Cooperative Satellite-based Flood Detection, Mapping, and River Monitoring in Near Real Time

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Based on global records from 1985-present, portions of eastern and northern India experience unusually high per capita fatalities from inland flooding (Figure 1). Also, economic damage is severe and frequent. As in the U.S., this natural hazard is dispersed along thousands of km of river and tributary reaches and it crosses political boundaries. Mitigation along one reach can make matters worse downstream; objective data are needed to determine flood hazard reliably and to resolve disputes.

Flooding is geographically extensive: individual flood events may affect regions extending many hundreds of km (Figure 2). It is also spatially restricted: actual inundation commonly occurs along narrow zones adjacent to rivers and streams, with widths of a few km (Figure 3). Finally, flooding is also temporally dynamic, and over time scales from hours to many weeks (Figure 3). This phenomenon is challenging to accurately measure and map.

There are important basic science reasons to study floods. If, for example, global climate warms, the amount of moisture in the atmosphere, governed by the Clausius-Clapeyron equation, rises much faster than the total precipitation amount, which is controlled by the surface heat budget through evaporation. The "character" of precipitation will change, towards more intense rainfall events, and also more droughts (Trenberth, Dai, Rasmussen, Parsons, *Bulletin of the American Meteorological Society*, 2003).

The North Atlantic Oscillation (NAO), the Pacific-North American (PNA) teleconnection pattern, and the El Nino-Southern Oscillation (ENSO) combine to influence the planetary wave structure over the northern hemisphere. Floods and droughts are associated around the world with ENSO through such teleconnections, and improved flood prediction relies on understanding them better. The scientific study of floods, and consistent measurements thereof, are needed in order to allow "Greenhouse warming" predictions about flooding to be tested, and the hydrologic effects of other phenomena such as ENSO to be evaluated. The needed tasks are: 1) detection/warning of flooding, 2) flood magnitude assessment, 3) flood inundation mapping, and 4) preservation of the record of flooding. Accomplishing these same tasks provides direct local societal benefits as well: they can save lives and reduce economic loss. We emphasize that the

basic science observations need not be divorced from the immediate practical applications: both can occur together, and just as is the case for meteorological remote sensing.

Each task above presents specific challenges and requires different information sources. High spatial resolution (locally) and large area coverage are both needed; cloud cover can greatly inhibit optical sensors during times of flooding (both radar and optical sensors are useful), and frequent updates are required. Data costs must be low for effective work because of the large data volumes needed. The ideal complete system would include sensor and data distribution components similar to that of contemporary weather satellites, as well as certain features of conventional land imaging sensors such as the SAR satellites, LANDSAT and ASTER, and IRS /Resourcesat.

Among the four tasks, satellite-based inundation mapping is today widely used in both India and the U.S., but too-often, as an *ad hoc* activity, in response to major events. In the 20th century, hydrologists employed *in situ* instrumentation in order to measure flood levels or discharges. It was not possible to economically map floodplain inundation, or to track such through time. Aerial photography is relatively expensive, the transition from photographs to maps is cumbersome and expensive, and the dynamic nature of flood events means that more than one survey is required. Society made do without preserving map records of even catastrophic floods. Particularly with the advent of the new array of orbital remote sensors in the 1990s, this situation changed. Wide-area, frequent repeat sensors such as the MODIS and AWIFS sensors now provide U.S. and Indian government agencies the potential to routinely and economically map flooding where and as it occurs. The frequent revisits (a few days at worst, more frequently if more than one satellite is used) allow gaps in cloud cover to be utilized. Also, spatial resolutions of approximately 200 m allow floods along even streams of moderate size to be mapped.

It is still generally under-appreciated how important it is to organize and preserve such data and maps. Figure 4 is a small portion of a multi-year map of flooding along the Brahmaputra River in Assam that was prepared for this conference. It illustrates both Dartmouth's rapid-response mapping via these "always on" sensors, and also the value of compiling such information over the years in order to produce flood hazard maps. Such maps have an advantage relative to modeled floodways (e.g. the U.S. flood insurance maps): they are based on the undeniable evidence of where flooding has occurred, rather than on estimation using hydraulic principles on where flooding should occur. They have scientific value as well, and can allow the measurement of relative flood magnitudes as increasingly long time intervals are represented. They are too important to be produced only by individual contracted projects hastily organized after particular large floods, either within the U.S. or within India. To address both the disaster response and hazards mapping tasks, a sustained partnership between government and private industry is needed. Some disaster response applications may best be performed by private sector, high spatial resolution imagers, but routine hydrographic monitoring and preserving a record of such changes, is an important government responsibility.

In regard to the critical task of flood detection and warning, the "always on" microwave and optical sensors are providing new kinds of information not currently being taken full advantage of. A new strategy of land surface remote sensing is emerging based on these data sources. Instead of being limited to disaster response, present wide-area satellite systems can in fact

monitor rivers, and provide early warning of unusual low or high flow conditions. Note that, in the 1980s, when NASA satellites such as TERRA and AQUA were being planned, it was commonly assumed that the "runoff" component of the Earth's water cycle (streams and rivers) could not be directly measured from space, but must instead be modeled. Our work is instead demonstrating that the direct remote sensing of river discharge changes is in fact possible. Sensors such as MODIS, AWiFS (optical wide area), AMSR-E, and SeaWinds (passive and active microwave) sensors can be employed in the same mode as are the weather satellites: their data output can be transformed to near-real time hydrographic measurements if appropriate processing methodologies are developed.

As an example, we use an array of 700 globally-distributed "satellite gaging reaches" (each 20-30 km in river length) for both flood detection and for the flood magnitude assessment task. The gaging reaches are simply permanent locations along a river and its local floodplain for which repeat measurements are obtained via satellite (Figure 5). Measurements may be water surface areas and resulting water discharge estimates based on repeat MODIS optical data, as shown in Figure 6. Or they may instead be other hydrology-related observations (AMSR-E soil moisture, Figure 7; QuikSCAT/SeaWinds radar polarization ratios, Figures 7 and 8). Figure 7 illustrates the present array of reaches, and Figure 8 the planned expansion providing more dense coverage within India.

Given improvements in automated data processing procedures, it should be possible to update surface water areas, or other hydrologic status measurements, each time one of the wide area sensors passes over each reach. As the time series accumulate, and reach behavior is observed through low and high flow conditions, numerical thresholds for overbank flooding, or for low flow, can be determined and this information provided in near real time. For example, the time series of QuikSCAT/SeaWinds polarization data along the Gandak River gaging reach, shown in Figure 9, recorded three monsoon seasons and is about to record a fourth. At this reach, the polarization ratio can be compared with MODIS and with higher resolution optical image data for validation. In this way, "flood alarm" thresholds can be determined. A similar approach can be used for the same reach using AMSR-E data and, again, with the aim of determining what values constitute unusually high or low reach surface water areas and river discharge status.

As noted, the addition of high quality topographic data can allow river stage measurements to be made: see again Figure 6, in which MODIS water surface extents were transformed to water stages by modeling floodplain inundation using topography measured by the Shuttle Radar Topography Mission (SRTM). Note that remote sensing probably cannot replace *in situ* river gaging: the methodology outlines here is relatively insensitive to modest discharge changes that are confined within the river channel. What can, however, be sensed and measured today, in a rapid and cost-effective manner, is the hydrologic status of river reaches: major flood, modest overbank flooding, in-channel "normal" flow, and unusual low flow conditions. This information is valuable for natural hazard evaluation, and, with proper validation, for actual flood warning. We believe there to be broad potential for further development of this and related approaches towards both monitoring rivers in general, and providing early warning of extreme flow conditions in particular.

ACKNOWLEDGEMENT

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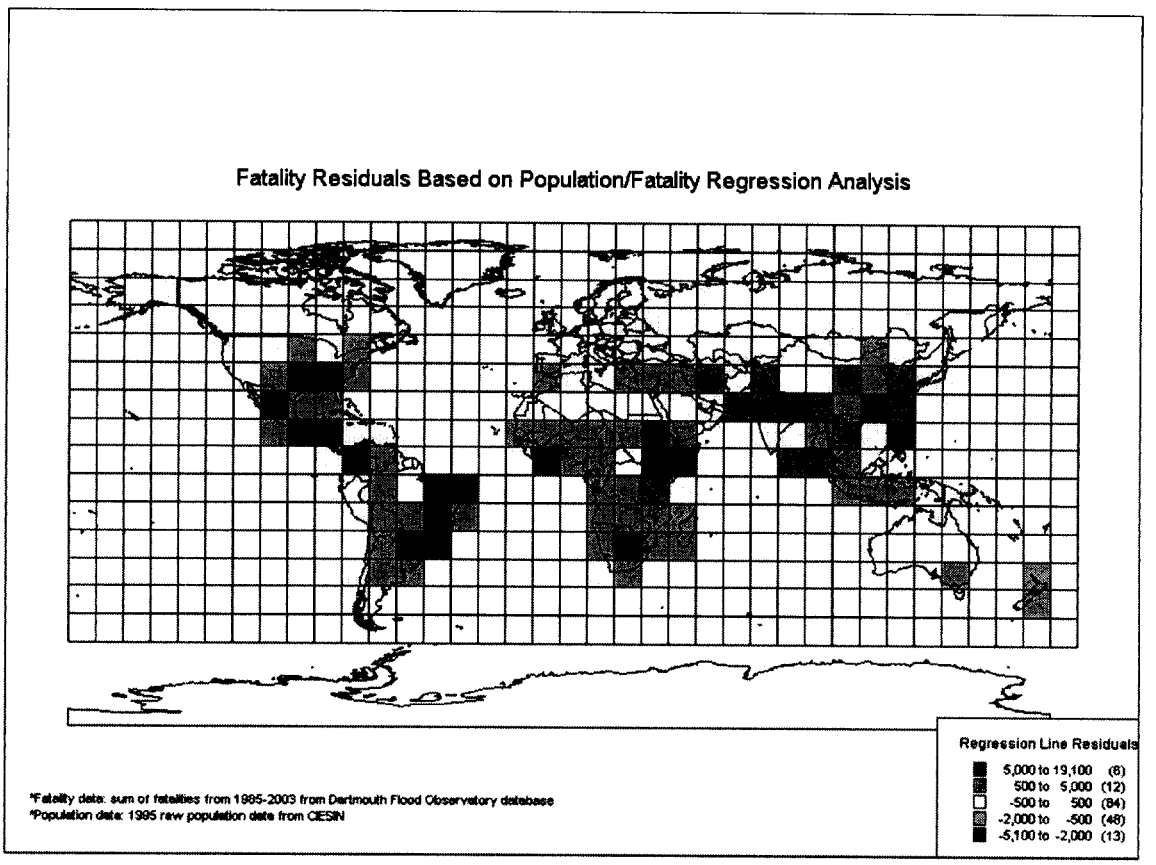

Figure 1. Comparison of actual fatalities from inland river flooding, 1985-2003 to local population density. Red areas have higher-than-expected fatalities.

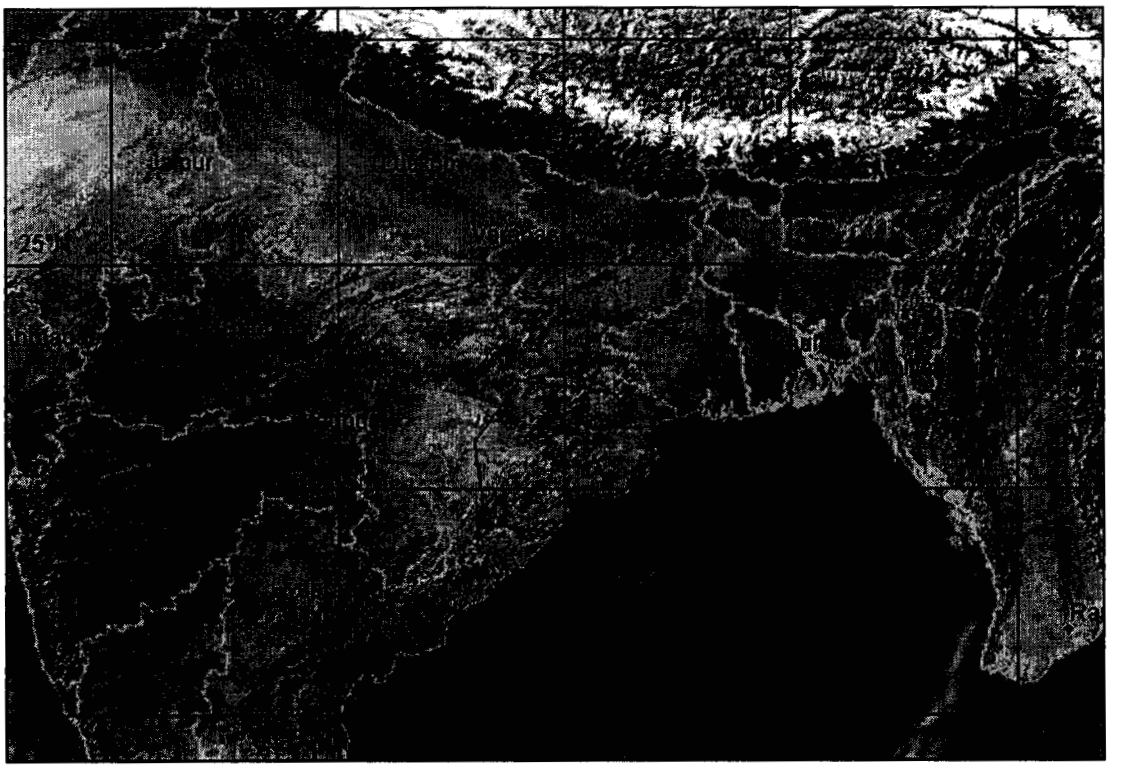

Figure 2. Area-affected map for flood in Orissa, DFO-2003-225, September-October, 1993.

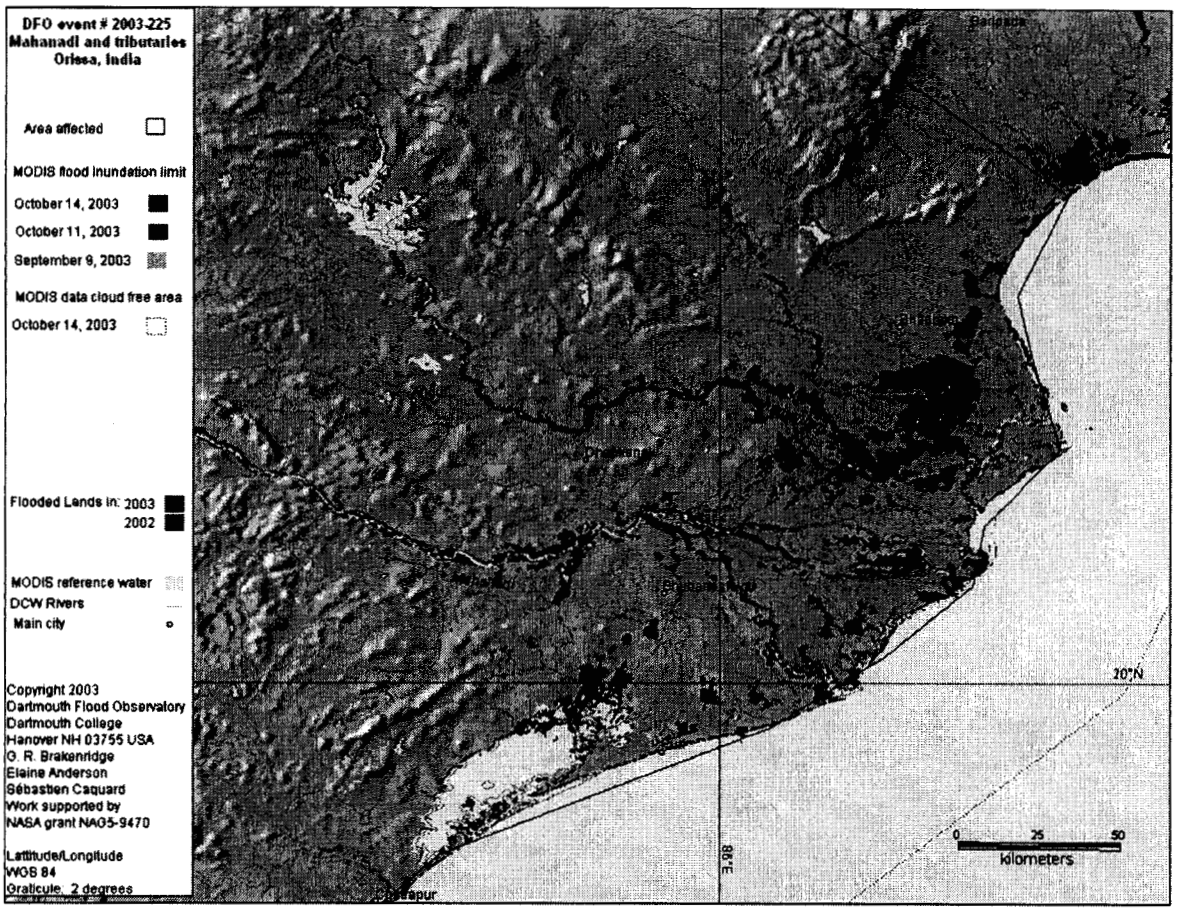

Figure 3. Rapid Response Inundation Map, showing the results of repeat MODIS imaging, Orissa Flood, September 9-October 14, 1993.

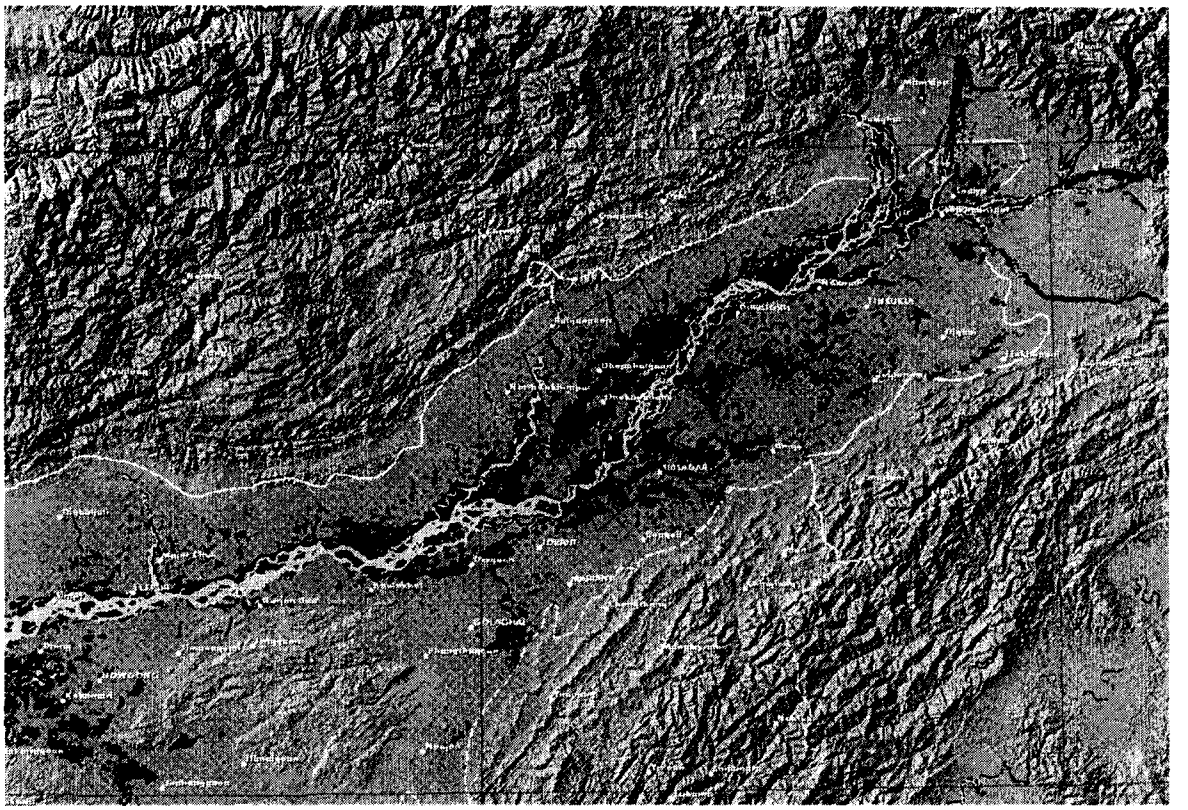

Figure 4. Portion of the Flood Hazard Map for the Brahmaputra River prepared for this conference. Light blue is Dartmouth's "standard reference water" which is that water seen on a routine basis by the NASA MODIS sensor during non-flood intervals. This is a GIS vector layer, as are all blue and green colors, but is based on standard water classification techniques using the MODIS image data. Dark green is flooding observed in 2004, and purple is flooding observed in 2003; other years are represented in other colors on the map. Gaging reach 79 is outlined in black and is being monitored by the U.S. MODIS, SeaWinds, and AMSR-E sensors aboard the TERRA, QuikSCAT, and AQUA satellites.

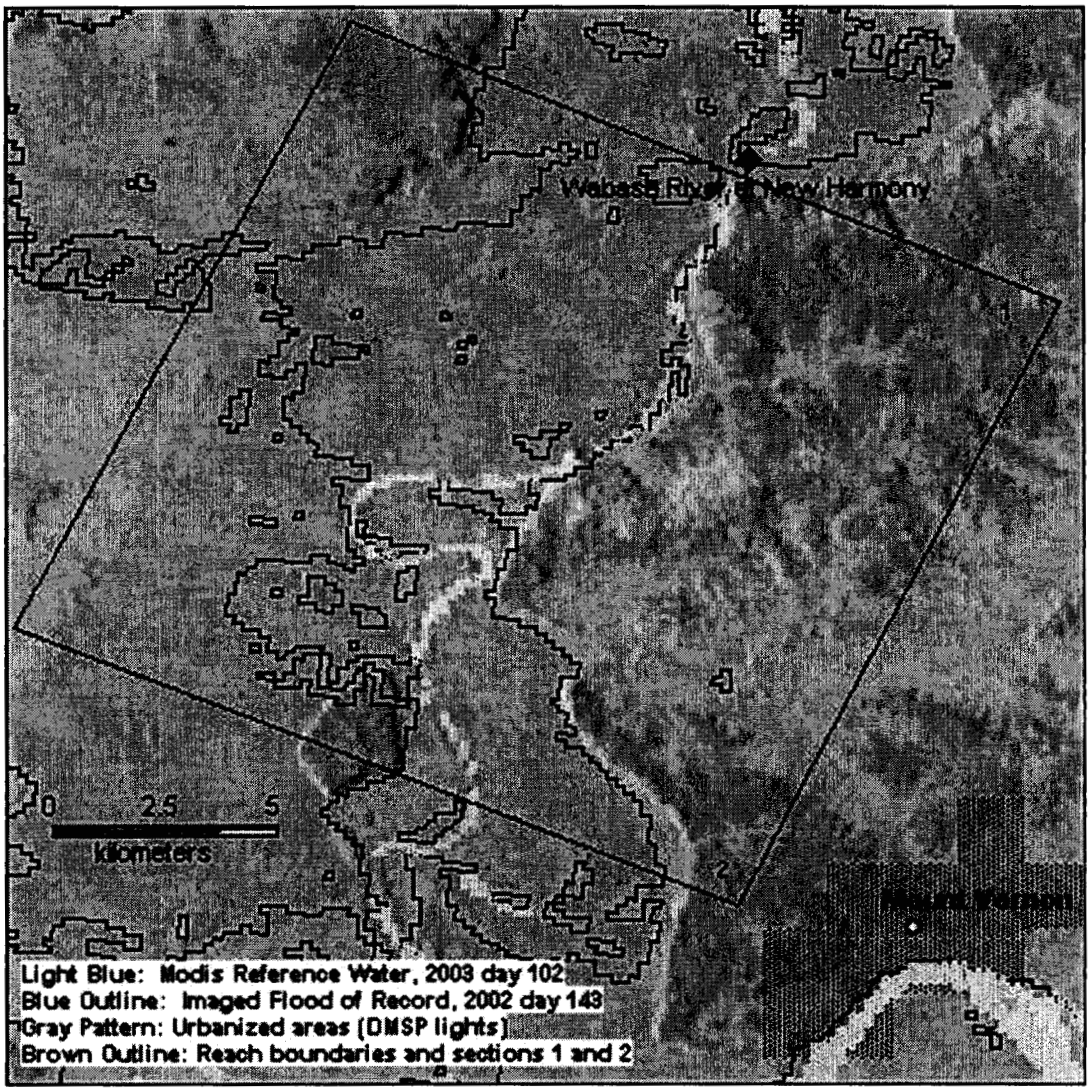

Figure 5. A typical gaging reach, here defined for the Wabash River, central U.S.

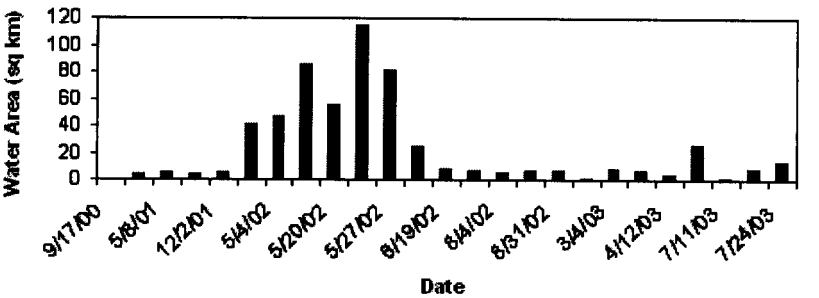

Figure 6a. Series of MODIS surface water areas for the Wabash gaging reach.

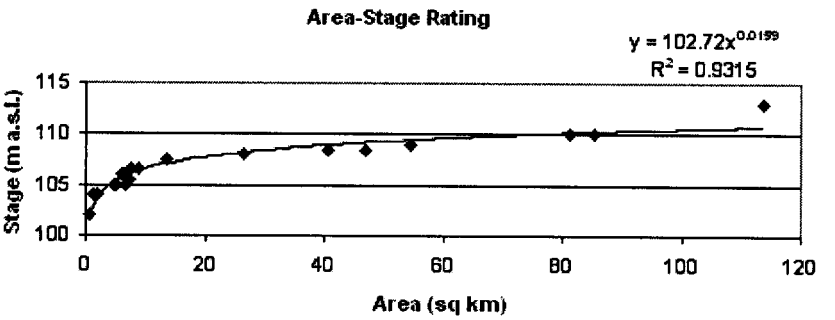

Figure 6b. Relationship of reach water surface area to flood stage (water level).

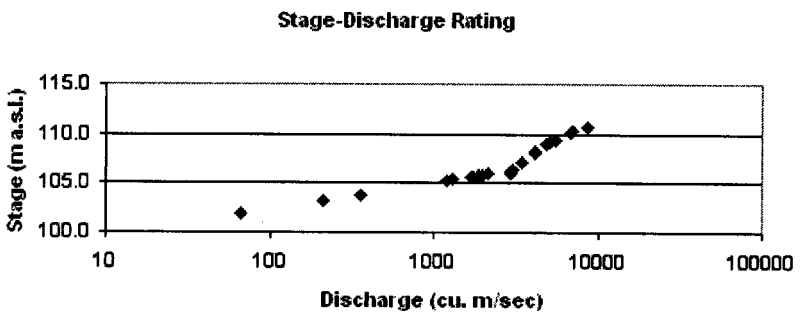

Figure 6c. Reach stage-discharge rating.

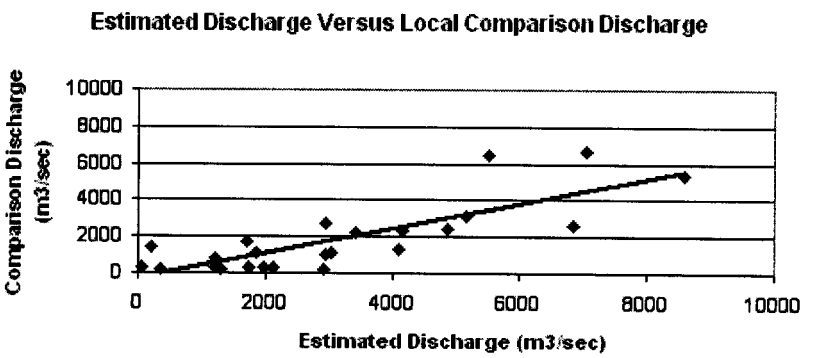

Figure 6d. Comparison of MODIS-estimated discharge at the reach to that measured at a local gaging station.

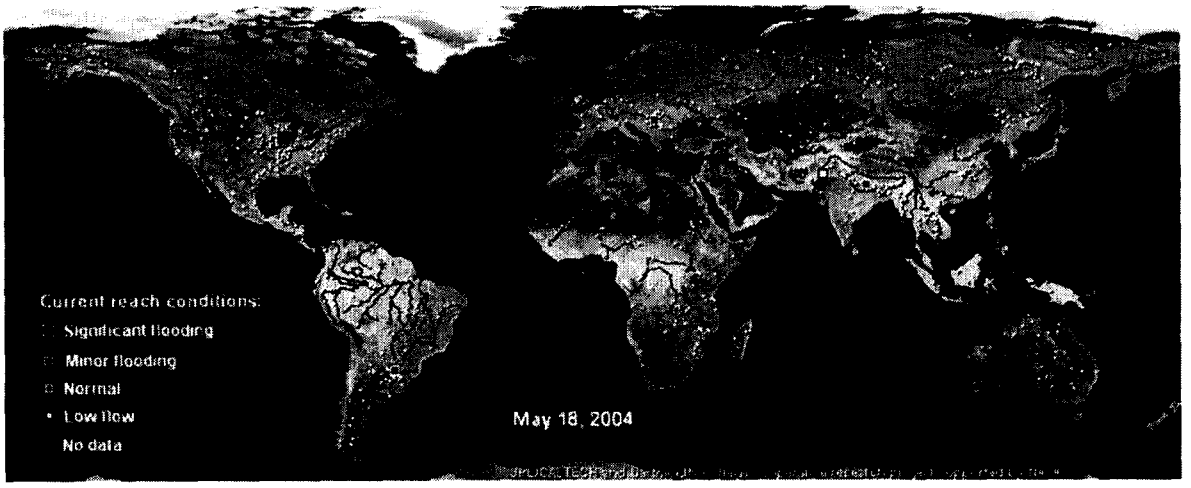

Figure 7. Global map of gaging reaches. This display is being developed in order to access AMSR-E soil moisture measurements over each reach.

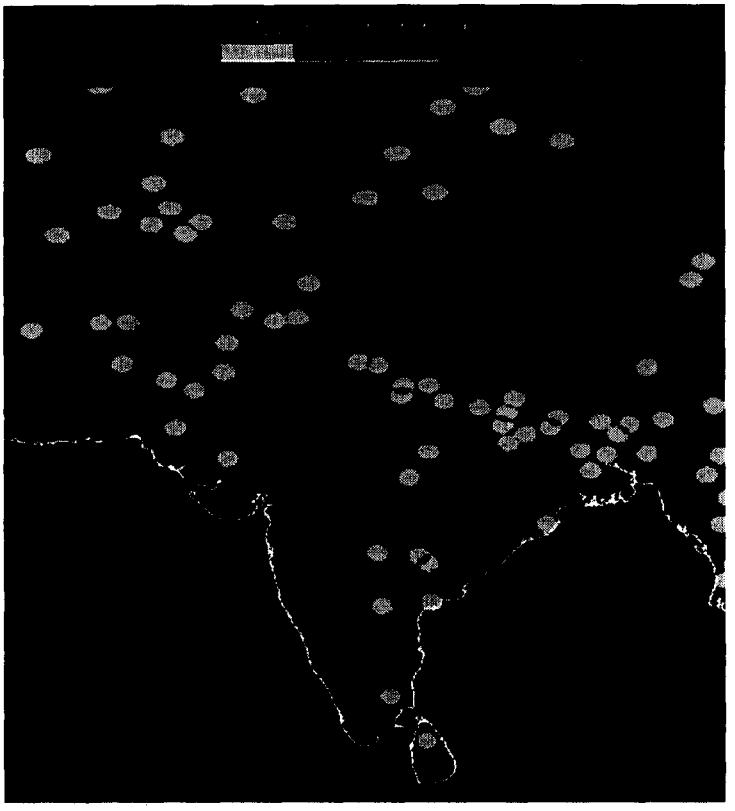

Figure 8. Expanded reach array under development for India. The locations shown are masks for analysis of QuikSCAT/SeaWinds radar polarization ratio data processed by Nghiem at JPL.

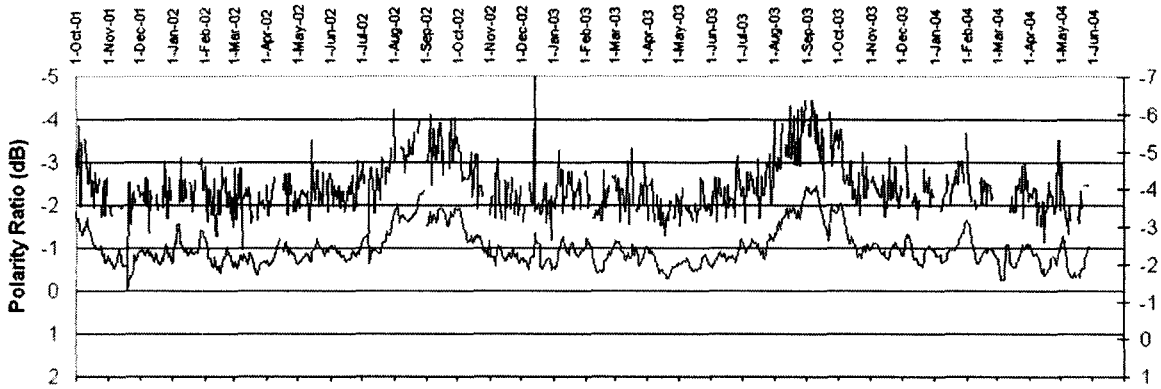

Figure 9. Time series of SeaWinds radar polarization ratio data (7 pixel average) over the Gandak River gaging reach. Three monsoon seasons are shown. More negative ratios indicate greater surface water area extent within the reach.