97	284	200000 Tszo
DFO-1997-31	E Nepal	Ilam	6/10/97	6/11/97	20	nd CSs**
DFO-1997-28	Somalia	Hawardre district 230 mi north of Mogadishu and Jowhar north of Mogadishu	5/2/97	5/7/97	0	1740 Tpz
DFO-1997-25	Bangladesh	nd	6/14/97	6/20/97	nd	nd Tszo
DFO-1997-18	Southern Tanzania	Linde Kilwa Kivinje Njia	4/1/97	4/15/97	60	thousands Tsz
DFO-1997-17	Upper Midwest	ND MN Manitoba Red Knife Boise De Sioux Sheyenne	3/22/97	4/25/97	nd	10000 TsuCpSe**
DFO-1997-16	Northeast Australia- Justin	Bruce Highway south of Cairns Justin Townsville Cooktown	3/22/97	3/24/97	2	nd Tszo
DFO-1997-15	Western Washington USA	Aberdeen Satsop Wynochee Satsop rivers	3/17/97	3/20/97	0	600 Cp
DFO-1997-14	Western Brazil	Acre Rio Branco (town) Rio Acre	1/15/97	3/15/97	8	thousands Tpz
DFO-1997-13	Ohio and Illinois Valleys	Salt Licking Green Kentucky Brush Creek	2/28/97	3/15/97	50	nd TsuCpSe*
DFO-1997-12	Malawi- Mozambique	Nsanje Chikwawa Makhanga Shire Ruo Zambezi Pungue Buzi	1/15/97	2/26/97	35	80000 Tso
DFO-1997-11	Palestine	Wadi Kaneh	2/21/97	2/23/97	14	0 TsuCs

DFO-1997-10	Northern Illinois	Chicago and south and west suburbs Hillsdale Erie Rock and Illinois rivers	2/21/97	2/25/97	0	700 TsuCpSe*
DFO-1997-09	Northeast Peru	Andes Tamburco District	2/17/97	2/17/97	40	nd Tpu
DFO-1997-08	Bolivia	8 of its 9 departments	2/1/97	2/15/97	40	tens of Tpu thousands
DFO-1997-07	Madagascar-Gretelle	Farafangana Vohipeno Vondrozo Vangaindrano Befotaka	1/20/97	1/26/97	140	tens of T thousands
DFO-1997-06	S Bangladesh	Midongy Sud Barisal Bholu Patuakhali Chittagong Ranagamati	3/19/97	3/24/97	25	5000 Tszo
DFO-1997-02	Northern California	ID NV OR WA Russian	1/1/97	2/1/97	20	hundreds Cp

Figure 7. Global map of the 1997 floods shown in Figure 6. Comparisons of such maps from one year to the next show changes in the geographic pattern of rare, extreme flood events. Preliminary analysis indicates many correlations to DMSP-derived global precipitation anomalies computed on a monthly basis: most monthly anomalies are associated with reported river flooding. A full resolution version is available to the public by FTP.

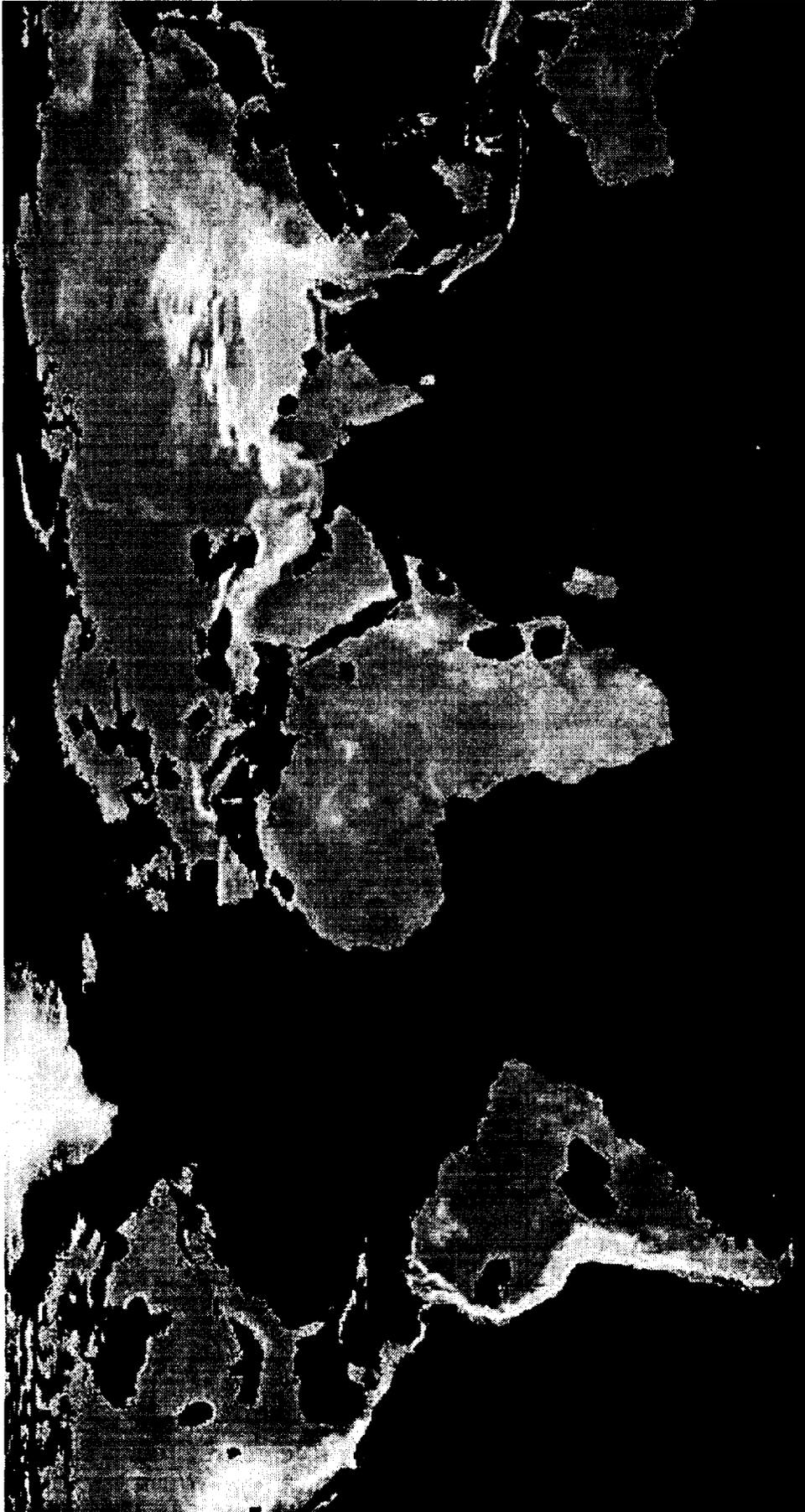


Figure 8. Looking upstream along the Napa River during the extreme flood of 1995 in northern California. An ERS-1 SAR image has been merged with USGS dlg vector cartographic data and with digital topography. An IHS transformation (described in an earlier renewal proposal) maintains the dark tone of floodwater typical in SAR images, but allows topography to be expressed by hue (see also Figure 8). This is a (much) reduced resolution image.

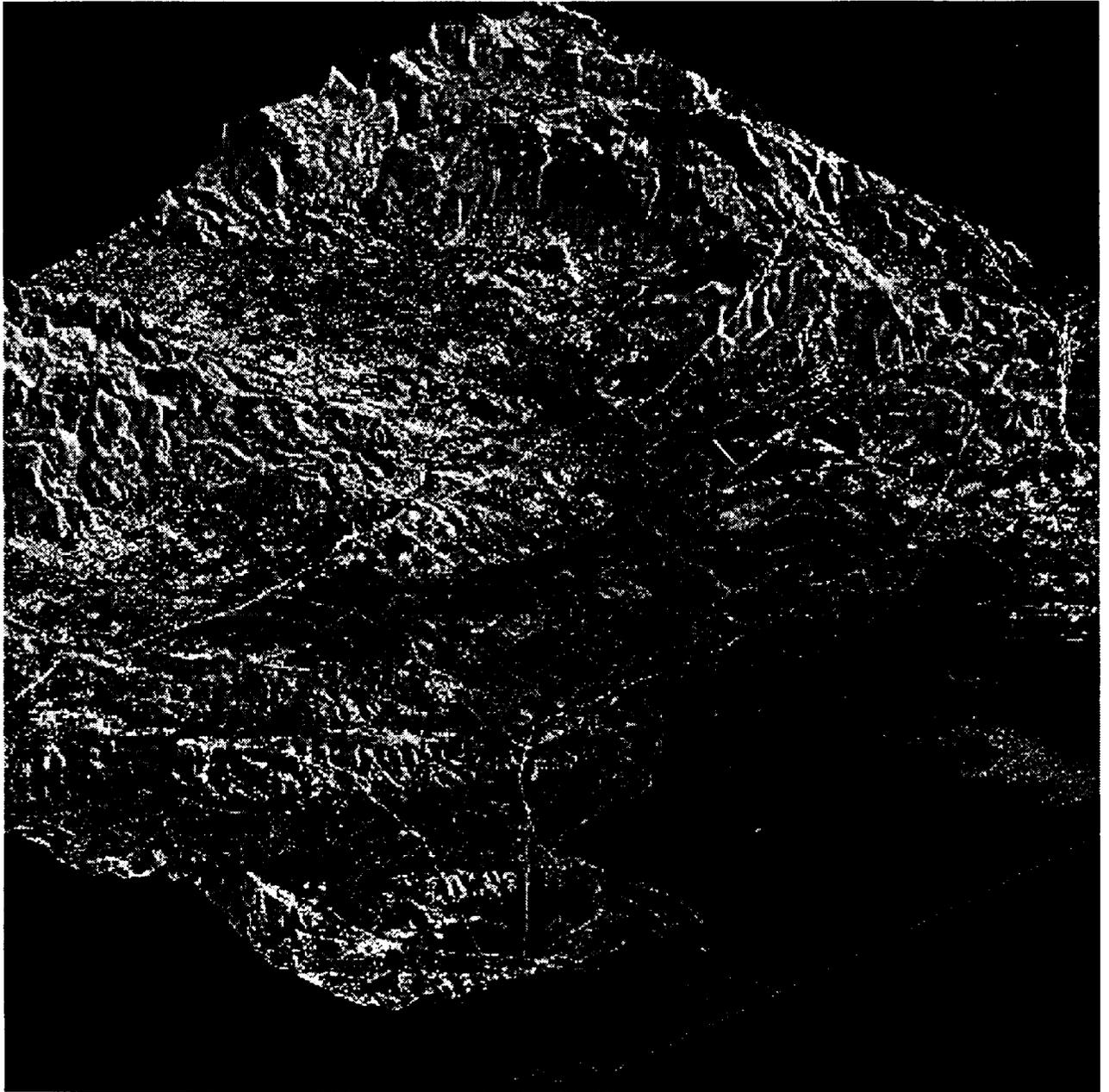




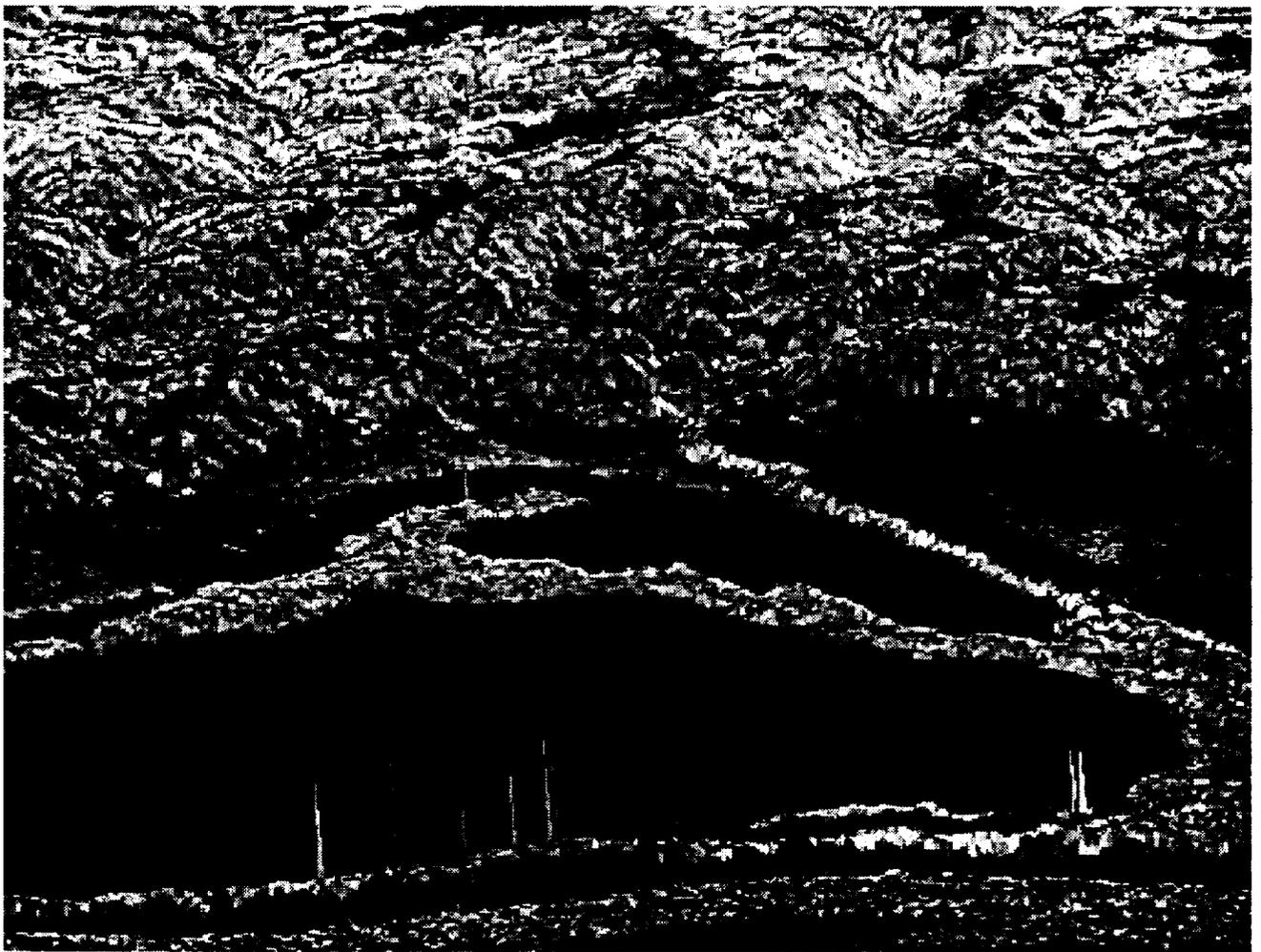
Figure 10a. Subscene of AIRSAR C-band image of flooding along the Illinois River Valley.



Figure 10b. A portion of the AIRSAR/TOPSAR interferometric topography results for the Illinois Valley. Note artificial levee along floodplain in back 1/3 of view.



Figure 10c. Subscene of the combined AIRSAR/TOPSAR data for the Illinois Valley flood. Here the C-band SAR is draped over the topographic data produced by interferometry. Again note artificial levee along floodplain, this time in center of view.



## COPIES OF SEVERAL ABSTRACTS AND PUBLICATIONS

*Paper prepared for 1996 Aspen Global Change Institute Meeting on "Natural Hazards and Global Change"*

### Orbital Remote Sensing For Reducing The Impact Of Flood Disasters

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There has been a recent and dramatic expansion in the availability of satellite data applicable to the remote sensing of extreme flood events. Prior to 1991, Landsat and SPOT were the main alternatives, and both are optical sensors with data price structures that make repeat imaging prohibitively expensive. Flood remote sensing was essentially not possible: data costs were too high, data acquisition opportunities too limited, and cloud cover commonly posed too great a constraint.

Since then, two European synthetic aperture radar (SAR) satellites have been successfully launched (ERS-1, ERS-2), as well as: a similar Japanese SAR satellite (JERS-1); a Canadian/American SAR satellite (Radarsat); and an extensive array of optical sensors with varying levels of data resolution and prices (the Indian remote sensing satellites, the Russian Resurs satellite, the high resolution PRIRODA-hosted sensors on Space Station MIR). All of these observe the Earth's surface and thus river floods; the SAR satellites do so even through heavy cloud cover and at night. This fleet of Earth observation tools will continue to expand over the next several years as (for the U.S.) EOS-AM (including MODIS), Landsat 7, and several commercial high resolution sensors are launched. There are also in the works many new European, Indian, Japanese, and other foreign satellites.

Of all natural disasters, large floods are perhaps those most easily detected and measured from orbit. Although most rivers remain difficult remote sensing targets because of their relatively small spatial extents, many expand to flow widths measured in km once major floods are underway. Extreme flood durations range from days to weeks: with the present constellation of satellite sensors, it is now possible to track the course of such events at intervals through their waxing and waning stages. For SAR remote sensing, the removal of cloud cover as a constraint not only allows early observation (while it is still raining), but more frequent and more certain repeats, which is critical for the successful incorporation of such technology into operational flood warnings. Extreme floods, like volcanic eruptions, are difficult to measure by in-situ apparatus; even low altitude aircraft or helicopter flyovers, under cloud cover, are hindered by nightfall. In contrast, orbital SAR remote sensing offers a safe, predictable, efficient and highly effective means to track the progress of large floods.

Satellite remote sensing is not a panacea. Not all floods can be successfully monitored by satellite: many of the most lethal floods are confined within relatively narrow valleys and are difficult to image, and it is these events which attain the highest flow velocities and shear stresses. Similarly, flash floods are almost immediately preceded by intense precipitation events which are themselves hard to predict. What is needed in order to reduce casualties within the U.S. from such events are upgraded computer watershed models into which Doppler radar-based precipitation estimates can

more quickly be assimilated. Thus, better application of already available technology and techniques, and better topographic data, can clearly improve flash flood warnings, and this path forward is already being pursued. In contrast, floods that are sustained over a day or more, and which occupy relatively large areas, can be directly imaged as they develop and much use can be made of such observations. Here the spatially extensive nature of satellite data is valuable; and remote sensing combined with GIS techniques can answer questions such as: a) What reaches in the region are being affected by flooding? b) Where are levees over-topped or breached? c) What structures, transportation links, and utilities are presently under water? d) What are typical flow depths, and calculated velocities and shear stresses being experienced on the floodplain? e) Where are these variables the highest and thus most hazardous? f) How much total land area is inundated? Finally, g) Which floodplain parcels have been protected from flooding by levees or other measures?

Routine monitoring of large flood disasters on a global basis is also in the national interest of the U.S., and perhaps any nation that is deeply involved in international relations and trade. For example, the Great Flood of 1995 in North Korea has caused on-going humanitarian and political crises, because many nations, including the U.S., Japan, and South Korea, have offered food aid but are unsure where exactly the affected areas lie or how severe crop losses actually were. In democracies too, floods can become the source of political instability: for example, perceived inadequate governmental response to floods fueled mass protests and turbulent electoral politics within Bangladesh in 1995. Finally, extreme floods in other nations affect global food supplies and thus within-U.S. agriculture economics and prosperity. Beginning in 1998, operation of NASA's EOS-based MODIS sensor will provide 500 m resolution global optical coverage at very frequent repeat intervals: this is a potential global flood detection tool. Other sensors may prove to be appropriate for this task as well. At present, internationally-shared satellite meteorological data enable major reductions of risk to life and property from tropical storms world-wide. In the near future, it would be technically feasible and in the national interest to support production of and similar sharing of river flood detection information.

# Orbital SAR Remote Sensing Of A River Flood Wave

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**Abstract** During the Great Flood of summer 1993 in the Upper Mississippi Valley, the European Remote Sensing Satellite (ERS-1) imaged overbank flooding with a ground resolution of ca. 25 m. When combined with topographic information, these data permit measurement of instantaneous longitudinal profiles of individual flooded valleys. Along a major tributary to the Mississippi in southwestern Wisconsin, a measured in-transit flood wave exhibits an amplitude of 1.5-2.0 m, and can be differentiated from a constant discharge, step backwater-modeled water surface for a distance of 5 km along the valley.

## 1. Introduction

The C-band, 5.6 cm wavelength synthetic aperture radar (SAR) aboard ERS-1 produced ground range (cross-track) spatial resolution of 26 m, along-track resolution of 6-26 m, and processed image pixel dimensions of 12.5 m (Canadian Center for Remote Sensing 1992). SAR backscatter return at this wavelength and incidence angle (23 °) is high from moist soils, whereas smooth water surfaces provide weak returns. As a result, water-land boundaries can be easily discriminated in agricultural regions. We report here an ERS-1 measurement of a flood wave along the Pecatonica River during the Great Upper Mississippi Valley flood of 1993. Many other ERS image data now in archive similarly record the passage of extreme flood events at many geographic locations.

During rare high magnitude events, gaging stations commonly fail to provide records of maximum stage because their design limits are exceeded. Peak discharges of large floods can still be reconstructed from post-flood analysis of high water marks (O'Connor and Webb 1988), but there are major uncertainties. For example, traces of large floods along a valley do not apply to a single moment in time, because peak stages are attained earlier at one position than at another (Magilligan 1988). Despite this problem, calculation of discharge from the array of such traces assumes time-synchronicity.

An earlier report describes the potential of ERS-1 data for measuring flood stages (Brakenridge *et al* 1994). Flood stages at many positions along river valleys can be determined to an accuracy of approximately 1-2 m if adequate topographic data are available, and a single image can provide a time-instantaneous portrait of flood stage along as much as 100 km of valley reach. ERS-1 SAR is used here to measure the water surface of the Pecatonica River during its 1993 peak flow. The flood wave itself appears to be visible in these measurements, and we test this inference by HEC-2 (Hydrologic Engineering Center 1982) step-backwater modeling of this flow.

## 2. The 1993 Pecatonica River Flood

The Pecatonica River and its tributaries (Figure 1) dissect nearly flat-lying Paleozoic limestone, dolomite, and sandstone formations. Thick accumulations of colluvium commonly occur along the basal positions of hillslopes, and the present river flows on relatively deep valley fills of sand and gravel. The river's opposing valley

margins are locally symmetrical and form steep bluffs 15-30 m high; large floods along these reaches may fill the entrenched valley from rim to rim. However, at other locations along valley bends, a steep bluff marks the outer portion of the bends and gentle "slip-off slopes" occur along the insides (e.g. see measurement site 15 in Figure 2). Small changes in flood stage cause relatively large changes in the water/land boundary at such positions and wherever the overbank flood reaches gently sloping terrain.

An exceptionally wet spring and summer occurred in this region in 1993: from April 1 to July 25, rainfall totals reached to 300 mm-750 mm, and this is close to the normal annual rainfall. Moderate to severe river flooding occurred along the Pecatonica River from mid-June to mid-July, and particularly in response to heavy rainfall on June 17-18, 29-30, and on July 5-6 (Figure 1). One ERS-1 SAR georeferenced fine resolution image is used in the present analysis and the SAR data were acquired at 0950 local time on the morning of July 7 (Figure 2). According to gage records, the time of acquisition was 27 hours after peak discharge at Darlington and 35 hours before the crest reached Martintown (Figure 3). The measured valley length between Darlington and Martintown is 57 km, and the observed velocity of the flood wave is .25 m/sec (57 km/62 hrs). If wave velocity (celerity) remained constant, then the flood crest at the time of image acquisition should have been 24.8 km downstream of Darlington.

The peak instantaneous discharge at Darlington was  $350 \text{ m}^3 \text{ sec}^{-1}$  and it was  $270 \text{ m}^3 \text{ sec}^{-1}$  at Martintown: there was significant downstream attenuation of the flood peak discharge. The instantaneous peak flow at Darlington was  $\sim 100 \text{ m}^3 \text{ sec}^{-1}$  higher than the mean daily flow on that day, whereas at Martintown the two statistics are similar. Thus, a brief, high amplitude flood wave passed the Darlington gaging station but Martintown experienced the flood as a more sustained but lower magnitude event.

### 3. SAR Image-based Water Profile Measurements

Flood stage measurements from ERS-1 images require accurate topographic data. United States Geological Survey 1:24,000 scale maps were used with contour intervals of 10 ft ( $\sim 3$  m); contours at 5 ft intervals are drawn locally in some low-relief bottomlands. Suitable local floodplain morphologies are also required for accurate stage determinations: only where the floodwater edge intersects gently sloping land can the map position of the water edge be accurately determined.

Four independent sources of error are important in measuring SAR-imaged water surface elevations from water edges located on topographic maps.  $s_1$  is map topographic error: we assume the published map accuracy standards, where 90% of the altitudes of point locations lie within 1/2 contour interval of the map value.  $s_2$  is operator positioning error and includes observational errors in locating water edge positions on the 1:24,000 maps. Repeat measurements ( $n=26$ ) of positioning discrepancies result in a calculated 90% confidence interval of 24 m in locating the measurement sites. In order to incorporate the positioning error into a total confidence interval, the local land surface slope is determined, and the maximum change in altitude corresponding to the position offset is calculated.  $s_3$  incorporates the altitudinal error implicit in map positional accuracy. For 1:24,000 scale maps, 90% of points lie within 12 m of their true locations, and we convert this interval to an altitudinal interval using local slope.  $s_4$  expresses the sensor-limited relative geometric image accuracy, in terrain with gentle slopes, of 40 m, and as per ERS-1 nominal operating specifications (European Space Agency 1993). This spatial error is also transformed to an altitudinal error. The square root of the summed 90% confidence intervals for measured flood stages along the Pecatonica River range between 1-3 m (Figure 2), with the smallest intervals occurring on the gentlest slopes.

Other potential error sources include topography-induced SAR image distortions and mistakes in SAR discrimination of water edges.

#### **4. Comparison to a Modeled Constant Discharge Profile**

Discharge can be estimated at a single valley cross section using the Manning equation and observed or estimated values for roughness, hydraulic radius, and slope. However, a more accurate method for steady, gradually varied flow is the step-backwater method, as accomplished by HEC-2 computer models (O'Connor, and Webb 1988; Hydrologic Engineering Center 1982; Hoggan 1989). HEC-2 computes a best fit solution for hydraulic variables based on input variables of slope, discharge, hydraulic roughness, and valley and channel morphology. In the present case, we use HEC-2 to model the profile of a constant peak discharge and thereby evaluate the influence of valley morphology and slope on local flood stage. The influence of these variables must first be calculated before unusually high stage along a local reach can be attributed to the flood wave.

Accuracy of a computed HEC-2 profile is influenced by the quantity, location, and accuracy of measured cross-sections. Cross-sections may be placed up to 1.6 km (1 mi) apart for large low-gradient rivers (Dingman 1984), but it is desirable to have more sections as well as accurate channel morphometric data. However, the objective here is restricted to consideration of whether large changes in valley floor morphology might cause locally elevated river stages and thus mimic the flood wave. We use twenty-five valley cross-sections with an average distance of 1.5 km between sections in modeling steady discharge. The flood cross sections are drawn from the 1:24,000 topographic maps. Bankfull channel widths vary from 25-36 m, and corresponding depths of 1.2-1.5 m are estimated from hydraulic geometry plots (Dunne and Leopold 1978). To assess the influence of the poorly known channel geometry on HEC-2 results, we also calculate profiles using a constant channel depth of 1.5 m. Such small depth changes do not greatly affect the flood flow model (D calculated stages  $\pm$  0.7 m). Although we cannot rule out more significant flood stage effects if large amounts of local channel filling or scouring occurred, no such adjustments were observed during field traverses after the flood. Finally: a) the instantaneous peak discharge at Darlington ( $350 \text{ m}^3 \text{ sec}^{-1}$ ) is used as the input discharge for the initial downstream cross section, b) Manning's n coefficients (Chow 1959) of 0.035 and 0.04 are used for channel and overbank roughnesses, respectively, and c) sub-critical flow is assumed and the modeling thereby proceeds in the upstream direction.

Figure 4 illustrates the SAR-measured water surface and the HEC-2 modeled, constant discharge surface. In this context, the HEC-2 analysis provides a measure of valley and channel geometry effects on flood stage. Because the HEC-2 profile incorporates such adjustments, departures in the SAR-observed profile from the steady discharge profile may reflect stage effects of the non-steady discharge. The water surface elevations for the first three sections upstream of the HEC-2 starting point (sections 20-23) exhibit agreement between the calculated and measured profiles. This is expected because the SAR measurement is provided to the model as the first starting water level (an estimated starting level is required). As more cross-sections are incorporated by the model, the HEC-2 surfaces increase in accuracy and are less constrained by the starting level (Hoggan 1989). The elevations of the water surface recorded by the SAR image at sections 12-15 (Figure 4) are 1.5 -2.0 m higher than the HEC-2 estimated water surface elevations. This reach of elevated stage extends along a valley reach of 5 km, and the anomaly is noteworthy because its position corresponds to the calculated position of the flood crest based on the times of passage at the gaging stations and linear interpolation. Thus, section 12 is 22.6 valley km downstream of Darlington whereas section 15 is 27.4

valley km downstream, and the high water observed at and between these sections brackets the calculated position (24.8 km) of the flood wave crest. We thus conclude that the flood wave is observed. The wave exhibits an amplitude of 1.5-2.0 m, and can be differentiated from a constant discharge, step backwater-modeled water surface for a distance of 5 km along the valley.

## 5. Conclusion

We have compared the profile of an actual flood event to a predicted constant high discharge water surface. Other local factors not included in the model can influence the water profile. For example, a raised railroad bed crosses the valley at two places within the reach of elevated flood stage, and such obstructions can cause locally higher stages even if discharge remains constant along the reach. However, cross section 15 is located downstream of both railroad crossings, and the SAR image there still records an anomalous high water surface at the moment of image capture (Figure 4). The general flood wave is apparently observed, as we lack reasonable alternative causes for elevated stage throughout this reach. We conclude that instantaneous profiles of flood waves can be obtained using presently available orbital remote sensing and topographic data. Also, because of the large archive of other ERS image data, this approach could be used to measure peak discharges and verify hydraulic modeling along many other rivers.

## Acknowledgments

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Figure Captions (Figures not included here)

Fig. 1. Topography of the studied reach in the Pecatonica River valley, showing also 2-day rainfall amounts, July 5-6, 1993 (National Climate Data Center, 1993). Rainfall data (in mm) were collected for the following Wisconsin towns: Dodgeville (Dv), Platteville (P), Cuba City (C), Darlington (D), Blanchardville (B), and Monroe (M). Letters G and S mark the locations of the towns of Gratiot and South Wayne.

Upstream drainage area at Darlington is 707 km<sup>2</sup>, at Martintown (57 km downstream) is 2678 km<sup>2</sup>, and the tributary contributing area at Blanchardville is 572 km<sup>2</sup>.

Fig. 2. A portion of the ERS-1 SAR georeferenced fine resolution image (orbit number 10334, track 169, frame number 2745) including the studied reach of the flooded Pecatonica River valley, 0950 local time, July 7, 1993.

Fig. 3. Hydrographs of Pecatonica River at Darlington and Martintown, Wisconsin, June 14 - August 14, 1993. The time of gaging station-measured instantaneous peak discharge was 0645 on July 6 and 2045 on July 8 respectively

Fig. 4. Flood profiles from step backwater-modeled and SAR-measured water surface elevations. A steady discharge of 350 m<sup>3</sup> sec<sup>-1</sup> (the instantaneous peak discharge at Darlington on July 6, 1993) was used in the step backwater (HEC-2) model.

**Lecture presented at the 1994 Association of American Geographers  
Annual Meeting**

G. Robert Brakenridge, Department of Geography, Dartmouth College  
Hanover, NH 03755. Synthetic Aperture Radar Remote Sensing of the 1993 Mississippi  
Valley Flood.

Although satellite images obtained on clear days can occasionally show the regional extent of large floods, most trunk stream flooding is accompanied by heavy cloud cover. The weather systems responsible for heavy precipitation are routinely tracked, but we have been unable, up to now, to directly observe the major surface process response to such precipitation: channeled and unchanneled runoff.

This is no longer the case. Successful operation of space-borne, non-military, high resolution, synthetic aperture radar (SAR) is providing an unanticipated but exceptionally valuable observational tool for studying floods. Radar sensors are not hindered by cloud cover, and the 1993 Mississippi Basin floods were repeatedly imaged by the three year-old European Remote Sensing Satellite (ERS-1). This polar-orbiting, three-day repeat cycle satellite includes a C-band SAR producing image pixel dimensions of approximately 12 m. The SAR data are retrieved by ground stations only for the geographic areas covered by each station's mask; they are not obtained at all unless scheduled in advance. However, appropriate ERS-1 scene acquisitions during the waxing of the flood in July were scheduled for unrelated reasons. These data are exceptionally valuable: when combined with topography, they provide the first spatially extensive time-series documentation of rising river flood profiles and surface runoff as observed from space. I thank NASA's Mission to Planet Earth (Geology Program), the Alaskan SAR Facility, and the National Geographic Society for support. Keywords: geomorphology, remote sensing, hazards

**Lecture presented at the 25th Binghamton Geomorphology Symposium, 1994**

**ERS-1 Remote Sensing Of Flood Water Surface  
Profiles**

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Remote sensing of river flood events has long been constrained by: 1) cloud cover and 2) low spatial resolution. Synthetic aperture radar (SAR) techniques remove the first constraint, but early civilian satellites were of low spatial resolution. Both constraints were removed with the launch of ERS-1 in 1991. This polar orbiter includes a C-band (5.6 cm wavelength, 23 degree incidence angle) SAR that produces ground range resolution of ~30 m, and azimuth resolution of 6-30 m. High resolution, non-military satellite SAR makes possible new approaches toward understanding the dynamics of extreme flood events. Thus, ERS-1 acquired SAR images of the Upper Mississippi Valley throughout the Great Flood of 1993. Where floodwater laps over gently sloping valley margins, 90% confidence intervals for stage measurements as low as 1.6 Ft obtain. We thereby measure spatial variations in flood stages occurring at particular instants of time over relatively long valley reaches. Along an 80 km reach of the Mississippi south of Keokuk, Iowa on July 16, 1993, the flood water energy profiles demonstrate that the valley's west side experienced overbank stages as much as 8 Ft (2.4 m) higher than analogous locations on the 11 km-distant east side. Des Moines River flood discharge entering on the western side is the probable cause of the west-east gradient: Des Moines overbank water was diverted down the western side of the Mississippi Valley and raised flood stages across this large expanse of floodplain. Also, a SAR-based flood energy profile for the Pecatonica River obtained for the morning of July 7, at which time a record-setting flood wave was in transit, reflects: 1) localized upstream backwater effects created by constricted portions of the valley, and 2) general downstream attenuation by floodplain storage.

*A contribution regarding the Mississippi Valley flood was also prepared for inclusion in the "Space borne Synthetic Aperture Radar: Current Status and Future Directions" National Research Council report.*

## Synthetic Aperture Remote Sensing Applications To Flood Disasters

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Three synthetic aperture radar satellites are now operating which can image changing water/land boundaries at high spatial resolution and through heavy cloud cover or at night: ERS-2 (European Space Agency); JERS-1 (Japan); and Radarsat (Canadian, with a significant NASA contribution). An American SAR satellite (LITESAR) is being planned. Possible data delivery pathways to disaster relief agencies are complex and vary for each satellite. Costs vary widely depending on the pathway used. For example: 1) For ERS-2 and Radarsat, licensed commercial vendors can perform most data order and delivery functions, but at a steep cost (some thousands of dollars per 100 x 100 km scene); 2) Applicable international memorandums of understanding allow ERS-2 data delivery directly to U.S. agencies such as NASA in the case of natural disasters; 3) In the case of Radarsat, approximately 15% of the data stream is U.S. owned and available for use by federal agencies. However, there are various restrictions, and there is no Radarsat planning set-aside for additional data acquisitions in the wake of U.S. natural disasters.

Following several recent U.S. flood disasters, commercial value-added remote sensing vendors have capitalized on the government's need for accurate inundation mapping with outdated or inappropriate, though still expensive, approaches. Some companies have been eager to sell slightly repackaged, but otherwise freely available government data back to the government. Post-flood federal contracts have also been let requesting that data from inappropriate sensors be used (e.g. Landsat partially cloud-covered scenes showing floodplain conditions days or weeks after flood peak, when ERS data for the actual time of flood crest are available at much lower cost). Federal disaster relief officials often lack needed knowledge concerning sensor options and capabilities. Regarding SAR satellites, in brief: 1) Automated image classification procedures developed for multispectral optical images cannot be used to identify flooded areas on most SAR images: flooded forested property appears much the same as unflooded forest when imaged by C-band SAR. 2) However, once geocoded, and merged with widely available U.S. topographic and GIS ("DLG") data, SAR images of flooded valleys provide a readily "photointerpretable" map of the extent of flooding. 3) On such image maps, and when forest cover is low or absent, the geographic position of the floodwater edge can be drawn with an accuracy of <30 m (comparable to position accuracy on the best U.S.G.S. topographic maps). 4) Where patchy forest cover exists, flood limits can commonly still be accurately drawn by interpolation and with the aid of topography. Once flood limits are determined, they can be exported to ARC/INFO or other common vector GIS formats, or used together with the topographic data to determine and map floodwater depths.

Prototype samples of SAR and digital topography-based flood image maps can be found at the Dartmouth Flood Observatory Internet site: <http://www.dartmouth.edu/artsci/geog/floods/>. We are presently also working with a National Weather Service office in Albany, New York, to demonstrate the utility of SAR for real time flood imaging using Radarsat.

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# THE DARTMOUTH FLOOD OBSERVATORY: AN ELECTRONIC RESEARCH TOOL AND ARCHIVE FOR INVESTIGATIONS OF EXTREME FLOOD EVENTS

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*Abstract* — Extreme floods occur only rarely in any particular location, but when the Earth as a whole is considered, such events are frequent: almost two per week. From the beginning of 1996 up to September of that year, over eighty extreme floods had occurred. Cloud cover previously made satellite observation of floods difficult or impossible, but, following launch in 1991 of ERS-1 by the European Space Agency, good quality data are available from a new generation of high resolution synthetic aperture radar satellites. These satellites can map peak and near-peak flood conditions along river valleys and through the heavy cloud cover typically produced by tropical storms or hurricanes. The NASA-supported Dartmouth Flood Observatory (<http://www.dartmouth.edu/artsci/geog/floods/>) includes a frequently updated listing of reported floods, a global map showing flood-affected regions, and an accumulating array of satellite-based image maps showing inundation limits along flooded river valleys from diverse geographical contexts. It was designed as a research tool for focused efforts to understand the origins, geographical distributions, and frequencies of extreme floods, but it also is temporarily serving as an archive of flood inundation maps used by the general public.

## INTRODUCTION

Extreme floods are not evenly distributed spatially or temporally. They are low frequency, high magnitude events whose prediction, or even observation, is fraught with difficulties. Recent papers discussing the history of geomorphology emphasize how understudied such events have been, compared to the more "respectable" and frequent phenomena which are more accessible to Earth Scientists (Baker, 1992). At the same time, the new era of global satellite remote sensing has removed observational constraints for many kinds of extreme natural events, including floods. Having the world as a stage forces the realization that extremely rare events occur, somewhere, nearly every week. Thus, nearly every week, the "flood of the century" occurs somewhere (for instance, at this writing, in January 1997, along many river valleys in northern California). We have found that wire services and WWW-based news services report an average of two extreme flood events per week. In the period from January to September of 1996, we logged eighty flood events.

Through satellite remote sensing, we can now detect and study these events as they happen.

Although geomorphologists are interested in extreme events from a research perspective, non-scientists — e.g., local and national disaster officials, humanitarian organizations, the general public — are directly involved in extreme flood events. The eighty events noted above incurred a cumulative loss of approximately 3000 human lives, U.S. \$2.18 billion in damage, almost 3 million Ha. of agricultural land inundated, and 3.8 million people displaced. There is thus a practical need for current reporting or observation of flooding. The WWW flood remote sensing site was designed for research purposes, but we have noted a heavy demand for existing flood inundation maps and other data products in the wake of particularly large flood events — especially from those locally affected. We thus continue to pursue our research within academia while also striving to make the results of such work available in a timely fashion to non-specialists via map and image product publication on the WWW site.

This paper describes the satellite and electronic news service technology that helps us to create our basic information, as well as the structure and content of the site. We consider that sites such as ours, which present new maps that are not otherwise published, pose interesting questions for information specialists: how best can such documents be published and archived, and should the long term preservation of such information depend on the sustained operation of our local group and WWW site?

## DATA SOURCES

The Dartmouth Flood Observatory (DFO) was initiated with NASA Mission to Planet Earth (NASA-MTPE) funding support and has been developed as a research tool to aid efforts to understand the origins, geographical distributions, frequencies, and magnitudes of extreme floods. Its research products are two-fold: (1) a running tally of flood events, with geographic locations and associated observational statistics recorded in a MapInfo® geographic information system (GIS), and (2) high resolution synthetic aperture radar (SAR) satellite images of particular flooded river valleys, rectified to various map projections and presented as 8 bit color GIF files. The DFO supports a World Wide Web (WWW, or simply, "Web") site available to any user with Internet access and a browser such as Netscape Navigator, Internet Explorer, or NCSA Mosaic. The Web site presents global records of extreme flood events (in text file and MapInfo Exchange, MIF, format) as well as maps (approximate scale 1:50,000) showing the spatial extent of particular large floods. There is much other related information presented on this WWW site, but the above, we believe, constitute the unique contributions of the site.

The original data for the global tally are electronic news service clippings received via various commercial and free (WWW-based) sources. The news information is analyzed in-house, compared for accuracy, and the basic statistics thus obtained are recorded both as a summary text description and as a data table within the global GIS.

The original data for the flood image maps are ERS (European Remote Sensing satellite) SAR images. In the near future, we will also be processing Radarsat SAR images. Both are C-band ( 5.6 cm wavelength) synthetic aperture radar images obtained from Earth orbit by a transmitter/receiver of an electronically "synthesized" large effective aperture. The images have a ground resolution of approximately 20 meters: objects of about this size or larger can commonly be discriminated. The radar signature

of relatively smooth-surfaced flood water is dark (low radar return), whereas even moist land surfaces are radar-bright; thus, floodwater/land interfaces are easily distinguishable. Each orbital image covers 100 km x 100 km; we commonly crop the images to cover only the areas of interest. The data are shipped to us as 16 bit image files, but we have found that transformation into much smaller 8 bit gray-scale images preserves the needed information. Image radar backscatter calibration is not critical, although comparison of before, during, and after SAR images of the same terrain can benefit by calibration to real values of radar return intensity.

The 8 bit images are first "geocoded" by matching image features to their known geographic coordinates (in either latitude and longitude or in Universal Transverse Mercator, or UTM, systems). In this step, digital image processing techniques are used to warp the image to achieve the best possible match of image geometry to a map projection. In hilly terrain and for radar images, such geocoding is best performed after an initial rectification using topographic information, since SAR image geometry is exceptionally sensitive to topographic distortion even from orbital heights. However, for mapping floods along low relief floodplains, topographic rectification is not necessary.

In summary, the combined global and valley-reach specific data are derived from: a) commercial news services, b) free Internet-based news services; c) government-issued flood information; d) European and Canadian/American SAR satellites. The European data source is available due to a unique research outreach sponsored by the European Space Agency: a selected group of scientists are provided free ERS data in return for their assistance in demonstrating new applications for this technology. The Canadian/American Radarsat data are to be provided to us as approved NASA principal investigators and through agreements between the Canadian and American space agencies. Both kinds of satellite SAR data include restrictions on further distribution of the raw data, in order to avoid competition with commercial marketing efforts. However, due to the research nature of our work and the academic institution sponsorship, the image maps we produce are in the public domain and available freely for copying or reuse with only the standard requirement of proper citation and attribution. Both satellite data sources also require that image products made using their raw data cite the raw data source and its copyright.

## A TOUR OF THE SITE

The site

(<http://www.dartmouth.edu/artsci/geog/floods/>)

is organized into six areas:

- flood databases;
- sample images;
- current flood information;
- links to related sites;
- links to staff home pages and email addresses.

The top page of the flood database area links to a presentation of extreme flood events in the current

year, and to an FTP download area for GIS databases for previous years, dating back to 1994.

The "current year flood events image map" page (Figure 1) presents a world map showing locations of extreme flood events for the current year, as point symbols ranging from red (most recent), through pink, to off-white (oldest). These symbols are "hot spots" on the map; they are linked to anchors in a list of information about the flood events, so that clicking with a mouse button on a particular symbol brings up, in a separate window on the page, the record for that event.

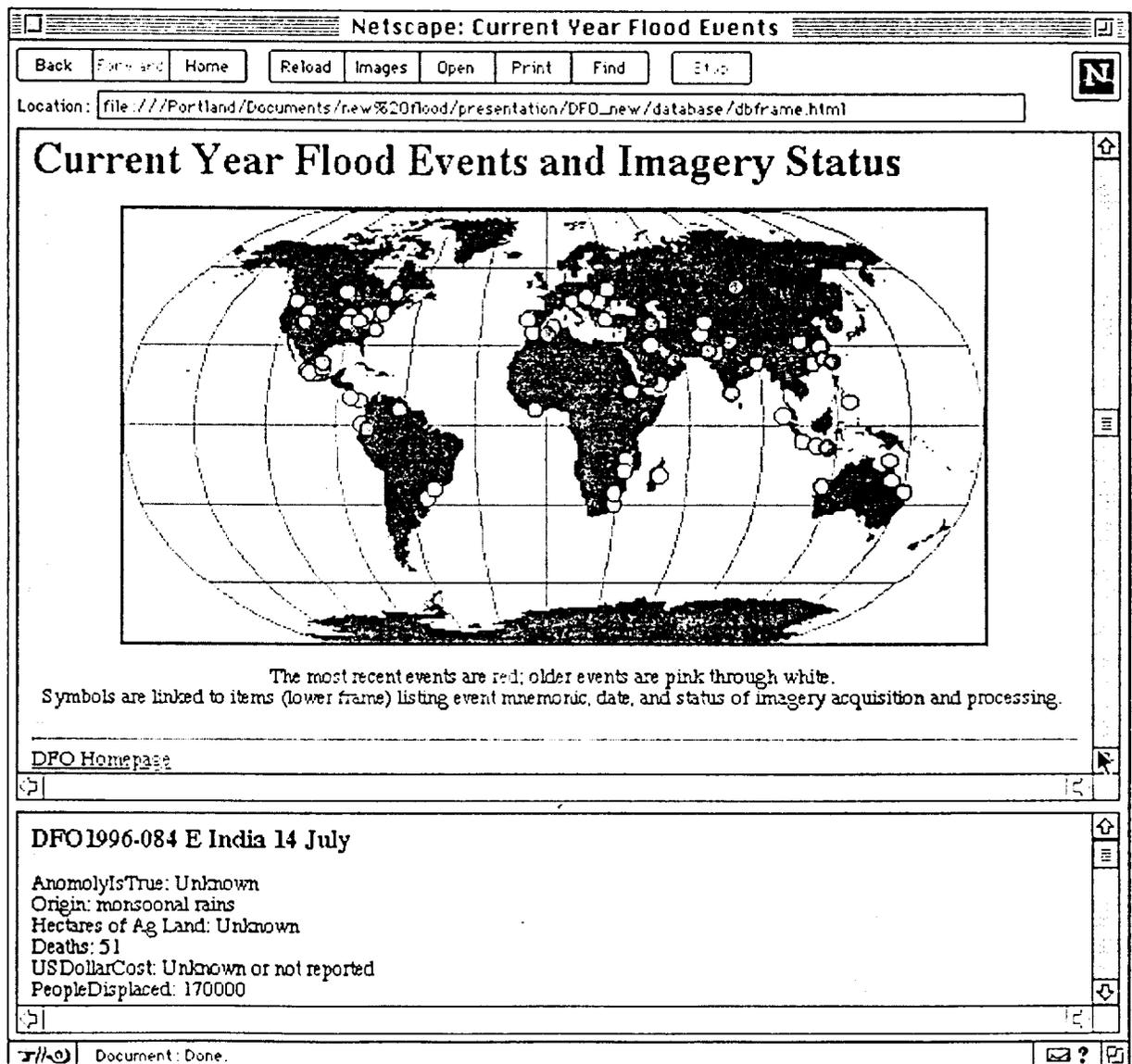


Figure 1: A screen shot of the current year flood events image map.

The FTP area contains information for 1994 through the current year. The current year database is used to construct the text file used in the current year flood events image map, and is updated periodically. For years 1996 and following, the database is available as a set of MapInfo tables in MIF (MapInfo Exchange) format, as well as DXF (Drawing Exchange Format). For 1994 and 1995, the data are in tab-delimited files. Most PC or Macintosh computer graphics programs can input linked object and attribute files in DXF format; and many GIS programs can import MIF files.

The database records information gathered from news reports, and links them to geographic objects. For flood events of known and reasonably large

geographic extent ( $> 500 \text{ km}^2$ ), these objects are polygons approximating the area involved; for events of small or unknown extent, these objects are points. A related MapInfo® table maps all events to point objects, for use in creating the current events image map and for small-scale browsing.

Table 1 shows the attribute data items recorded for the MapInfo® table "floods96." The information for fields such as "DateStart," "DateEnd," and "Origin" is gathered from news services on the Web, and coded as indicated in the "Notes" column of the Table. For instance, "Origin" (which is coded using a small integer number) is arrived at by summing up the codes for individual causal factors listed in the news reports for a particular flood event. Since the

Table 1: Data Items and Definitions in Flood Events Database

Attribute Name	Data Type	Notes
Year	SmallInteger	4-digit year number
EventNumber	SmallInteger	Assigned by DFO
Name	Char(30)	Assigned by DFO
DateStart	Date	
DateEnd	Date	
AnomolyIsTrue	Char(1)	Possible values: Y,N,U (for yes, no, unknown)
Origin	SmallInteger	Coded in powers of 2
HaAgLand	Integer	Hectares of agricultural land involved
Deaths	Integer	
USDollarCost	Integer	
PeopleDisplaced	Integer	
Notes	Char(250)	

individual causes have codes that increment by powers of 2 (see Table 2), all possible combinations of causes will sum to unique numbers, which can be decomposed into individual codes.

The "Rivers" data table records the names of the river drainages associated with a particular flood event. The DFO inventory number can be used as a foreign key to access this table.

There are several cross-reference tables to event identifiers used by agencies such as FEMA (the US Federal Emergency Management Agency) and DHA (Department of Humanitarian Affairs, a UN agency).

SAR imagery, processed to enhance visibility of inundated areas and combined with digital elevation models and other vector information such as transportation routes, is available through another

Table 2: Codes for "Origin" data item

Code	Origin
0	unknown or not recorded
1	rains
2	snowmelt
4	tropical cyclone
8	frozen ground
16	monsoonal rains
32	flash floods
64	frontal storms, thunderstorms

page on the site: "Flood Images". Emily Bryant, one of the DFO staff, provides this description of the process (personal written communication):

"After being scaled from 16-bit to 8-bit, the [SAR] image is registered to UTM coordinates, using US Geological Survey (USGS) 1:100,000 scale Digital Line Graph (DLG) files downloaded from the Eros Data Center web site. USGS 1:250,000 scale Digital Elevation Model (DEM) data for the same flooded area are also downloaded and registered to UTM coordinates, using the same DLG data. An inverse Intensity-Hue-Saturation (IHS) transformation is then used to merge the registered SAR and DEM data. The SAR layer is designated as intensity, the DEM layer as hue, and a third layer (often just a uniform middle-gray image) as saturation. When this is transformed to three RGB layers, color (hue) corresponds to elevation (typically navy blue for the lower elevations, green and yellow for mid-elevations, pink for higher elevations), and overall brightness (intensity) corresponds to the SAR return. Smooth surfaces such as open water have a low SAR return and hence look black. The DLG vector data are overlaid on the registered RGB image, with hydrology features represented in bright blue, roads in red, railroads in yellow, and 'miscellaneous transportation' (e.g. pipelines, power lines, airports) in white."

At the top level of the flood images area of the site, reduced-resolution thumbnail and browse images are displayed on the Web pages. This enables users with relatively low-speed connections to view sample data in reasonably short times. If users then wish to download the full-resolution imagery, they can do so by using the FTP area linked to the browse image pages.

"Current information" consists of links to Web sites that provide flood related data and information. For instance, the National Flood Summary WWW page, with flood information for the United States, is updated daily by the US National Weather Service headquarters. The Water Resources Information homepage, which is a product of the US Geological Survey, often has information about current flooding as well as real-time hydrologic data and links to other sites. A page maintained by the US Army Corps of Engineers page also links to real-time hydrograph data for a number of river basins in the Midwest. The current flood information page links to a number of non-US sites, US sites that focus on international weather and disaster information, and sites set up by international organizations

"Related Sites" links are to sites maintained by organizations having some connection with the DFO. These sites include the NASA/JPL Imaging Radar Home Page, the European Space Agency's Earth Remote Sensing User Services, the RADARSAT

Home Page, the Alaska SAR Home Page, the Canada Centre for Remote Sensing Home Page, and the home pages for the Earth Sciences Department and the Geography Department at Dartmouth College.

## FUTURE PLANS

The real-time hydrograph data mentioned above presents an opportunity for us to develop a graphic display showing river stage as map symbols on a base map of streams. This would entail development of certain scripts or possibly Java-based applications, and would provide real time flood mapping as opposed to the present numerical data stream generated by the gauging stations.

Refining the current flood events map display is a pressing issue. We plan to do this by increasing its temporal resolution, so that accumulating a year's worth of flood events does not cover the oldest entries.

Planned improvements to the database — both the on-line current events version and the downloadable one — involve adding imagery acquisition information for each event. We would also like to make available a larger number of transfer formats — perhaps Arc/Info Exchange format as well as the current MapInfo and DXF.

As our goals and experience with the Web site continue to evolve, we are considering the implications of using a Web-compliant map server to present the spatial database of flood events. This approach would allow users to pan, to zoom in to examine an area in detail, as well as to perform more flexible attribute-based database searches. But this solution may not be the one most appropriate to our own needs. At present, we are in an academic computing environment based on the Apple Macintosh for client applications, with a shared Web server in another unit of the College. Present map-server solutions are based on UNIX, Win95, or NT environments, and would entail the DFO unit's taking responsibility for its own site in a physical as well as virtual sense.

## CONCLUSIONS

As with any Web site, ours is a work in progress. We have experienced one major redesign and continue to modify the existing site. In the process, we continue to learn, and re-learn, important lessons in the creation, maintenance, and renewal of tools to provide information.

One such lesson has to do with the difficulty of maintaining continuity of effort in an academic environment. Without a staff dedicated to Web site

maintenance, we rely on student workers and our own labor for the monitoring of news reports, collation of data, updating of the MapInfo database, transferring of information to the Web site, and so forth. Maintenance of a Web site of this nature is technically demanding and time-consuming, and can absorb as many resources as one cares to devote to it.

As a consequence of this realization, our response needs to be an examination of our goals for the site and the resources available to fulfill those goals. There is a large, and ever-expanding, array of possibilities for information delivery; the challenge is to choose the ones that are appropriate to the task and to commit the effort to develop those possibilities.

Questions such as those raised in the Introduction to this paper are clarified if not answered as our experience increases. When considering how best the database and imagery products produced by the DFO should be published and distributed, or in what way these products are best associated with the Web site, we face a paradox resulting from the popularity of the Web and rapid growth in Internet usage. That is: the availability of more volume and types of geographical and earth science data has made it harder to track down the subset that is relevant to a particular problem. As a response to this, initiatives such as the Alexandria Project (<http://alexandria.sdc.ucsb.edu/>)

and the National Spatial Data Infrastructure (<http://fgdc.er.usgs.gov/fgdc.html>) are underway and in development to provide links, catalogs, and metadata sources for geographical data. Because of the existing institutional linkage between DFO and NASA, NASA's Earth Observation System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAAC) (information at (<http://ecsinfo.hitc.com/>)) form a straightforward avenue for distribution of DFO datasets. At this point the most intriguing possibility is for the DFO to archive database and imagery information, perhaps on a yearly basis, on CD-ROMs. This would allow the Web site to focus on current information and rapid response imagery, while, with the right choice of file format and data organization, users of the CD-ROMs would be able to perform useful analyses of imagery data as well as the global flood event GIS data.

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