

Flood Warnings, Flood Disaster Assessments, and Flood Hazard Reduction: The Roles of Orbital Remote Sensing

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Abstract—Orbital remote sensing of the Earth is now poised to make three fundamental contributions towards reducing the detrimental effects of extreme floods. Effective *Flood warning* requires frequent (near-daily) radar observation of the Earth's surface through cloud cover. In contrast, both optical and radar wavelengths will increasingly be used for *disaster assessment* and *hazard reduction*. These latter tasks are accomplished, in part, by accurate mapping of flooded lands and commonly over periods of several days or more. We use radar scatterometer data from QuikSCAT to detect changes in surface water area and with global coverage every 2+ days. Also, MODIS, RADARSAT, and other higher spatial resolution data are used for flood mapping and other flood measurements. These records are preserved in a global flood hazard atlas at <http://www.dartmouth.edu/~floods/Atlas.html>.

Keywords: floods, hazards, radar, scatterometry, MODIS

1. INTRODUCTION

The mapping of floods from space, however worthwhile, is not the sole contribution orbital sensors can make towards reducing the detrimental effects of extreme floods on society. There are actually three major areas of work, and each requires a different suite of sensors, processing methodologies, and end-product dissemination pathways.

The first area of work, detection of new flood events and public warnings thereof, is still experimental but it is making rapid progress. Radar sensors are preferred due to their cloud penetrating capability. Relatively low spatial resolution, but wide-area and frequent coverage, are appropriate: the objective is to locate where within a region or watershed flooding is occurring, and not to map small-scale inundated areas due to the low resolution. The second area, rapid-response flood mapping and measurement, provides information useful for disaster assessment, and has become a relatively common activity. A wide variety of sensors have been used (Barton and Bathols 1989; Brakenridge et al. 1998). However, the capabilities are still relatively immature, and there is much potential for development of advanced measurement capabilities that can better define flood severity and damage. Finally, the third area of work, flood hazard mapping, is based on the recognition that not only can floods be imaged and mapped as they occur, but these records of extreme events can and must also be preserved in archival form. In this way, maps of lands actually flooded complement maps of land areas predicted via modeling approaches to be subject to flooding.

2. FLOOD DETECTION

2.1 Potential of Satellite Radar Scatterometry

Floods are transient surface events and can occur at the same time over widely separated geographical locations (even on different

continents). To record such events, timely information with frequent and large-area coverage is necessary. Even within the U.S., in-situ instrumental data are not abundant. Thus, an event such as the Great Flood of the Upper Mississippi Valley in 1993 destroyed many gaging stations, and was so geographically extensive that assembling a comprehensive, mainly Landsat TM-based survey of affected rivers and tributary systems took the U.S. government several years. This task depended on the availability of clear-sky optical data, much of which was processed long after the actual flooding. A space borne Ku-band scatterometer with a large swath but low spatial resolution, such as SeaWinds on QuikSCAT, can, in contrast, provide near daily global coverage with the capability to see through clouds and darkness. It can, in principle, detect where flooding is occurring without necessarily imaging such flooding in detail.

For QuikSCAT data analysis, we are using an innovative technique that is based on the polarization reversal of radar backscatter, measured by the scatterometer, over flooded areas. The total backscatter over the landscape within the radar footprint consists of: (1) scattering due to rough surfaces, (2) direct scattering from volume scatterers such as vegetation and buildings, (3) scattering of reflected waves, (4) reflection of scattered waves, and (5) double-reflected scattering. Term (5) is generally small in the total backscattering and can be ignored.

Over unflooded landscapes, the reflection from the underlying medium (soil, concrete, or other) is weak and the scattering is dominated by direct volume and rough surface scattering mechanisms (terms 1 and 2). In this case, the polarization ratio VV/HH, where VV is the vertical polarized backscatter and HH is the horizontal component, is about 1 or larger than 1 in linear scale and about 0 or positive in dB scale (Nghiem et al. 1990; Tsang et al. 1985). However, when the landscape becomes flooded, the reflection becomes strong due to the large permittivity of the underlying water. Moreover, the reflectivities for horizontal polarization (HH) are much larger than those for vertical polarization (VV) at large incidence angles (>40°). Thus for the flooded case, the backscattering is dominated by the reflection terms (3 and 4) and VV/HH is significantly less than 1 in the linear scale, or negative in the dB scale. Note that the total backscatter may or may not change significantly because terms 1 and 2 decrease due to submerged volume and surface scatterers while the reflection terms increase.

The current flood detection algorithm uses QuikSCAT data, binned to the resolution of 0.25 x 0.25 degree in latitude and longitude (about 25 km x 25 km). The scatterometer has been collecting data at 13.4 GHz over both ocean and land. Backscatter data, at a radiometric resolution of 7 km x 25 km, are acquired with the vertical polarization (VV) at a constant incidence angle of 54° over a conical-scanning

swath of 1800 km, and with the horizontal polarization (HH) at 46° over a 1400 km swath. The local overpass times are approximately 6:20 and are 12 hours apart in a sun-synchronous orbit. Calibrated science data have been obtained since 19 July 1999 (Tsai et al. 2000). The polarization ratio data are processed at the Jet Propulsion Laboratory, in California, and then shipped daily via ftp to Dartmouth. There, the global raster is rotated, inverted, and sub-set, to produce two rasters for the eastern and western hemisphere that can be integrated into the observatory's geographic information system. Because rainfall events, particularly over urban areas, produce strong but short-lived negative polarization anomalies, 7 day running means are computed in order to dampen such effects. Then, for year 2003 data, a difference result is computed comparing the present weekly mean to the appropriate bimonthly mean for the year 2002. The influence of non-transient land surface variables affecting the polarization results, such as topography, is thereby reduced. Figure 1 shows one of the "flood alert" maps, where current wetter-than-last year land areas are contrasted with dryer-than-last year land areas.

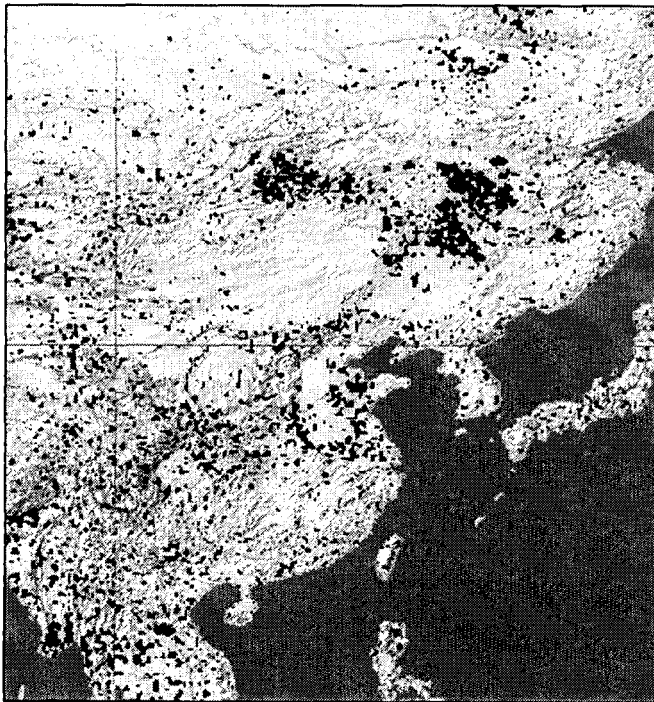


Figure 1. QuikSCAT polarity ratio ("flood alert") display for September 28, 2003. Blue (dark shading) and yellow (light shading) indicate increased and decreased surface water extent compared to September-October, 2002.

Similar displays are produced for all other continental land areas, are updated daily, and are currently available at the observatory web site (<http://www.dartmouth.edu/~floods>). Also being disseminated at this address and with the same frequency are 7 day animations of these displays, and other regional maps showing the location of strongly negative but undifferentiated polarity ratios

(including large permanent wetlands such as the Sudd marsh in southern Sudan). Together, these results provide the rudiments of a global flood alert system.

Inland river flooding is spatially extensive and restricted, at the same time. Flooded river reaches can extend for hundreds of km, but widths may be only on the order of a few km or tens of km. Although regional displays such as figure 1 are useful in localizing areas of excess moisture receipts, there remains an additional step needed for further constraining the locations of actual flooding. We are exploring a two-pronged approach towards this end:

1) As part of NASA's "Sensor-Web" demonstration project, wherein different orbital sensors are inter-connected through artificial intelligence technology, QuikSCAT-determined areas of anomalous surface water are being intersected each day with the geographic locations of the Flood Observatory's "Global Hydrographic Array". The array consists of several hundred river reaches, each measuring approximately 20 km in river length (Figure 2). We can now identify, for imaging by high spatial resolution satellites, specific reaches that are experiencing excess surface water. As the period of observation lengthens, we hope thereby to specify, for each reach, thresholds in the polarization ratio data that indicate reach-specific overbank flooding and as corroborated by independent data.

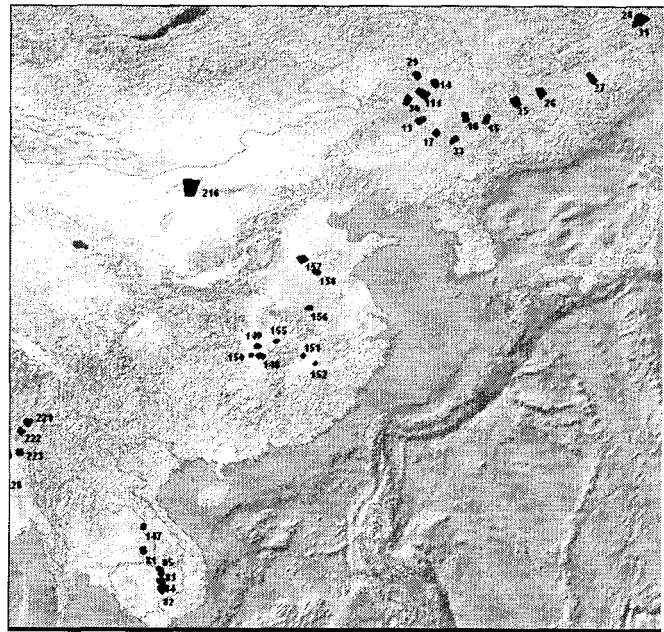


Figure 2. Location of satellite river gaging reaches so far established in this region (a subset of the global array). Automated intersections of these reaches with QuikSCAT flood alert areas provide targets for high-resolution imaging via the pilot Sensor-Web.

2) The entire time series of QuikSCAT data for each of the reaches are also being examined, and compared with optical image data such as from MODIS and ASTER, and also to *in situ* river gaging station data (Figure 3). Preliminary results indicate seasonal variation in the polarization ratio signal, due to surface soil moisture and to changes in vegetation and agriculture. These trends can be removed in order to better define flood thresholds.

2.2 Potential of MODIS Rapid Response

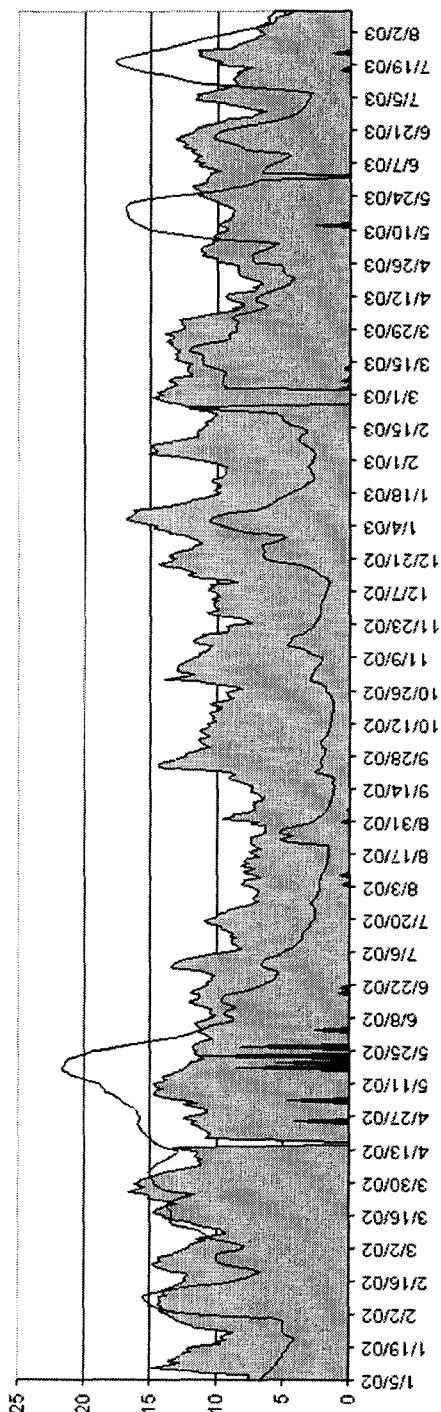


Figure 3. Continuous daily monitoring of a river reach within the U.S. (Wabash River, reach 196, southern Indiana) by QuikSCAT running mean polarization ratios (blue or gray solid shading) compared to daily river stage (level) data from an in-situ recorder (black line) and a series of MODIS-based reach water surface area measurements (red or black peaks). Note seasonal trend in the QuikSCAT series.

MODIS Rapid Response data are available from Terra and Aqua in near real time at: <http://rapidfire.sci.gsfc.nasa.gov/>. Several spectral bands at spatial resolutions of approximately 250 and 500 m are appropriate for accurate discrimination of water from land. Excluding the effects of cloud cover, there is also global coverage on a near-daily basis. In principle, MODIS could serve as a global flood alarm technology in the same manner at which it presently is providing near-real time fire information via the Rapid Response system and web site.

In practice, the spectral signature of river flooding is more complex than that of fire. Floods affect tropical riverine forests as well as agricultural lands; they occur in desert and steppe and urban areas and with varying degrees of visibility of the substrate below the water column; they occur with abundant sediment concentrations and also as, for example, clear water in low gradient, bare-soil areas such as the Red River Valley of northern Minnesota, U.S. This spectral variability poses difficult challenges to automated flood detection.

Cloud shadows also interfere with accurate discrimination of water from land, and particularly using the critical band 2 (841-876 nm). Finally, and unlike the case for fire, surface water is also a permanent feature of the Earth's land surface. Therefore, a change detection approach is essential to recognize new water. This in turn requires new MODIS data to be precisely registered to older data and/or to "permanent water" masks (which have not yet been created at adequate spatial resolution). Indeed, seasonal changes bring large-scale changes in surface water extent over many areas of the Earth's surface and "normal" conditions in map view have never been rigorously defined. Even as MODIS and QuikSCAT are revealing the dynamics of such large-scale changes, these technologies raise the question of how to define flooding in order to isolate unusual changes from seasonal events.

The change detection requirement has inhibited progress in flood detection using MODIS and due to the very large spatial coverage and associated data volumes. However, the globally distributed gaging reach approach provides a path forward. At such reaches, a time series of MODIS data are being assembled (e.g., figure 3), and normal versus flood conditions can be defined: a MODIS flood threshold can be established. We are developing spectral unmixing techniques to estimate total reach water surface areas, and we are validating such estimates with intermittent ASTER optical data, whose much higher (15 m versus 250 m) spatial resolution provides effective "ground truth". It will not be possible to monitor each reach on a predictable and frequent basis using MODIS, because unusual cloud cover conditions can obscure individual reaches for days and even weeks at a time. However, it will be possible to continually update all clear-sky reaches scanned by new MODIS scenes, using change detection and standard reference scenes, and this can allow sensitive detection of surface water area changes. Ultimately, it may be possible for satellite gaging reaches (Brakenridge 2002) to also record smaller flow fluctuations and thus assist in monitoring the global hydrologic cycle: low water as well as high water conditions should be detectable using both QuikSCAT and MODIS techniques.

3. DISASTER ASSESSMENT

MODIS rapid response data are exceptionally useful for flood inundation maps in the wake of large flood events. This is because, unlike other data that may appear more appropriate, due to higher spatial resolution (RADARSAT standard beam, for example), the MODIS sensor is always on and the data are being quickly processed. In contrast, other sensors often require advance notice for insertion of acquisition requests. The Dartmouth Flood Observatory has used MODIS data since launch of the initial sensor aboard Terra in late 1999 to map floods worldwide and to immediately publish such maps at its web site. We have also made available vector GIS data products indicating land areas inundated, and to such disaster responders as the UN World Food Program. Figure 4 is a portion of such a map that was published rapidly after orbital data collection and because of the efficiency of the MODIS rapid response processing and dissemination system.

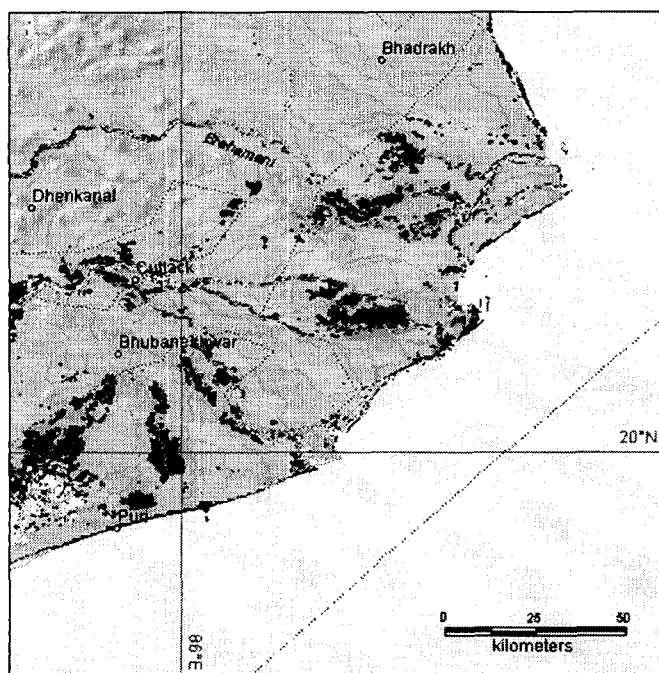


Figure 4. Flooding in the Orissa region of eastern India (DFO-2003-225) along the Mahanadi River and its distributaries on September 9, 2003, as shown in a small portion of the online map. Dark or red shading is new surface water, light blue or lighter gray is permanent, including marine, water. Over 3 million were made homeless in Orissa and at least 1397 villages were submerged.

Several characteristics can enhance the value of such maps to the end users: 1) the use of standard map projections (such as UTM) and inclusion of fine-scale graticules, which allow for accurate geolocation, 2) multi-temporal imaging, which, for large regions and long-duration floods, can help in damage assessment: damage is, in part, a function of flood duration, and 3) inclusion of the limits of previously imaged and mapped floods, which allows comparative assessment of flood severity (see below). It is also necessary to present the information at several map scales: small scales, in order to allow all MODIS-determined areas of flooding to be presented, and large scales, at selected locations, to illustrate in detail local flooding situations. It is for this reason as well that

many end-users request the vector data files, which can be incorporated into local geographic information systems.

In regard to damage assessment, there are additional measurement capabilities from such frequent-repeat image data and when coupled with other information. For example, as digital topographic data become increasingly available with high spatial resolution and vertical precision, flood limits can be co-located with elevation measurements to produce longitudinal (energy) profiles of floodwater along river reaches. In effect, and depending on topographic data quality, a geocoded image of a flood event also provides information, at many locations, of flood stage (Brakenridge et al. 1994; Brakenridge et al. 1998). Hydrologists can use such information to constrain flood discharges and flood wave celerities; disaster responders can make use of the thereby-measured water depths to infer flood damage.

4. FLOOD HAZARD MAPPING

To remember the past is a special human capability that has long helped our species to survive and even prosper. As global human population continues to rise, many regions are becoming more densely populated, and natural processes, such as flooding, are increasingly becoming natural disasters. It is remarkable that these events are not everywhere being measured and recorded by governmental agencies in an intensive and organized manner, and in particular, now that the era of sustained observation of the Earth from space is underway.

Many flood events cross international borders, and it is well known that changes upstream, such as additional river engineering to prevent local flooding, can exacerbate problems downstream. Flood hazard assessment thus may require data from outside the nation of concern. Orbital remote sensing is the only method available to document what land areas have actually been affected by flooding and without the constraints presented by national borders. Such maps can provide hydrologists with information concerning what floodplain areas become temporary water storage sites during large floods (thus attenuating the downstream flood wave). They can also provide society at large with immediately useful information concerning what land areas have been inundated and may, therefore, be considered at risk for flooding in the future.

Remote sensing-based flood hazard mapping, which records what lands have actually been flooded, is a complement to, and does not compete with, traditional floodway mapping based on topography, local hydrologic data, and hydraulic modeling. (See also Horitt and Bates 2002; Townsend et al. 1998). The first records for posterity what has actually happened, the second estimates what may happen in the future and, again, as based on history: the local *in-situ* gaging station record of large floods. Mapping of actual floods, as they occur over years of time, can increasingly inform the last, but other information is also relevant for integrated flood hazard evaluation: for example, that concerning watershed landuse changes, levee construction or removal, and climate change (see for example Bronstert, 1995; Dilley and Heyman, 1995; Hirschboeck et al. 2000; Mirza, 2002; Savenije, 1995). Note also that, in many regions of the world, there exist only sparse *in-situ* instrumental data or perhaps none at all: in these cases, the record of flooding as observed from space becomes critical to any objective assessment of flood hazard.

The Dartmouth Flood Observatory has embarked on an ambitious project of recording in both digital and hard copy map form a Global Atlas of Flood Hazard. This work in-progress is available online at the observatory web site and a sample portion from one of the more than 127 maps is given here as Figure 5. The Atlas is presently organized into 10-degree latitude and longitude map tiles, with high latitude tiles extended an additional 10 degrees in longitude. Geographic coverage is global, although ice-covered regions are excluded. Raster versions are presented online and are available for download at a map scales of approximately 1:1.5 million; however, MODIS mapping spatial resolution can support map scales as high as: 1:500,000. Locally, much higher spatial resolution is provided and where Landsat ETM, ERS-1 and ERS-2, RADARSAT, ASTER, or other sensors have provided image data. The shaded relief base maps were generated from GTOPO digital topography and will be upgraded as updated versions of such global data sets become available.

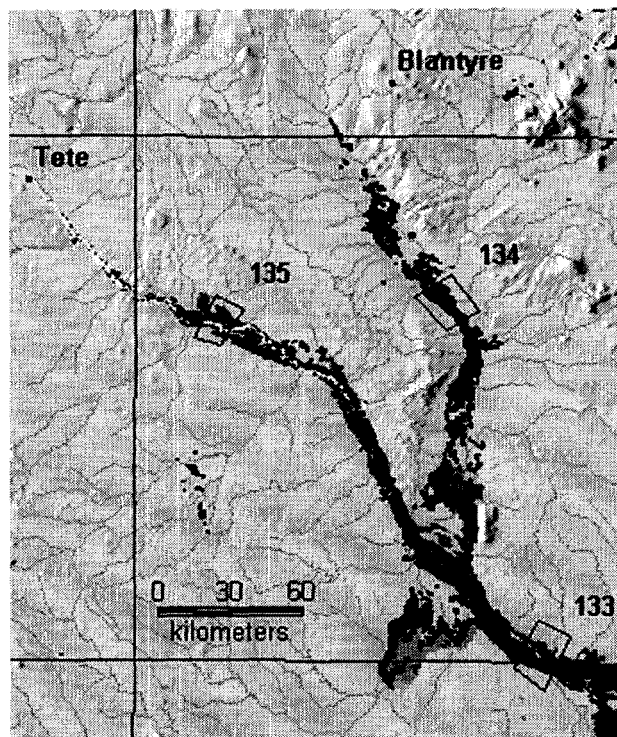


Figure 5. Portion of the Atlas of Global Flood Hazard from the online version and illustrating the history of observed large floods along the Zambezi and Shire rivers in Mozambique. The lightest blue tone is “MODIS standard reference water” and shows pixels classified as water on MODIS data obtained during non-flooded conditions. Other blue floodway tones indicate flooding occurring during different years within the period of observation; the darkest such tone corresponds to the year 2003. Three numbered satellite gaging reaches are also shown. At these locations, floods from different years can be compared according to the area of surface water generated within reach boundaries.

Prior to the initiation of this project, there existed no global flood hazard map, and the symbology keys of both “flood rapid response” maps (figure 4) and flood hazard maps (figure 5) based on remote sensing have no legacy in prior works. They must,

therefore, be designed and formalized following from general cartographic first principles concerning the effective communication of information, and from anticipation of user needs. Similar digital vector “layers” are used to generate both kinds of maps, but the needed symbology differs. Timely maps for disaster responders should show the prior history of flooding only as an outline (this is the area of previously-known flood hazard) and emphasize the current status of flooding. Various shades of red or yellow are appropriate in order to highlight even small areas, flood limits from different days and satellite passes should be differentiated, and where possible estimated water elevations from waterline intersection with topography can usefully be provided. In contrast, flood hazard maps show the accumulated history of flooding over many years, and blue tones, differentiated by years, are appropriate: this strategy conveys at a glance both the total land area affected by flooding, and during which years such flooding has been most extensive. These maps also include two important qualifications: 1) that, due to the so-far quite limited period of observation, the maps depict only what lands have been observed to be flooded, and not what lands could be flooded in even the near future, and 2) that satellite-based observation of flooding along high gradient rivers in hilly or mountainous terrain is less effective due to the small river surface areas as well as the quick passage of flood waves. These exceptionally hazardous floodways are commonly unmapped in the Atlas.

5. CONCLUSIONS

Of all natural disasters, inland river floods are the most spatially extensive and thus are the most easily observed and measured from orbital sensors. There is some irony to the realization that, during the years of scientific discussion leading up to the design of NASA’s “EOS” satellites (including Terra and Aqua), the direct observation of the “runoff” component of the Earth’s hydrologic cycle was considered to be unobservable. Instead, modeling, combined with *in situ* data, were assumed to be required. As is sometimes the case, once an observing tool has been created, uses and capabilities are found that were unanticipated. The use of Terra and Aqua for global flood monitoring is one such surprise. At least this component of river and stream hydrologic regime can effectively be measured. Work underway involving repeat data collections over the gaging reach parcels, briefly noted here (e.g., figure 3) is also demonstrating that present sensors may be used as well to obtain useful information about non-flood discharges.

As orbital mapping and measurement of river flooding continues, the Atlas of Global Flood Hazard becomes increasingly comprehensive and useful. Within monsoonal as well as high latitude regions, there occur strong seasonal contrasts in the extent of surface water, and such variation is being captured as well on the global atlas. This increasing storehouse of hydrographic information is revealing how poorly known indeed is the variability of surface water at these spatial scales. Soil moisture is now widely acknowledged to be an important variable for global circulation models of the Earth’s atmosphere. Climatological studies after the Great Flood of the Upper Mississippi River, in 1993, also demonstrated that flooding itself was a significant input into regional circulation. Thus, it appears that, in addition to soil moisture changes, the expansion and contraction of surface water areas can be significant in regulating atmospheric circulation. Once

such changes are described and quantified, they may usefully be incorporated into such models.

Finally, and because sustained observation allows the extent of flooding to be preserved and local flood histories to be defined, we are increasingly able to identify, as new floods occur, whether such are unusual events, or instead fall within the realm of annual seasonal variation. This is a simple task in some areas, but a difficult one in others, such as some monsoon-affected lands. Our monitoring work shows that "extreme floods" occur at the rate of several hundred per year, worldwide. Long-term trends in patterning and causation are already evident for the 1985-present period of observation (Caquard 2003). Assessing the magnitude of each event requires knowledge about its *intensity* (size of the discharge compared to statistics such as the mean, and/or recurrence frequency), its *duration* (total flood volume increases with duration), and the *geographic area affected* (a flood along many rivers over a large region is a higher magnitude event than that along only one river). Although this paper has focused on inland river flooding as a natural hazard, there is also a pressing need to understand how flood frequencies and magnitudes may change as the Earth's climate changes (Allan et al. 2003; Birkett et al. 1999; Brakenridge 1980; Bronstert 1995; Buerger 2002; Burn and Arnell 1993; Dilley and Heyman 1995; Hirschboeck et al. 2000; Knox 2000; Mirza 2002; Savenije 1995). Orbital remote sensing, if carried out with a global scope and over a sustained period of time, is well suited to provide the information needed to address such scientific questions.

ACKNOWLEDGEMENTS

We thank NASA's Office of Earth Science for funding support, the Department of Geography, Dartmouth College, for hosting this research project, and many student research assistants for their thoughtful and competent inputs, including E. Bryant, B. Plumer, T. Villalon, A. Vakhovsky, B. Risk, H. Carlos, J. Greene, H. Fassnacht, D. Finnegan, A. Stender, B. Tracy, and A. Bramley-Miller. The research carried out by the Jet Propulsion Laboratory (JPL), California Institute of Technology, was supported by the National Aeronautics and Space Administration.

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