TOWARDS A NEAR-REAL TIME GLOBAL FLOOD DETECTION SYSTEM (GFDS)

Zsofia Kugler[a], Tom De Groeve[a], G. Robert Brakenridge[b] and Elaine Anderson[b]

[a] Joint Research Centre, Ispra Site, European Commission, Ispra 21020, Via Fermi 1, Italy – tom.de-groeve@jrc.it, zsofia.kugler@jrc.it
[b] Dartmouth Flood Observatory, Dartmouth College, Hanover, NH 03755, USA – G.Robert.Brakenridge@Dartmouth.EDU, Elaine.Anderson@Dartmouth.EDU

Commission VI, WG VI/4

KEY WORDS: Flood detection, passive microwave, AMSR-E, global monitoring, orbital gauging

ABSTRACT:

The methodology for flood detection developed at Dartmouth Flood Observatory (DFO) (Brakenridge and others, 2007) on a global scale, was implemented at the Joint Research Centre (JRC) of the European Commission on an automatic operational basis. The technique is using AMSR-E passive microwave remote sensing data of the descending orbit, H polarization, 36 GHz band to detect flood events from space around the globe with a daily temporal resolution. DFO was formerly using the daily global composite images having 3 days of lag in time whereas JRC implemented the model on the near-real time swath data available about 24 hours after acquisition. A ratioing of the water/dry signals described in the article are considered as a tool to observe surface water area changes. Thresholding the calculated observation ratio allows the detection of riverine inundation events. Validation of the model results is ongoing. Nevertheless, preliminary results show a promising correlation of the increase in river discharge on-site and changes at the observed signal of the sensor. Thus following the technique the detection of flood events in ungauged and inaccessible remote river channels is feasible from space.

Software was developed at the JRC to automatically acquire and process the remotely sensed data in real time on an operational basis. After the validation and calibration of the satellite based near-real time Global Flood Detection System (GFDS) the remotely observed flood events are planned to be integrated into the Global Disaster Alert and Coordination System (www.gdacs.org/floods). GDACS is running at the JRC providing near real-time alerts about natural disasters around the world and tools to facilitate response coordination, including news and maps.

1. METHODOLOGY OF THE GLOBAL FLOOD DETECTION SYSTEM (GFDS)

1.1 Introduction

The Global Flood Detection System (GFDS) is part of the Global Disaster Alert and Coordination System (GDACS), which aims at providing near-real time information for rapid and effective humanitarian response to natural disasters. GDACS is a project of the European Commission and the United Nations.

Of all natural disasters, floods account for more then 70% of human fatalities and property losses around the world. The severity of flood crisis can also be expressed by the frequency of their occurrence: they constitute almost 50% of the events among other natural hazards (CRED, 2006). For this reason the systematic monitoring of this phenomenon is essential in supporting sustainable and effective mitigation efforts.

As Bjerklie et al. (2003) and Fekete et al. (1999) stated, less than 60% of the runoff from the continents is monitored at the point of inflow in the ocean, and the distribution of runoff within the continent is even less monitored. Moreover, the number of operating hydrometric gauges is decreasing since the 1980s, the delivery time is often longer than several months, and there is a great spatial disparity in the gauges (Roux et al, 2006). The Global Runoff Data Centre (GRDC) is collecting a large set of river discharge data from in situ gauging stations with near global coverage (figure 1). However, such internationally-shared runoff data are provided as monthly mean values not daily values in near-real time.

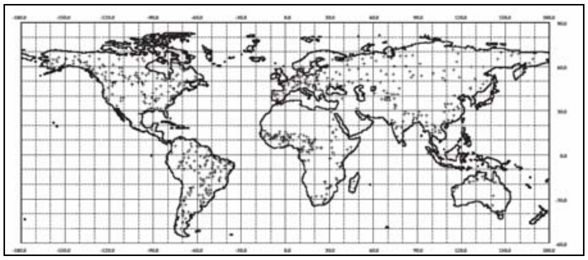

Figure 1. Best on-site gauging discharge stations around the globe collected at GRDC

Therefore, the use of remotely sensed information to derive hydrological parameters especially to monitor flood events could usefully extend or substitute for the missing measurements.

For this reason the Joint Research Centre (JRC) of the European Commission together with the Dartmouth Flood Observatory (DFO) joined forces to set up a global flood monitoring system from space. The aim of GFDS is to provide satellite based flow information around the globe substituting the missing on-site gauging in many parts of the world. The methodology discussed in the next chapters is based on Brakenridge and others (2007) and was implemented on a global operational monitoring scale at the JRC.

1.2 Related studies

The use of satellite based observations for river gauging measurements has the great advantage of enabling observations with a global coverage using one systematic methodology with a high repetition frequency. Moreover it has the potential to become a near-real time observation that supports rapid response to flood crisis around the globe.

Hydrographic data obtained from satellite systems and other remote sources offer the possibility of broad and potentially frequent global coverage of river discharge estimates (Barrett, 1998). Assessing river flow using remotely sensed data may then be a mean to increase the global stream flow monitoring network. Moreover, remote sensing is able to provide information over large areas, including those where ground-based data is difficult to obtain (Roux *et al.*, 2006).

The use of remote sensing tools in flood observations dates back to the early years of the first operational optical satellite systems like the Landsat Multispectral Scanner (MSS) in the 1970's and 1980's. Inundation maps were derived from satellite images in particular for flood events inside the USA (Smith, 1997). Activities of impact assessment using satellite images of the visible range is still ongoing in many scientific and also operational services (RESPOND, 2006) yet feasibility is significantly limited by cloud cover conditions.

For this reason many applications have flourished in the past using microwave remote sensing systems penetrating though the clouds for flood inundation area/stage or discharge estimations. Both passive microwave and active radar systems were studied and evaluated in their performance to support missing on-site gauging measures. However due to their different techniques results have provided different kind of information about river flow.

Besides using active systems for inundation area delineation (Hess 1995) radar altimetry was used in different studies (Brikett, 1998; Koblinsky, 1993) to measure stage elevation or changes directly. The well-known scientific study of Alsdorf (2000) and his group resulted in the measurement of water level changes based on radar altimetry over the Amazon acquired from the Space Shuttle Radar Topography (SRTM) mission. Interferometric phase observations could detect water surface elevation changes in cm range. Still, the SRTM mission was providing observations only over a short period. The technology could not be implemented on an operational basis.

Other applications were using passive microwave emission of the earth's surface to estimate inundation area. The first pioneer study of using passive microwave sensor data to estimate flooded area was set up by Stippel *et al.* (1994) in the Amazon basin using the Scanning Multichannel Microwave Radiometer (SMMR). The sensor was providing measurements from 1978 to 1987 and has been used to measure time series of water levels on very large rivers, such as the Amazon. Flooded areas were derived using linear mixing models of the microwave emission from major landscape units. The measurements of the SMMR instrument were only available in weekly intervals.

All these applications do not support operational daily observations and near-real time global coverage. For this reason the JRC together with DFO has developed a technique that uses passive microwave observations of Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) mounted on NASA EOS Aqua satellite together with the well known MODIS sensor (Ashcroft, 2003). Acquiring data on a global scale every day unrestricted by cloud cover enables surface water measurements from space operationally in near-real time. With current fast internet technology data can be delivered to the users in about one day after the acquisition. The U.S. National Snow and Ice Data Center (NSIDC) provides preliminary swath data available within 24 hours after the acquisition on board.

1.3 Methodology

The methodology aimed at setting up a routine that provides a systematic detection of flooding over river reaches around the world. The Dartmouth Flood Observatory (DFO) (Brakenridge, and others, 2007) developed a methodology to monitor river sites detecting flooding by using the difference in microwave radiation between land calibration parcels and water-including parcels along the rivers to be monitored. On global daily near-real time basis AMSR-E (Ashcroft, 2003) is providing the observations for the flood monitoring system. The methodology was implemented on a global scale at the JRC using automatic procedures from downloading to processing data and outputting of the results. Since night time radiation is more stable then day time, only descending swaths of the sensor are used. The 36GHz frequency with H polarisation appeared to be the most optimal one for monitoring aims. This frequency has a footprint size of approximately 8x12km. The selection of the H polarisation is described in detail in Brakenridge and others (2007) based on a model simulation study analysing the sensitivity of different polarizations to increases in fractional area of open water and increase of soil moisture on floodplains. Obtained Level2 swath products are associated with geolocation coordinates which makes the observed signals easy to grid into a geocoded image.

Microwave radiation over river sections and inundated swampy areas generally accounting for a lower brightness temperature (Tb) then land which is due to the different thermal inertia and emission properties of land and water. River sites to monitor were selected by having a significant empirical relationship between flow conditions and inundation area in a subpixel dimension. In case of a flood event – assuming that river flow goes over bank - land cover change can be observed along the river. With the increase of the inundation area on the floodplain Tb decreases in the wet/measurement pixel due to water's lower emission properties. Thus by monitoring the same river site over time inundations can be observed from space.

To monitor flood events, observations over selected river sites were extracted from AMSR-E data. First pixels obtained over a river site were extracted from the swath data. During historical flood events these pixels were observed to be sensitive to river flow by enlarging their water surface area in case of discharge increase. In a second step dry (calibration) pixels - observed over land - were extracted. They were selected to be close to the measurement pixel to enable the assumption of constant physical conditions nevertheless they were not affected by flood inundation.

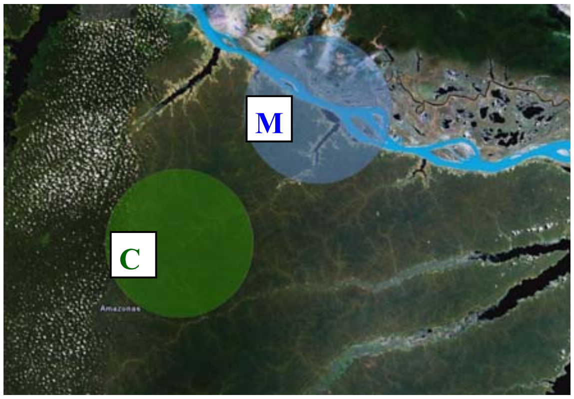

Figure 2. Observation sites over the Amazon in Brazil. Blue dot refers to the footprint of the "wet" (measurement) pixel observation, green dot to the calibration "dry" pixel. (Background: Google Earth)

Brightness temperature measures are influenced by many factors including physical temperature, permittivity, surface roughness, moisture etc. Whereas the relative contribution of these factors cannot easily be measured, they are assumed to be constant over a larger area. Therefore, by dividing the "wet signal" received over the river channel by the "dry" (calibration or comparison signal), the mentioned influences can be minimized in a consistent way. Thus, a ratio can be set up defined by the relationship:

$$\text{M/C Ratio} = Tb_m / Tb_c \qquad (1)$$

where Tb_m and Tb_c is the brightness temperature of the measurement/wet and calibration/wet pixel respectively. Resulting normalisation eliminated most of the daily and seasonal temperature variation, soil moisture effects, vegetation influences (figure 3.). Because it adapts automatically to different land surface characteristics, the methodology has the capability to be applied systematically over the globe.

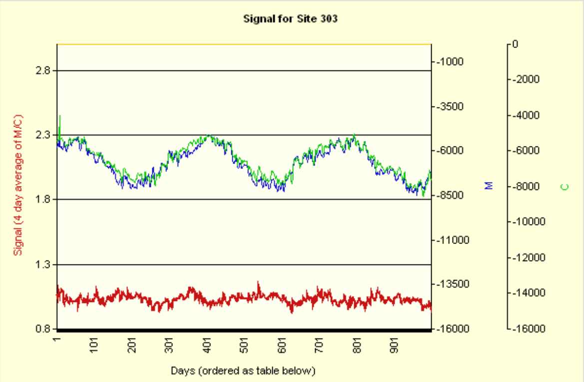

Figure 3. M/C ratio (red line) minimises radiation variation originating from seasonal variations, soil moister, cloud cover and vegetation influences. M and C observations are blue and green lines respectively.

The time series of the M/C Ratio (1) provides the basis of river gauging measurement and flood detection from space. In normal flow conditions where water flows in-bank, dry and wet signals have nearly the same trend over time (although unusually low flow, as well, can be detected). As soon as the river floods over-bank, the proportion of water in the wet pixel greatly increases and there is a strong response in the M/C ratio. Due to the lower emission of water the signal of the wet pixel lowers consequently, the M/C Ratio increases (figure 4.).

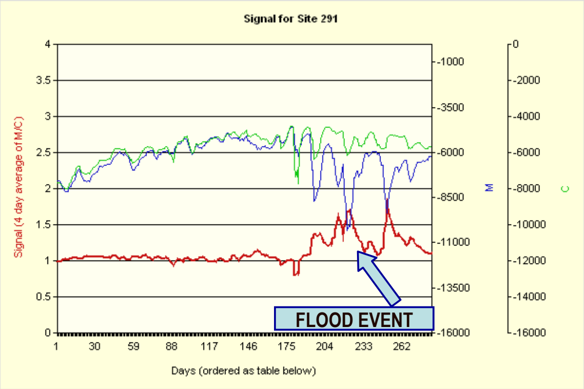

Figure 4. Flood event detected on the River Chenab in Pakistan in September 2006 from the M/C time series (red line).

Significant correlation was measured between the satellite based gauging signal and the on-site gauging measures of the selected river location (Brakenridge, and others 2007). However, the task for flood detection is simplified to the monitoring of current river status and distinguishing between normal flow and flooding. For this reason a separate process was set up to threshold the signal of riverine flooding without the need for local gauging station data. Thresholds were set by using the statistics of the time series. Signal was extracted from the complete 4 years of AMSR-E data reaching from the launch of the system June 2002 to the time of writing this paper (March 2007). The download and processing of near-real time satellite data is automatic and the signal extraction is ongoing, extending the time series of the gauging signals and updating their statistics every day.

River flooding is defined when M/C ratio is higher then 80% of it's cumulative frequency in the time series. Major flood is the 95% percentile, flood is the 80% percentile and normal flow is below the 80% percentile of its cumulative histogram. Detected flood events based on AMSR-E satellite observations are converted to disaster alerts and are implemented into the GDACS automatic disaster alerting system of natural hazards.

At present, approximately 2600 river gauging sites are monitored automatically on a daily basis from AMSR-E satellite observations around the globe (figure 5.). Observations and flood alerts are summarised in database and visualised in form of maps on the GFDS web page distributing information on the internet (www.gdacs.org/floods).

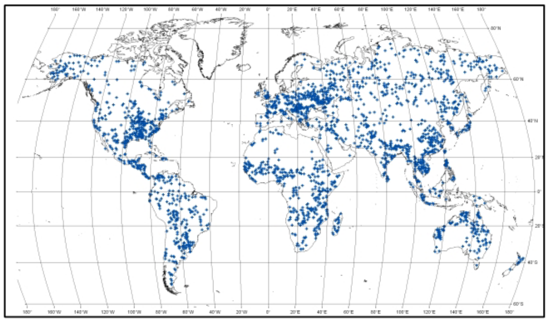

Figure 5. Space borne gauging stations around the globe monitored daily by GFDS

2. SIGNAL PROCESSING

2.1 Different sources of noise

As noted, correlation was found between the orbital gauging signals and the on site stage hydrographs at many sites (Brakenridge and others, 2006). However the signal was found to be noisy when comparing to daily discharge data provided at gauges on-site. This might be due to several influences on the received microwave radiation at the sensor.

The intensity of passive microwave radiation over an object is dependent not only on the object’s temperature and incident radiation but also on the emittance, reflectance and transmittance properties of the object. Due to the variety of its possible sources and its extremely weak magnitude, the signal obtained from various ground areas is noisy (Lillesand, 1999).

A variable of great magnitude is the different radiation intensity related to the viewing geometry varying from swath to swath and from observation to observation. Nevertheless this effect should be minimised by the rationing of the two detected signals (M/C) that are separated by a short spatial distance. Secondly, the signal is influenced by many different factors besides the water surface area change. Factors like physical temperature, permittivity, surface roughness, moisture etc. not mentioning current cloud cover over the scanned area have an impact on the emitted radiation. These variations can be minimised by the proper selection of the dry/calibration pixels unaffected by river flow change but situated near to the wet pixel ensuring to have similar physical properties suitable to reduce noise after ratioing with the wet pixel.

Still different approaches were tested to reduce noise from M/C signal.

2.2 Spatial averaging

Spatial averaging was first tested to reduce noise from observed and calculated M/C ratios. The fractional area of the water in the wet pixel varies from swath to swath due to the different observation geometry every day. Therefore a spatial averaging was tested in order to stabilise the M/C signal.

A spatial resampling of all frequency channels is provided in the L2 data set to simplify the comparison of different channels with different footprint size. All frequency channels are available at an unsampled Level 1B resolution. The higher-resolution channels are resampled to correspond to the footprint sizes of the lower-resolution channels. The Level-2A algorithm spatially averages the multiple samples of the higher-resolution data into the coarser resolution instantaneous field of view (IFOV) of the lower-resolution channels with the Backus-Gilbert method (Ashcroft, 2003).

The use of the spatial averaged ratio resampled at 27x16 km (resolution 3) was tested instead of using the unsmoothed original 8x12 km spatial resolution. Results are shown in figure 6.

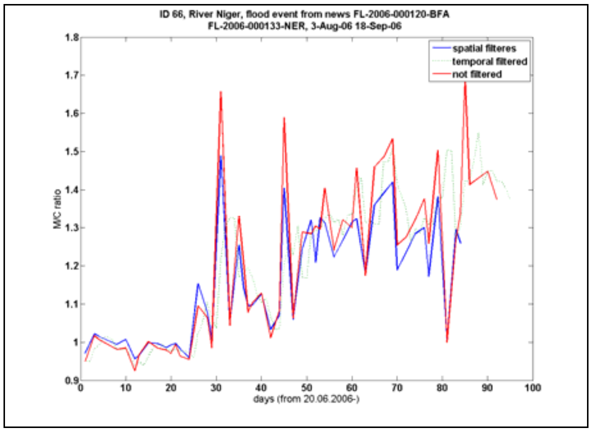

Figure 6. Spatial averaged and temporal filtered M/C signals for site along the River Niger in Mali

As visible from the figure the smoothening effect of the resampled channel did not significantly reduce the noise as expected in advance. For this reason in a second step a temporal filtering was applied to the signal.

2.3 Temporal filtering

Temporal filtering was introduced to reduce the swath to swath variation of the signal. The signal for one day was averaged from the last 3 days signal and the signal for the current day. This 4 days average provided a better result to stabilise the signal then the spatial resampling described in the previous section (see figure 5). A further advantage related to the temporal averaging compared to the spatial means is that on days when data are missing or near-real time data are provided with significant delay, the M/C ratio can still be calculated from the average of the observations from the previous days. Thus from the trend of the previous days an estimation for the current day can be provided. This method accords with the multi-day duration of most floods.

At the moment GFDS is applying the 4 days average to calculate M/C signal around the globe on a systematic way. Observations are provided on a daily basis and thresholds to detect flood events described in the methodology chapter are calculated based on the temporal filtered observations introduced to reduce signal noise.

3. VALIDATION PROCESS

3.1 Validation approaches

Different validation strategies could be applied for different sites. Rivers can be classified as flowing within either gauged or ungauged regions depending on if on-site measurements are taken systematically for the river. For gauged river sites, AMSR-E observations are easier to validate: hydrological measurements of either water surface elevation gauging or discharge measurements can be correlated to AMSR-E signals directly. However, care has to be taken with comparing water elevation with space borne river gauging. The last is measuring emissivity variation in time due to flood area extent changes. The location of the river gauging sites were selected so that flood extent had a good correlation with water surface elevation changes thus also discharge changes, however in case of a flood event flood extent increase can still be observed while stage is already in the falling limb.

For ungauged river sites the validation is more difficult. Yet, known flood events help to confirm or disprove observed inundations from satellite data. Several databases exist on disaster events around the world where information was collected from news or other sources but not from physical measurements or observations. The following ones were downloaded and processed ones: CRED EM-DAT[*], GLIDE [*], ECHO project database[*], OCHA Financial Tracking System[*], DFO[*]. Most databases record inundation events according to the starting and ending date, duration, and country where it did occur. Unfortunately, the detailed information on the location and the river basin is not consistently available.

3.2 Validation of ungauged river sites

The disaster event databases serve the basis for the validation for sites having no on-site gauging measurement records. Flood alerts detected from AMSR-E observations of each river site described in the methodology chapter were converted into a list of detected flood events for the given site. Detected flood events were defined as a period during which a site has continuously been facing flood or major flood alerts with no gap longer than 3 days in between. This was automatically derived from the time series of the space borne gauging measures.

Flood events detected from physical measurement can be compared with known events from the mentioned databases by matching records according to country and overlapping starting/ending date (figure 7.). From this match the correlation between remotely observed events and known events can be calculated.

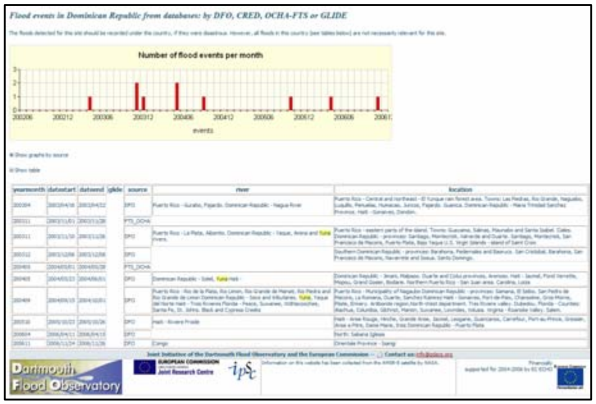

Figure 7. Validation process. Comparison of satellite based flood observations and reported flood events from news.

The first result from the ongoing validation process was not satisfactory: only about 50% of the detected events fitted the flood event databases. This was due to the fact that the flood events were matched only according to the country of their occurrence and not to river basins or regions. The matching on river name basis is ongoing. However much manual work is still to be done to extract and mach river names exactly between the two sources.

However, since non of the databases can be considered as complete, comprehensive and error free, human interpretation is necessary to confirm this match. Moreover some flood events detected from satellite imageries do not appear in the database. Thus alternative approaches can be considered like flood mapping from other satellite resources.

3.3 Quantification of accuracy

The correlation between observed and known events give a rough estimation of the accuracy of one site. The error of commission and omission could be calculated for each site following the rule table 1.:

	Known flood event	**Unknown flood event**
Observed flood event	*Correct*	*Commission*
Not observed flood event	*Omission*	*Correct*

Table 1. Different sources of flood detection error

In this case of course the error of comission is going to be more difficult to determine since there might be flood events that were not recorded in any of the databases however were present in field. In this case alternative approaches can be considered like comparing results with flood extent maps. Nevertheless in the first step we assume that all flood events were recorded in the databases.

The quantification of error can serve the basis for ranking sites. As a result of this validation sites could be flagged as good or bad site if a certain rate of error is achieved.

3.4 Qualitative evaluation

In case a site is flagged as a bad site not reflecting flood events from its signal peaks manual editing can be applied. For this reason a tool was set up to enhance flood detection results from signal based on several strategies:

- In a first step thresholds can be changed from the default value of 80% cumulative frequency to individual ones to fit better site specifications. Some sites can have a threshold function over time (e.g. seasonal variation) and some sites can have signal increase that is not correlated to flood events. An additional user interface has been created in the model for this purpose. This way, different analysts can manually analyse different sites and record their findings in the central database. After altering threshold values an automatic recalculation of the sites statistics and the flood events is followed.
- If threshold changes do not enhance results, the location of calibration and measurement pixel can be changed. A tool is about to be set up to automatically

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[*] http://www.em-dat.net/disasters/list.php

[*] http://www.glidenumber.net/glide/public/search/search.jsp

[*] https://hac.cec.eu.int/

[*] http://ocha.unog.ch/fts2/pageloader.aspx?page=emerg-emergencies&section=ND&year=2006

[*] http://www.dartmouth.edu/%7Efloods/Archives/index.html

re-extract signals from AMSR-E data in case of location change.

- Sites on the same river must be compared with each other. For this reason a tool was set up to summarise flood alerts in the same country along the same river.

3.5 Validation knowledge base

A knowledge base will be added to the current flood web site. It will be possible to store extra information per site and per event. This information is necessary to see the progress of the validation and record what works for which site. JRC will propose such a knowledge base.

4. OPERATIONAL TEST DURING THE RECENT FLOODING IN BOLIVIA 2007

The first operational use of the GFDS was during the devastating flood crisis in Bolivia from the beginning of the year 2007 (glide number*: FL-2007-000012-BOL). Harsh rainy season due to El Nino was causing flooding throughout the country, 8 provinces out of 9 were severely hit, 350 000 people were affected. Capital city Trinidad was under water; most of Beni province was inundated. Bolivian government declared a national emergency on 18th January 2007 and appealed for international help (Brakenridge, 2003).

The European Commission responded to the request and the Environment Directorate-General (DG ENV) requiring spatial information about the flood disaster to support decision making processes.

Besides the operational GDACS internet portal a separate home page was set up for emergency management of the crisis. Besides collecting information and maps from news and different humanitarian relief communities we tried to elaborate the severness of flood situation daily from AMSR-E observations. Inundation mapping from MODIS images was delayed by cloud cover throughout the whole month of February. Partially cloud free scenes could be acquired only at the end of the month. At this stage we can conclude that the temporal resolution of AMSR-E flood observations is one of the great advantages during the operational use of the system compared with other satellite resources like optical MODIS or active radar systems. While cloud cover or repetition time is limiting the use of the two latest satellite systems, GFDS has the advantage to provide a situation overview on a daily basis. If necessary the number of gauging locations can be extended considering the conditions set and discussed in the methodology.

To get a better overview of the disaster situation in the whole Rio Mamore river basin - where the city of Trinidad is located - we increased the number of operational orbital gauging sites (figure 8). We located one observation every 50 km along the river to ensure the spatial continuity of the observations along the channel using one calibration site over the whole reach.

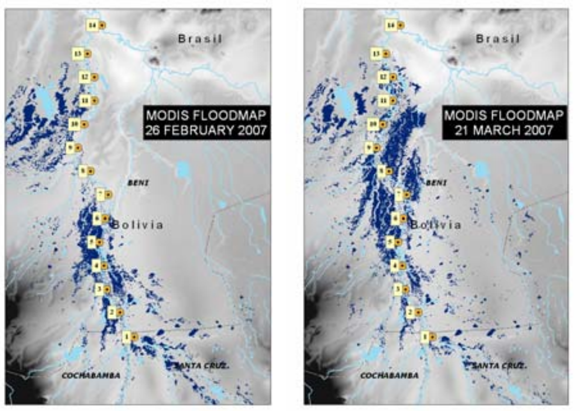

Figure 8. Location of orbital river gauging sites (yellow dots numbered sequentially) set during the flood emergency in Bolivia overlaid with the flood map derived from MODIS images (dark blue areas). Background: gtopo elevation model.

Inundation mapping was performed during the disaster event from MODIS satellite images. Comparing the flood maps obtained at the end of February and March we can observe that the flood extent decreased at the southern upstream end of the river reach while increased in the northern downstream area reflecting the flood wave propagation with time along the river. Nevertheless inundation mapping was limited by cloud cover over the region due to heavy rain fall.

Following the enlarge number of orbital gauging sites the AMSR-E observations were providing a better temporal resolution with a high spatial sampling along the Rio Mamore then compared to optical low-resolution satellite systems. A situation overview of the whole river basin could be provided every day regardless of the cloud cover conditions.

The 3D graph below (figure 9.) provides a good overview of the river gauging signal along the channel in time during the flood event. Where x axes refer to river gauging sites – numbered sequentially along to reach from upstream to downstream – y axes presents the time scale during the flooding from 01.01.2007 to 22.03.2007 and z dimension refers to the M/C gauging signal.

The propagation of the flood wave was visible on the gauging peaks highlighted with red on the graph. The signal of orbital gauging stations set along the Rio Mamore were showing a high correlation with the flood maps derived from MODIS images (figure 8.). The upstream peak at the end of February is well distinguishable from the downstream peak at the end of March in the graph. This matches perfectly with the flood maps estimated from MODIS images of the same period. Thus flood monitoring from AMSR-E observations compared with inundation mapping possibilities from MODIS images provides a higher temporal resolution thus a better situation overview in time.

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[*] GLobal IDEntifier number (GLIDE) is a globally common unique ID code for disaster events issued by Asian Disaster Reduction Center (ADRC)

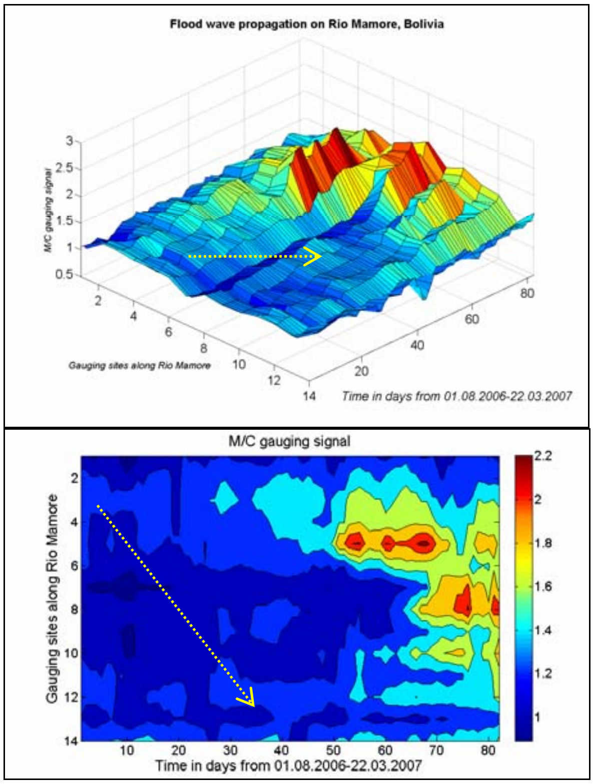

Figure 9. Three dimensional graph of the flood propagation along the Rio Mamore from AMSR-E observations. X axes: orbital gauging stations along the river; y axes: time scale; z axes: M/C values. Yellow arrow refers to the flood propagation in space and time.

5. CONCLUSIONS

This paper discusses the implementation of a daily flood detection technology on a global scale. The monitoring system provides a daily overview of the flow conditions of river systems in the world. Because of its general applicability, the methodology can be extended to include an arbitrary number of locations for orbital gauging. This is particularly interesting for rivers that are not monitored with on-site gauging stations.

Moreover, the use of AMSR-E observations for flood monitoring can prove to be an alternative to flood mapping in case of a persistent cloud cover over the inundated region. While the spatial resolution is low, orbital gauging observations can give a spatial overview of the disaster situation in different river sections of the same river. In addition, compared to other satellite observation systems (such as MODIS or Landsat optical images) the method provides a high temporal resolution which can be presented in a course but frequent map of the river flow conditions.

The use of the monitoring system during the Bolivia flood event in the first quarter of 2007 showed that the system can already provide operational results. Nevertheless, the same case study also showed that validation needs to be done taking into account local conditions.

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5.1 Appendix

This project is a joint project between the European Commission and the Dartmouth Flood Observatory.