

**Mapping of Flood Events and Estimation of River Flow
in Latin America and the Caribbean**

**A Joint project by the Darmouth Flood Observatory
and the GeoSUR Program**

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Project Summary

Introduction to the Flood Observatory

The Dartmouth Flood Observatory (DFO) is a not-for-profit entity. It is part of the University of Colorado, USA, and has been operating since 1995. Because of its global scope, it produces data products of utility to GeoSUR, as its staff (<http://floodobservatory.colorado.edu/Staff.html>) performs work under a variety of research grants (from NASA, the European Commission, and other organizations). DFO benefits from the extensive computing/IT infrastructure provided by its major research university home. Its mission is to:

- 1) Acquire and preserve for an international public a digital map record of the Earth's remotely sensed changing surface water, including changes related to floods and droughts;
- 2) Conduct remote sensing-based measurement and mapping of surface water changes, when appropriate, in "near real time", and make immediately available the GIS files underlying the resulting maps, so that they may be incorporated into end-user decision-support systems; and
- 3) Support and encourage operational and scientific uses of remote sensing-based surface water information, including both map and numerical data.

DFO partners with operational water organizations such as the U.S. Geological Survey for further development of technical capabilities, and to participate in meeting their operational needs. The Observatory also actively collaborates with international relief agencies, emergency managers, and the global re-insurance industry during and after major flood events, to provide independent and objective information concerning flood inundation severity and extent.

Two DFO Remote Sensing/Data Product Activities

1) Near-Real Time Flood Mapping and the "Surface Water Record"

DFO currently ingests several automatically-generated, near-real time surface water-related data products, which its personnel have helped develop and design. The first of these is the *NASA MODIS NRT Surface Water product*; DFO uses these data to make flood maps with global coverage. The initial data product is generated at NASA Goddard Spaceflight Center (GSFC) in fully automated fashion and with a data lag time of only several hours; the resulting product is transmitted to DFO as it is produced. However, at present, these "flood water extent" GIS polygon data must be manually further processed: for different regions and as major flooding occurs. Thus, although the raw data provide full global coverage, daily, the production of the high level Surface Water Record (Fig. 1) regional maps at DFO, although routine, is not yet automated. The details of the complete present system, including production at GSFC and the special nature of the Record displays are now provided.

The two NASA MODIS instruments provide twice-daily, global coverage at 250 m spatial resolution in two optical bands (floods larger than ~ .5 km in width are mapped). The [LANCE- MODIS](#) processing system at NASA GSFC, initiated in early 2010, produces daily, projected and geocoded, corrected band 1 and 2 reflectance products within a few hours of satellite overpass. The Terra-MODIS equatorial overpass is at ~10:30 AM local solar time, and Aqua-MODIS is at 1:30 PM. Although other orbital instruments provide higher resolution data, none provide global daily coverage at this high a spatial resolution.

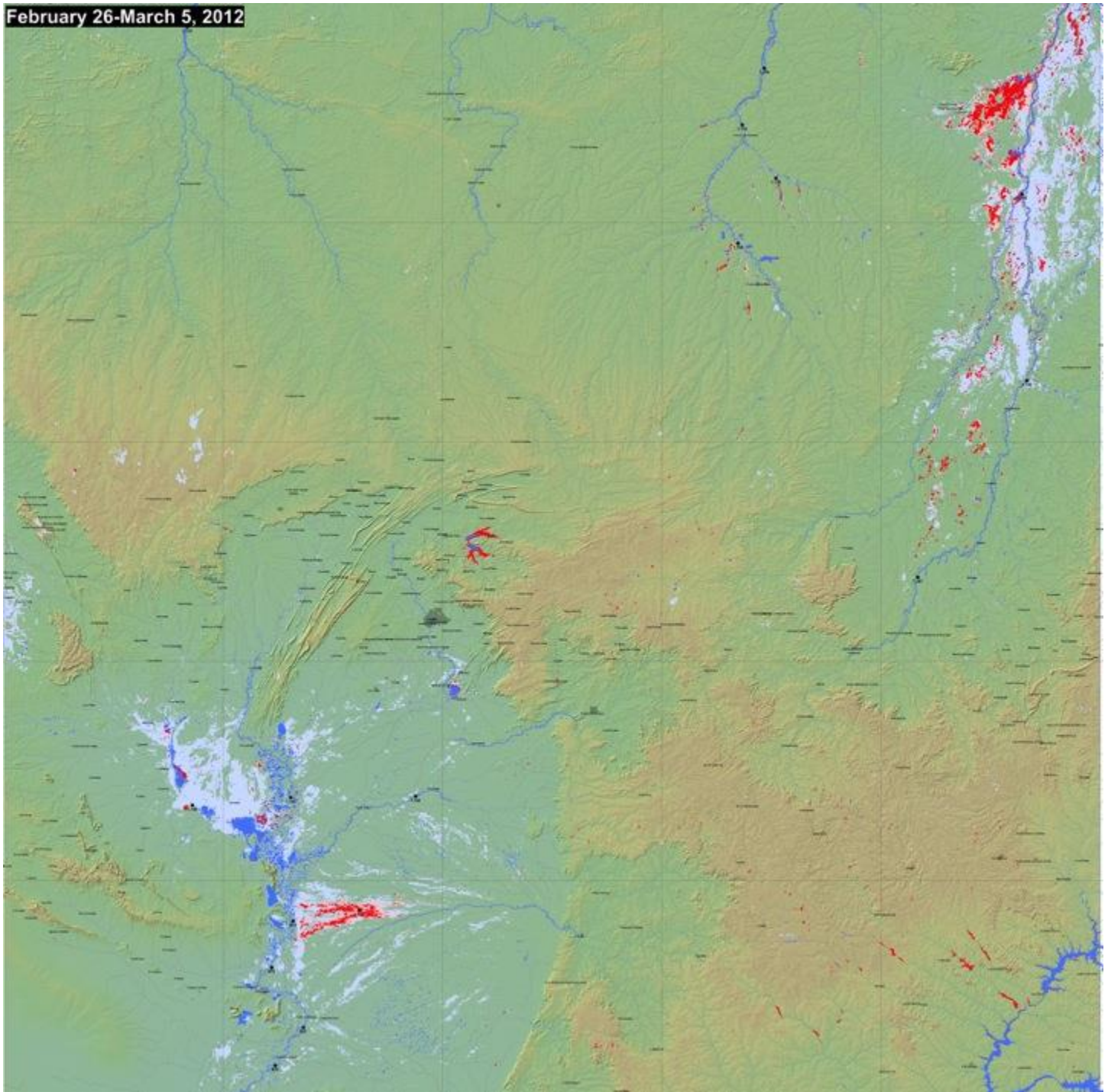


Figure 1. Reduced-scale sample DFO “Surface Water Record” web display (sheet 060W010S, coordinates refer to NW corner, scene includes portions of Bolivia, lower left and Mato Grosso, Brazil). Red: current flooding during present 10-day accumulation phase; light red, previous flooding, same year; light blue, previous flooding, 200-2011 dark blue, reference “normal” surface water. Data including geotif, kmz, and .shp formats accompany each display. See also: <http://floodobservatory.colorado.edu/Version2/060W010SSWR.html>. The Record approach is unique to DFO flood mapping: previous flooding is stored and illustrated even as current conditions are monitored.

This spatial resolution is sufficient for mapping many flood events and including seasonal surface water changes (Fig. 1). Eventually, VIIRS (newly-launched) data at a similar spatial resolution can be incorporated.

From MODIS data, water is detected using a ratio of Band 1 and Band 2 surface reflectance data in each 10 deg. lat. X 10 deg. long. LANCE reflectance product land area. LANCE (Land Atmosphere Near Real Time Capability for EOS) is an expedited (< 3 hrs) data distribution for the Terra, Aqua, and other NASA satellites. The water classification is accomplished by: $(\text{band2} + A)/(\text{band1} + B)$, with constants A and B determined empirically. Below a numerical threshold, all pixels are classified as water and all above as land. Threshold values have ranged, as experience was gained with this algorithm, from 0.6 to 0.9. Numerical thresholds in band 1 and 7 data are used to remove clouds and partially shadowed clouds.

The output from the GSFC automated processor that ingest the LANCE data includes an updated (new file) raster of water versus land pixels, and also a GIS (.shp file), with polygons fitted around all classified water areas, including individual pixels. See [Brakenridge *et al.*, 2012a; Westerhoff *et al.*, 2012] for more information.

Unfortunately, during times of cloud cover these optical data provide no information, even though what is most needed by end users is ready access to *the most current information known* about a flood in progress. To address this need, DFO manually ingests the automated .shp file output, and incorporates these into 10 day accumulation products and the “Surface Water Record” (Fig. 1). These displays, published online at full MODIS resolution (as jpeg files within individual map sheet .html files), and also as full resolution OCG-compliant geotif and kmz files, provide information that is relatively independent of current cloud cover. We stress, however, that this is not presently an automated product or one supported by other agencies. The Record displays are only intermittently refreshed, at present, and in response to specific large flood events and perceived value of such updates. There is no dedicated funding for this activity for any region, but instead intermittent map updates are supported as part of the grant support that is for their development.

In this regard, however, and as part of its overall mission, DFO specializes in the large-area, frequent-update capability provided by the NASA MODIS sensors, and also, uniquely, in *storing the* flood imaging results over the years: to produce a research-grade digital map “Surface Water Record” of where flooding has occurred and been mapped (Fig. 1), while also depicting where change is occurring at present. This allows ongoing flooding to be immediately placed into the useful context of “how large” the event is compared to previous events.

Although MODIS provides a consistent data source, during major flood events, other, higher spatial resolution sensor data commonly become available (e.g. though such mechanisms at the *International Charter for Space and Major Disasters*). During such events, DFO commonly also uses these data, incorporates the mapping result into the relevant Surface Water Record and any special flooded area-focused maps and displays, and makes available the source GIS files if data restrictions allow.

DFO thus collaborates with other flood responders, such as the *Charter* (<http://www.disasterscharter.org/home>), by sharing the generated data products. Where GIS data are publically available, the Record incorporates higher spatial resolution flood products which UN-supported entities such as UNOSAT create on a case-by-case basis. However, experience at DFO over the years indicates that the “always-on” capability provided by the two MODIS sensors and related (free, near real time) data systems are uniquely valuable. They are continuously available for all land areas, and do not require Charter activation or high resolution satellite acquisition planning to produce immediately valuable flood extent map data. For example, following the catastrophic landfall of Hurricane Katrina over the Gulf Coast, USA, MODIS provided the first coverage of the major flooding caused by that event and within only hours of landfall [Brakenridge *et al.*, 2012a]. More recently, flooding in Mozambique was first captured by MODIS and mapped by DFO: (<http://floodobservatory.colorado.edu/Version2/030E020SSWR.html>).

Through this approach, the Surface Water Record approach is producing, as each flood event is observed and incorporated, 10 deg x 10 deg quadrangle maps of future flood hazard, simply by preserving the long term

record of where flooding has actually occurred. We consider that it is imperative that this map record of past flood events be preserved for easy access, in both map and GIS data form, for future use by development agencies, reinsurance companies, local governments, other private industry, and society in general.

The present proposal is for work needed for production and automation of the Surface Water Record displays for all of Latin America. Once accomplished, end users will be able to, on a daily basis, access geospatial information for not only current flood extent (red areas in Fig. 1), but also the complete, 2000-present record of flooding in the area of interest. As well, many man-made reservoirs show significant water area variation at this scale, and the historical MODIS-based data can be used to characterize reservoir operations, and, potentially monitor water storage changes [Birkett and Brakenridge, 2013].

2) Satellite-based River Discharge and Watershed Runoff Measurements

In collaboration with the European Commission Joint Research Centre (JRC), DFO is providing to the public a second operational output, which, unlike the high-end mapping, has already been fully automated at DFO. The GDACS/DFO “River Watch” river discharge measurements have a period-of-record from 1998-present (<http://floodobservatory.colorado.edu/CriticalAreas/DischargeAccess.html>). Fig. 2 shows a subset of the existing River Watch global display, which also provides links to discharge data retrieved for the marked sites. River Watch provides both: 1) a geographic display over large areas, indicating which watersheds are currently experiencing unusually low river flow (hydrological drought) or flooding, and 2) the remote sensing-based discharge values and time series back to 1998 of each measurement site (Fig. 3). Further calculations using the discharge data and contributing watershed areas also allow the analyst to produce, for example, watershed runoff anomaly displays (Fig. 4).

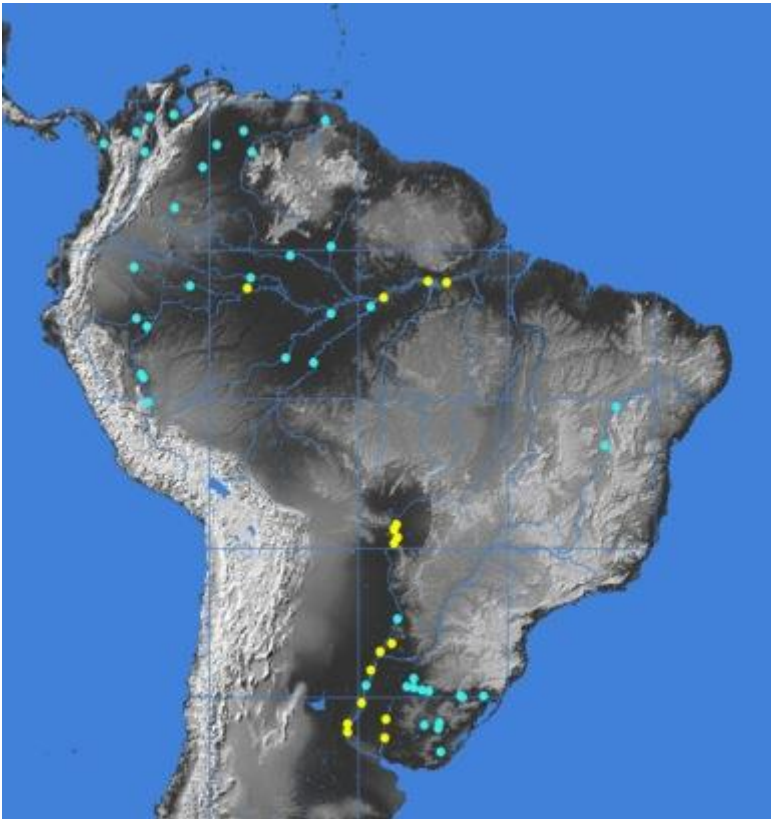
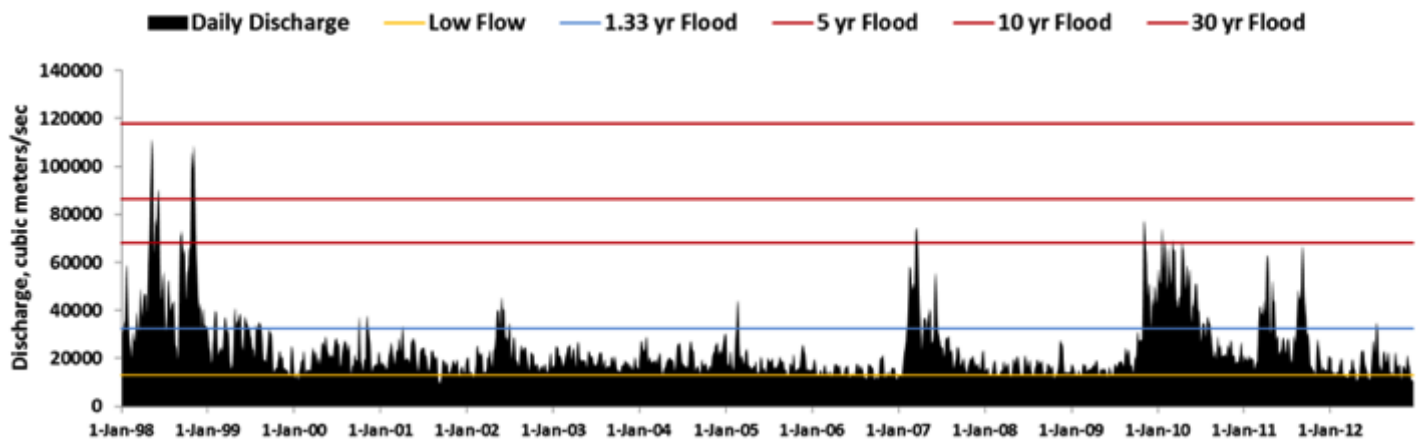


Figure 2. *Subscene of DFO’s current “River Watch, Satellite River Discharge Measurements” global display, with clickable links to the individual river measurements site. See online version at: <http://floodobservatory.colorado.edu/CriticalAreas/DischargeAccess.html>. The map sheet boundaries of the Surface Water Record displays are also illustrated by the light blue 10 deg. latitude and longitude graticule.*



Satellite microwave sensors provide global coverage of the Earth’s land surface on a near-daily basis and, at

Fig. 3. The 1998-present flow record of Site 822 along the Parana river, Argentina provides a sample of the South American River Watch output (see site locations in Fig.2). Present status is low flow (yellow dot on the Fig. 2 display); previous flooding at intervals illustrated above triggered display symbol change to red. The numerical discharge daily time series is also available from this site’s web location: <http://floodobservatory.colorado.edu/SiteDisplays/822.htm>.

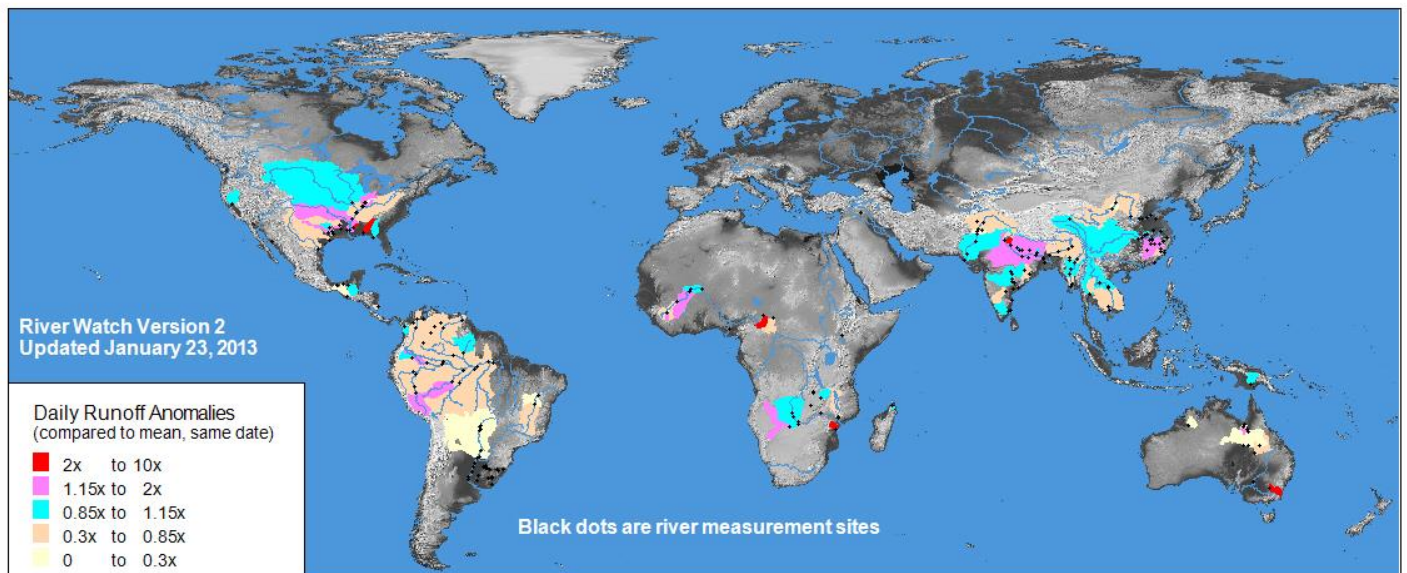


Fig. 4. Global map of River Watch-based watershed runoff anomalies for a recent date. This display is presently automated and operational; a better runoff anomaly display would calculate 7-day runoff totals as compared to the mean, same date (1998-2011). As well, many sites in Latin America remain to be installed online, and matched with associated contributing watersheds. Plans are to create more detailed, large scale displays: for the Caribbean and for all of Latin America. See also: <http://floodobservatory.colorado.edu/RunoffAnomalies.html>.

These data and associated displays are novel research products, but they have already shown much promise for operational applications. For example, our colleagues at GDACS (the European Commission’s Global Disaster Alert and Coordination System) are now using the same data to provide near real time global flood alerts: <http://old.gdacs.org/flooddetection/> [Kugler and De Groeve, 2007]. 10,000+ river measurement points are being monitored daily at GDACS; from these, DFO is progressively calibrated individual sites to actual river discharge units (~ 200 world-wide; Figs. 2-4). The DFO site analyses, also proceeding daily, calculate

hydrological statistics and time series that allow more rigorous measurement of flood magnitudes, durations, etc. Some further discussion of this technology follows.

River Watch 2 uses satellite microwave sensors that provide global coverage of the Earth's land surface on a near-daily basis. At certain microwave wavelengths, there is very little interference from cloud cover (floods can be observed and measured even when the ground surface is obscured from optical sensors such as MODIS). Using a strategy first developed for wide-area optical sensors [Brakenridge *et al.*, 2005], such data can be used to measure river discharge changes [Brakenridge *et al.*, 2007]. As rivers rise and discharge increases, floodplain water surface area increases. Microwave emission over river measurement sites, observed from space, can monitor such changes, and with greater precision than was previously recognized.

Transformation of the remote sensing signal to actual discharge values is accomplished via use of a rating equation (as the case for gauging stations on the ground). For River Watch 2, the calibrating discharge values are obtained via runs of a global runoff model (WBM). Five years (2003-2007) provide abundant data for calibration. The model is run to produce daily discharge values for these years, at each measurement site (the global model grid resolution is 10 km). As shown on the site displays (click "obtain data" on each site), a signal-discharge rating curve results. The rating curve equation then transforms all daily signal data, including new data, to discharge. A recent paper describes the calibration procedure in more detail [Brakenridge *et al.*, 2012b]; there is also a technical summary: <http://floodobservatory.colorado.edu/SatelliteGaugingSites/technical.html>.

Because a river reach, ~10 km in length (one pixel in the microwave image), is used to sense discharge changes, it is important that the pixel include a relatively uniform stretch of river without major tributary junctions, nearby streams, or other variable water bodies. Local site characteristics strongly affect the sensitivity and signal/noise ratio of this method. Each site display provides a link to visualize the measurement pixel (river and floodplain reach) being used as the monitoring site (e.g.: <http://old.gdacs.org/flooddetection/area.aspx?id=822>). Many more sites (in Latin America and the Caribbean, at least several hundreds) can be added, and at locations provided by local workers and according to their needs for discharge information. However, each site must be individually quality-controlled so that the above, and other, factors are considered.

The approach is novel in that microwave sensors (TRMM, AMSR-E) previously used mainly to monitor the atmosphere and precipitation are here employed to directly measure river discharge changes and watershed runoff. This is an unexpected capability. It came about because, in order to measure atmospheric conditions, such as precipitation, ground-sensing channels were included on the satellite missions to provide a comparison (background) component of upwelling microwave radiation. River Watch 2 uses just these channels to monitor surface water changes. River Watch 2 replaces an earlier version that used only AMSR-E and a different calibration-to-discharge method; it is now running forward in time using only TRMM information (AMSR-E has ceased operation). AMSR-2 information will be added as it becomes available in early 2013.

Discharge data are fundamental for observation of *surface runoff* (commonly expressed as discharged water volume/watershed area, in mm). Daily runoff maps showing runoff and runoff anomaly values for each watershed associated with a discharge measurement site are presently online. 7-day accumulated runoff and runoff anomaly displays can also be provided. A research paper is in preparation that further quantifies error statistics of this approach. [Cohen *et al.*, in preparation, 2013]. River Watch data have already been demonstrated to be useful in improving long term river flood forecasts [Hirpa *et al.*, 2013].

The present proposal is for work needed to: a) increase the number of GeoSUR-region river measurement sites from the current 55 to between 1,000 and 2,000 sites; b) provide for input from regional specialists in the location and installation of at least these new sites, more if possible given the time needed; and c) further test the accuracy and precision of these remote sensing-based results by comparison to local ground station data; so that error estimates can be added to the discharge and runoff

information. All sites would be added during the first year; two years of operation are needed in order to perform the necessary quality control/end user interaction and comparison (where locally available) ground station data.

Maturity and Automation of Data Products

As noted, the MODIS-based water mapping poses unique benefits because of the deliverables: sustained (twice-daily since early 2002) frequent repeat, wide area coverage; rather than ad hoc, after the event, imaging only at time steps determined by sensor availability and orbital parameters. Both are useful during flood events, many of which occur over large areas and long periods of time, but which cause the most damage in specific areas which should be imaged and mapped in detail.

The automated GSFC global flood processor is already operating and is being enhanced, and is (now manually) combined with further processing at DFO and its historical archive. A large amount of water area data have been and are now being generated, including in .shp file GIS format: the challenge is integration, synthesis, and dissemination of useful end results. The DFO mapping system output is already being used, on a per event basis, in operational disaster responder environments, including within the World Food Programme and the International Red Cross. Its level of maturity is high; ready for operational users even with the issues considered below. However, only an automated product can be sustained at low personnel cost. The present work is to accomplish that task for an important and large region: all of Latin America, and in collaboration with the GeoSUR project. Unlike commercial vendors, using in some cases commercial sector satellite imagery, both our source data and the DFO display and data outputs are public, and licensed only under the “Creative Commons” approach which allows free use provided the source is cited.

In contrast to the mapping products, River Watch is already more fully automated, but the capability is relatively new and the associated errors need to be quantified more fully. Newly published research has incorporated the River Watch river discharge measurements into flood prediction models, so this practical use has been demonstrated. It is also being used, as noted, to provide flood alerts and flood warnings. DFO, in cooperative work with GeoSUR participants, seeks further demonstrations of its utility as we work to improve, validate, and publicize this product. Also, because the quality of the data are dependent on the choice of measurement sites, considerable personnel effort needs to be expanded on examining the sensitivity and quality of data output from each site; possibly deleting some sites from the array, and adding the many more sites needed to address regional water measurement needs.

There are in fact technical issues under active scrutiny affecting also the map products. DFO can assist GeoSUR users in understanding these, so that the data have maximum and most widespread utility. The following are some examples, which will also allow further reviewer assessment of the level of maturity of these data products and the on-going efforts to improve them.

1) Under conditions of relatively low sun angle and abundant scattered cumulus cloud cover, the 4-image compositing procedure does not remove all cloud shadows, and results in intermittent errors of commission (land pixels misclassified as water). This is being addressed by extending the compositing period to 3 days/6 images, so that more than 2 “water” class results are required for a final water identification. Alternatively, the GSFC team is also presently pursuing a sun-angle-based approach as well towards masking cloud shadows. We are together examining, with NASA funding support, which product provides the highest quality results. At

present (January, 2013) it appears that the 3 day/6 image processing method does minimize the cloud shadow errors and is an acceptable solution, but that, in other regions, the 2 day/4 image product is more sensitive. Thus we anticipate providing recommendations on each map sheet over which GIS product is the best choice.

2) Terrain shadowing remains a source of persistent errors of commission in upland areas. Such shadowing is always misclassified as water. A solution may be to implement a “height above nearest drainage” algorithm, create a mask, and use this mask to remove such errors. This is presently being tested at GSFC and in collaboration with DFO and a team at Deltares, the Netherlands.

3) We earlier observed minor geolocation errors in higher latitudes areas (possibly including southern South America). DFO and GSFC team members are currently working with the NASA LANCE-MODIS facility to determine how and when such errors are being locally introduced into the 10 degree surface reflectance composites generated at LANCE. In general, the MODIS 250 m information is geolocated to within +/- 50 m, so with quite acceptable level of accuracy.

Work Tasks and Deliverables

The tasks will be performed by two researchers: Prof. Robert Brakenridge, and Dr. Albert Kettner, both senior research scientists at the University of Colorado (their vitae are below). The first leads this work and will be responsible for overall project success, the second provides important skills in GIS and its automation.

A work period of two years is planned, in order to:

- 1) Complete and update the Surface Water Record map sheets for coverage of all of Latin America and the Caribbean;
- 2) Automate these displays, so that they update daily as the new GIS data arrive from GSFC;
- 3) With input from regional workers and GeoSUR, create and install between 1,000 and 2,000 new River Watch river measurement sites and associated watershed displays for Latin America and the Caribbean, and including access to the discharge and runoff data output;
- 4) Test and automate the new displays;
- 5) Accomplish visits to regional workers involved with GeoSUR in Latin America and the Caribbean; host one visit of CAF/GeoSUR personnel at DFO.
- 6) Continue to run all processing systems forward during the second year, fix errors, perform routine maintenance (e.g. some updating of format of each display will be needed with the arrival of 2014), and cooperate with GeoSUR-related personnel to ensure a smoothly functioning, high quality, and useful system.
- 7) Prepare for long term, post-2015 fully-automated production and dissemination of the data products to GeoSUR at very sustainable maintenance costs.

The deliverables are as follows:

- 1) Five customized River Watch access displays prepared for the GeoSUR region, maintained and updated online at the Flood Observatory web site and mirrored at GeoSUR if desired.

These (daily update) displays and data include:

a) river measurement site status as colored point symbols: Yellow dots: low flow (<50 % mean daily runoff for this date); Blue dots: normal flow; Purple dots: moderate flooding (>1.33 yr recurrence); Red, major flooding (> 5 yr recurrence). Period of record for the sites begin January 1, 1998. The Log Pearson III distribution is used for recurrence interval calculation.

b) daily and weekly watershed runoff, expressed in mm, depicted as 5-interval color shading (e.g., Fig. 4).

c) daily and weekly watershed runoff anomalies, in percent, with runoff values compared to average of same dates during the preceding period of record. The displays should provide much greater detail than the global example shown in Fig. 4, but still be easily viewable online. GeoSUR can provide input regarding best geospatial format for import of such graphics into its portal. A 7 day accumulation of runoff is desirable in order for comparison to several precipitation products for the region, as well as runoff modeling.

- 2) Increase in the number of automated and online River Watch sites in this region from 55 to between 1,000 and 2,000; location of new sites chosen with input from GeoSUR-related personnel.
- 3) Manual production and update of all Surface Water Record displays covering the region. Then, full automation of each, such that: current surface water is updated daily (and any flooding) is thereby mapped, cloud cover permitting, in near real time, and in the context of previous flooding and normal seasonal water variability. Related GIS and OCG-compliant files to be accessible from both DFO and GeoSUR web pages, so that organizations within the region can import such surface water extent data into their own systems and as well visualize the updated map displays.
- 4) Continued collaboration is underway with the NASA GSFC team to support improvement in the MODIS NRT GIS daily product (DFO's role is validation and testing). If expected NASA funding occurs, the product will be back-processed at least four years. These archival water extent data will also be made available to GeoSUR and, as well, incorporated into the Record displays to provide more accurate knowledge of maximum flood limits reached during the extended time period.
- 5) In collaboration with GeoSUR, consider implementation of both data products in the GeoSUR Regional Map Viewer.
- 6) Accomplishment of two visits to GeoSUR region to hold 2 meetings in Latin America and the Caribbean (one with specialists to show them the system and one with managers to promote its use). CAF to cover all travel and meeting expenses staff. Also, host one site visit of CAF personnel to DFO and to explore further collaboration.

- 7) Prepare total cost estimate for continued, fully automated systems operation after year 2. Also explore possible implementation of a user subscription service to defray these costs.

Work Schedule

Schedule for the work tasks and deliverables is for two years, March 1, 2013-February 28, 2015. Anticipated sequence of work is and planning deadlines are:

- a) River Watch-related work, including new displays and full automation, to be completed by July 15, 2013.
- b) Manual production and updating of complete Surface Water Record coverage by September 15, 2013.
- c) Two work visits to GeoSUR to be accomplished by June 15, 2014. The first visit should occur early in the project period so that the maximum input from GeoSUR and CAF be realized in early stages of the work.
- d) Hosting of visit to DFO/University of Colorado by GeoSUR/CAF personnel (flexible).
- e) Trial automation of the Surface Water Record displays by March 1, 2014.
- f) Successful forward operation of both data products in near-real time, March 1, 2014-February 28, 2015.
- g) DFO will provide a Final Report at the end of the project period describing all of the work accomplished.

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