Integration of NASA Global Precipitation Measurement Mission Data into the SERVIR Flood Decision Support System for Mesoamerica

Joel S. Kuszmaul¹, Elizabeth G. Johnson¹, Greg Eason¹, Faisal Hossain², G. Robert Breckenridge³, Emil Cherrington⁴, Timothy Gubbels⁵

July 31, 2008

Preliminary report

¹ University of Mississippi Geoinformatics Center (UMGC)
² Tennessee Technological University
³ Dartmouth Flood Observatory
⁴ CATALAC
⁵ Science Systems and Applications, Inc., Lanham, MD 20706
EXECUTIVE SUMMARY

This Rapid Prototyping Capability (RPC) experiment explores the feasibility of using new and future satellites, namely the Tropical Rainfall Measurement Mission (TRMM) and the next generation Global Precipitation Measurement Mission (GPM), to support flood water measurement by SERVIR. Currently available SERVIR products depend upon the continued availability of the AMSR-E sensor, which will not be available long term due to the expected decommissioning of the associated satellite. This RPC experiment constitutes a first attempt to lead to that transition. We have two components of our experiment; each employed TRMM data as a proxy for the planned GPM sensor. Experiment 1 uses the current AMSR-E 36.5GHz channel from the radiometer to the equivalent 63.5GHz band of the TRMM sensor. The current Dartmouth Flood Observatory’s practices regarding a flood hydrograph measurement were applied to data from both sensors. In Experiment 2, the potential for using rapidly available or real time sensor data from TRMM (as a proxy for GPM) to estimate rainfall and river flooding estimates was examined.

The results of Experiment 1 give encouraging results in the continued or improved offering of the Dartmouth Flood Observatory’s flood inundation map. Of the eighteen regional sites where AMSR-E and TRMM results were compared, the six sites with a moderate or strong flood signal revealed a strong correlation (rave= 0.80) with only slight variability between the correlation on these six sites (the standard deviation was 0.072). When the twelve sites without a strong flood signal are considered, the correlation is weaker (rave= 0.143) and much greater variability (the standard deviation was 0.414).

The results of Experiment 2 give encouraging results in the improvement in the detection of flooding in Mesoamerica. Our estimates rainfall during 1 to 10 October 2005 at the two study sites revealed good agreement between measured and estimated rainfall at one of the sites and poor agreement at the other site. When we applied an empirical approach to estimate cumulative discharge associated with this rainfall, we found fairly good agreement with stream gage measurement of discharge and estimated discharge at one of our sites and poor agreement at another site. These results shows that the planned enhancement of TRMM-based real-time satellite rainfall estimation based on a regional and dynamic bias adjusting scheme may hold promise to overcome the shortcomings observed for the site with poorer agreement.

The combined RPC results suggest that continued availability of the SERVIR flood measurement products will require calibration procedures with the transition to new NASA sensors. The potential for additional products, including the possibility of estimated flood “now casts” may be possible with the continued development of the dynamic bias adjusting scheme using real-time satellite products.

1. INTRODUCTION

This Rapid Prototyping Capability (RPC) experiment explores the feasibility of using new and future satellites, namely the Tropical Rainfall Measurement Mission (TRMM) and the next-generation Global Precipitation Measurement Mission (GPM), to support flood water
measurement within the SERVIR architecture. The current method of measuring floods in Mesoamerica uses Advanced Microwave Scanning Radiometer (AMSR-E) data providing measurement of flood water approximately every two days (see example flood map in Figure 1). SERVIR is a NASA managed program integrating satellite and geospatial data with the aim to develop scientific and decision making knowledge for issues affecting Mesoamerica. The issues addressed by this program include disasters, ecosystems, biodiversity, weather, water, climate, oceans, health, agriculture and energy of the region.

![Central America Flood Hazard Map 1998 - 2006](image)

**Figure 1**: Shows example flood water mapping currently available from SERVIR using AMSR-E data. (SERVIR, 2008)

### 1.1 Relevance to NASA

This RPC experiment is directed at sustaining and improving the performance of a NASA-managed decision support tool (DST) with a well established track record of credibility and utility. This RPC experiment directly contributes to the NASA Applied Sciences Programs mission to extend the results of NASA Earth Science Division’s (ESD) contribution to national priority applications by supporting the ongoing mission of SERVIR’s Flood Measurement as related to National Application Areas of disaster management, ecological forecasting, and water management. Within the six National Focus Areas established by NASA ESD, this RPC contributes to an improved understanding within the categories Surface & Interior, Weather, and Water & Energy Cycles.
1.2 **Introduction to the Decision Support System**

SERVIR is an internationally supported visualization and monitoring system for improving environmental decision making in Mesoamerica. SERVIR has created modules which address nine areas to benefit society under the Global Earth Observation System of Systems (GEOSS): disasters, ecosystems, biodiversity, weather, water, climate, oceans, health, agriculture, and energy. The currently available visualization of flooding is prepared in cooperation with the Dartmouth Flood Observatory (DFO) using the AMSR-E data to yield a web-based product describing floodwater measured every two days. This product is included within the disaster, water and weather modules. While flooding data is valuable, it lacks the real time quality that could potentially be used more effectively in disaster and water management. In particular, the time required for this data to become available limits the value of the data for decision making in disaster management. The first goal of this experiment is to examine how alternative imagery might be substitute for current methods to provide more real time measurement of flood water. Such data could be more useful for disaster management response. In other areas of its mission, SERVIR seeks to provide short-term forecasts (or now casts) of significant weather events. The second goal of this experiment examines the potential usefulness of rainfall measurements by current and future NASA missions in combination with knowledge local drainage basins to provide predictive flooding information. Such now casts of flooding that would be more useful not only in disaster response, but also during emergency conditions.

1.3 **Partners in the Interdisciplinary RPC Experiment**

Our partners in this RPC Experiment bring a diverse set of skills. We have partnered with experts in the science and application of the SERVIR flood mapping tools. These include Dan Irwin of NASA’s Marshall Space Flight Center (NASA-MSFC) and project manager for SERVIR, to provide an understanding of how SERVIR is applied. NASA-MSFC is partnered with CATHALAC to manage the SERVIR project and serve information products to users in Central America. For understanding of the current AMSR-E-based flood modeling system we have relied on Dr. Bob Brackenridge of the Dartmouth Flood Observatory and Tim Gubbels, of SSAI. We also incorporated experts in the NASA next-generation sensors including Dr. Faisal Hossain of Tennessee Technical University who works extensively with TRMM and simulated GPM data.

A. Science Systems and Applications Inc. at National Aeronautics and Space Administration (NASA) – Goddard Space Flight Center (GSFC).

Timothy Gubbels – Tel.: 301-867-6260 Email: timothy_gubbels@ssaihq.com Address: 10210 Greenbelt Road, Suite 600 Lanham, MD 20706

Dr. Gubbels is a senior scientist with SSAI and his areas of expertise include Earth system science, remote sensing technology and applications, and information systems.

B. Tennessee Tech University (TTU).

Faisal Hossain – Tel.: 931-372-3257, Email: fhossain@tntech.edu Address: Department of Civil and Environmental Engineering, Tennessee Technological University - Prescott Hall
Dr. Hossain and his research group have agreed to contribute to the project by post processing the data provided by GSFC and convert it to simulated GMI rainfall estimates.

C. Water Center for the Humid Tropics of Latin America and the Caribbean (CATHALAC)

Emil Cherrington – Tel.: (507) 317-0053 Email: cathalac@cathalac.org Address: City of Knowledge, Clayton, Panama. P.O. Box 873372, 7 Panama

Dr. Cherrington and his group provide data and support for research based in Guatemala.

D. Dartmouth Flood Observatory (DFO).

Robert Brakenridge – Tel.: 603-646-2870; Email: G.Robert.Brakenridge@dartmouth.edu
Address: Dartmouth College, Fairchild 121, Hanover, NH 03755

Dr. Brakenridge has agreed to provide technical support for AMSR-E data processing to measure discharge and runoff.


Dan Irwin, Marshall Space Flight Center-Tel.; 256-544-0034 Email: Daniel.irwin@nasa.org
Address: Marshall Space Flight Center, 320 Sparkman Derive, Huntsville, AL 35805

Mr. Irwin has agreed to provide access to the SERVIR Flood Decision Support Tool to integrate experiment results.

2. THE SERVIR DECISION SUPPORT SYSTEM FOR FLOOD MONITORING AND PREDICTION

2.1 The Flood Mapping Decision Support Tool

SERVIR integrates satellite and geospatial data to improve scientific knowledge and better decision making. SERVIR addresses nine societal benefit areas of the Global Earth Observation System of Systems (GEOSS): disasters, ecosystems, biodiversity, weather, water, climate, oceans, health, agriculture, and energy. The SERVIR DSS for floods provides several products for both monitoring existing and analyzing historical events. Some of these products include discharge measurements and runoff from watersheds, and flood maps of river reaches in Central America (Figure 2). This SERVIR DSS has been developed to aid the work of environmental monitors and disaster management personnel.

Flooding, or changes in the ground surface water condition, is detected by satellite microwave
radiometry. The flood tool from DFO ratios the radiance from a calibration pixel on dry land against radiance for a pixel centered over targeted portion of river to estimate change in discharge. Ground based gauging station data provide for conversion from remotely sensed signal to water discharge values. The method is sensitive enough to measure 1.3 year and 5 year floods as well as daily fluctuations. To date, DFO has only implemented this method using microwave responses from AMSR-E data at 36.5GHz.

The DFO processes the discharge measurements and watershed runoff data to observe ongoing flooding. Flooding information is transferred to the SERVIR DSS and thereby delivered to the public. The revisit time of Aqua limits AMSR-E data to approximately every two days.

The limitation of the flood inundation map product is that its works best over large, clearly delineated river reaches in relatively flat terrain where swollen rivers can be easily detected by satellite imagery. As seen in figures 1 and 2, the vast majority of visible flooding is on the coastal plains.

**2.2 Future SERVIR Flood Mapping**

Currently, the immediacy of the flood inundation maps is limited by the availability of microwave data. One objective of this study investigates the applicability of alternate sources of similar microwave data so that flood map is 1) insured by more plentiful sensors providing a data product that can be integrated and 2) improved by data sources that provide input data more frequently. To meet this objective, the TRMM Microwave Imager 37 GHz product will be tested as a possible alternate product to replace AMSR-E 36.5 GHz data. TRMM data could augment and improve the existing AMSR-E data. Additionally, TMI is due to be superseded by the GPM Microwave Imager so the ability to integrate TRMM data would ensure a continuation to the
flood product in SERVIR.

2.3 Future SERVIR “Now Casting”

The current flood decision support system is only capable of mapping the extent of flooding in low relief areas for clearly delineated river reaches. If satellite-derived rainfall rates could be constantly monitored and converted into flood potential, then a predictive system could be developed. As an initial step, ground-based and satellite-based rainfall estimates are compared with ground-based river gage data to determine if the rainfall is predictive of discharge.

3. THE ONGOING NASA CONTRIBUTION TO THE SERVIR DECISION SUPPORT SYSTEM

3.1 Current Sensor and Limitations of Current Sensor Product

At present, the DFO-generated flood maps rely upon AMSR-E data from Aqua. The Advanced Microwave Scanning Radiometer is a multichannel passive microwave instrument provided by the Japanese Aerospace Exploration Agency (JAXA) for the National Aeronautics and Space Administration (NASA) as part of the Aqua global hydrology mission. AMSR-E measures a number of geophysical parameters including: Sea Surface Temperature, Surface Wind Speed, Atmospheric Water Vapor, Cloud Liquid Water, and Rain Rate.

Precipitation rates from AMSR-E data are generated at the Global Hydrology and Climate Center Science Investigator-led Processing System (GHCC-SIPS), in Huntsville Alabama. These data can be accessed at the National Snow and Ice Data Center Distributed Active Archive Center (NSDIC-DAAC) (Regner, et al, 2005). The data is generally available 9 hours after observation.

The current sensor used for DFO flood inundation maps is the 36.5 GHz channel from the AMSR-E radiometer onboard the Aqua Satellite. The Satellite was launched in 2002 with a design life of 5 years; it has now exceeded its design life. Aqua is a sun-synchronous satellite in an orbit 705 km above earth at an inclination of 98.2°. The number of satellite passes per day is a function of latitude (NSIDC, 2008). In the area of Guatemala, Aqua’s revisit time is just over once a day (JAXA, 2003). Data from AMSR-E is processed through the National Snow and Ice Data Center and provided with both vertical and horizontal polarization at a resolution of 14.4 x 8.2 km (instantaneous field of view) for the 36.5 GHz frequency with a swath width of 1445 km. AMSR-E is a conical scanner with an incidence angle of 55°.

The flood product and associated work of SERVIR is threatened with the future decommissioning of primary period missions such as Aqua. River measurement activities for SERVIR would have to be stopped if AMSR-E data discontinued and no replacement would be available. The need to ensure a continuous measurement of geophysical parameters through the use of new EOS increases. Our goal is to establish the suitability for the Flood Product of microwave information from current and future NASA missions (namely TRMM and GPM) for
3.2 **TRMM, Expected Improvements and Problems**

The TRMM provides sensor data similar to AMSR-E. The TRMM Microwave Imager (TMI) is a passive microwave sensor that measures the intensity of radiation at 37 GHz. NASA and JAXA launched the TRMM in 1997 as a three-year mission but TRMM has been collecting data for seven years. The main improvement of TMI over AMSR-E is improved ground resolution because TRMM occupies a lower altitude at 402 km compared to 705 km of AMSR-E. TMI has an 875 km wide swath on the surface with 10x7 km field of view at 37 GHz. Pixels are 5km. The TMI is similar to AMSR-E in that is also a conical scanner inclined at 52.8° (Lee, 2002). TRMM 37 GHz vertical and horizontal polarizations can be imaged without the need for further processing.

One of the primary differences between TRMM and Aqua is their orbit. Most near-sun-synchronous like Aqua have polar orbits with orbital inclinations of about 98° and view spots on the earth at two specified local times 12 h apart. The TRMM orbit is circular, inclined 35° with respect to the equator, which allows excellent coverage in the tropics. TRMM was placed in a low-inclination orbit both to improve the sampling of tropical latitudes and to enable it to visit points on the earth at many different local times. TMI offers 15–16 orbits per day with a swath width of 875 km. The drawback is that there is a long interval between the TRMM visits to a specific region at a given hour of the day and its next observation at a similar hour (23 days at the equator and 46 days at the highest latitudes accessible to TRMM) (Imaoka, 2000). Climatological studies using satellite data must be done with appropriate averaging of the data in order to minimize biases in the averages due to varying sample sizes at different times of the day (Salby and Callaghan, 1997). Negri et al (2002) show that the optimum period of accumulation is 4 hours to minimize the potentially large variations in sampling error due to this pattern.

3.3 **GPM, Expected Improvements and Problems**

The value of testing the viability of 37 GHz data from TRMM is that it serves as a proxy for the future GPM with a 37 GHz channel. The GPM will be similar to the TRMM with frequent measurements (3-hourly). The GPM is another JAXA/NASA collaborative satellite mission and is set to launch in 2013 to replace the TRMM. It will be similar to the TRMM in its altitude (400km) but its orbit will be circular at 65° instead of non-sun-synchronous at 35°. A GPM microwave imager, GMI, will replace the current TMI and will function similarly with a conical scanning passive microwave radiometer inclined at 49°. GMI’s swath width will be 850 km and it will capture 37.0 GHz horizontal and vertically polarized radiation. Level 1 data (calibrated, geo-located, instrument values at the instrument field of view) will be made available to users within 20 minutes of collection.
4. THE RPC EXPERIMENT: PLANS TO UTILIZE NASA NEXT-GENERATION SENSORS

Our goal is to test simulated GPM data and assess its ability to replicate or improve the flood products currently generated using AMSR-E data. Because GPM data will be very similar to TRMM data but with increased temporal and spatial resolution, we assessed whether TRMM data products could meet two objectives; 1) to enhance the current satellite-based inputs into SERVIR by replacing AMSR-E data used for SERVIR’s Flood Decision Support System and 2) to provide predictive information about increased flood risk by comparing storm related runoff discharge with stream discharge. To accomplish these objectives, we created two experiments related to a specific time and place, namely Hurricane Stan rainfall event in southwestern Guatemala.

4.1 STUDY TIME FRAME AND SITE

Hurricane Stan (October 2005) was a relatively weak storm embedded in a larger non-tropical system that delivered torrential rains to SERVIR countries including Guatemala, El Salvador and southern Mexico. Storm related flooding and mudslides lead to between 1600 and 2000 deaths with damage of approximately $1 billion U.S. dollars. Figure 3 shows rainfall accumulations of up to 500 mm (20 inches) over parts of Central America.

4.2 EXPERIMENT 1

The objective of Experiment 1 is to examine how alternative imagery types might be substituted for current methods to provide more real time measurement of flood water. Our method requires finding the closest proxy to meet DFO’s current model input requirements and testing DFO’s ability to a generate flood inundation map products from the new sensor. Our aim was to compare flood inundation products from two different sensors against ground data from river gauging stations.
Study Site

DFO generated river and calibration pixel measurements for both TRMM 37.0 GHz and AMSR-E 36.5 GHz sensors across 18 sites from September 25, 2005 through October 29, 2005. Figure 4 shows the locations of the sites. Figures 5 and 6 show AMSR-E and TRMM acquisitions respectively for the time of Hurricane Stan.

Figure 4: River locations for AMSR-E comparisons with TRMM (Image base map from GoogleEarth)
Flood Measurement Procedures

Microwave radiometers can measure flooding by differentiating brightness temperature in a given pixel over a reach of water compared with a calibration pixel over land. The amount of radiation emitted from the earth’s surface is a function of the temperature of the surface and also of the wavelength of the radiation. The brightness temperature of water covered surfaces is usually 50% of the actual temperature compared with 90% for land surfaces.

The key to satellite-based flood measurements is the utilization of gauging reaches rather than gauging stations. River flow cross sections are difficult to measure from space, but measurements of changing water surface areas within carefully defined river reaches can be retrieved with relatively high precision using existing methods. Such gauging reaches range from ~10 km to 30 km in length (Brackenridge, 2005).

When comparing scenes, a calibration area over dry land (but within 50 km of the river) maintains a relatively constant brightness temperature while the brightness temperature of a measurement area over a river varies as a function of the water surface area. When total water surface area increases along the river, the mean radiance declines for the measurement sub-reach, but not outside it so the radiance ratio records the water area increase. Because of the large
difference in water and land radiances at this spectral band (841–876 nm), the ratio calibration reach/measurement reach is a sensitive and consistent measure of surface water (Brackenridge, 2005). A ratio of the brightness temperatures in the measurement and calibration areas yields a fairly reliable hydrograph of river levels which can then be calibrated with data from gauging stations. It should be noted however that space-based surface water observations are not as precise as gauging station data and the relationship of reach surface water area to discharge may be affected by errors such as hysteresis (Brackenridge, 2005).

Methods

DFO, in conjunction with Dr. Tom De Groeve of the Joint Research Center (European Union Commission research lab in Ispra, Italy), adapted a system created to access NASA AMSR-E hdf formatted swath data to access TRMM hdf formatted swath data. The system queries files using the latitude and longitude of the two targets per scene and returns only the signal numbers within 5 km radius of the target locations. A four-day running mean smoothing and data-filling algorithm is used because both sensors do not return daily data (AMSR-E returns data every 1 to 3 days while TRMM similar but slightly more frequent) (Breckenridge, Pers. Comm.).

4.3 EXPERIMENT 2

The objective of the second experiment is to test and validate Global Precipitation Measurement Mission data as: 1) an enhancement to current satellite-based precipitation inputs into SERVIR, and; 2) a replacement for the Advanced Microwave Scanning Radiometer Earth Observation System to improve the determination of ground surface water conditions. This experiment examines the potential usefulness of rainfall measurements by current and future NASA missions in combination with knowledge local drainage basins to provide predictive flooding information. Such “now casts” of flooding that would be more useful not only in disaster response, but also during emergency conditions.

Study Site

Guatemala was chosen as the study site for several reasons, 1) there is good on site support infrastructure and data through the National Institute of Seismology, Volcanology, Meteorology and Hydrology (INSIVUMEH) and 2) Guatemala suffered the largest loss of life associated with Hurricane Stan. The southwestern coast of Guatemala was focused on because it received the heaviest rainfall associated with Hurricane Stan and it includes the village of Panabaj, site of a devastating landslide which resulted in over 1000 deaths.

The climate of southwestern Guatemala is divided based on elevation into three zones that run parallel to the Sierra Madre mountains and the coastline: the coastal plain (0 – 300 masl), The Bocacosta (300 – 1400 masl) and the high plain (>1400 masl). The Bocacosta receives the greatest rainfall in the country with maximum rainfall from June to September. It has two climate seasons (wet and dry), the vegetation is jungle and the temperature is a function of elevation. The high plains have a drier climate overall with two seasons. The wet season is from
May to October. Weather in this zone is highly variable with many microclimates and it is affected by dense population centers. The coastal plain is much hotter than the other two regions with significantly less rainfall. The vegetation is forest and grassland.

Guatemalan watersheds were chosen from those in the southwest with both stream gage and rain gage data collected by INSIVUMEH across the period from Oct 1-Oct 10, 2005. Of nine possible sites, two basins met that criteria: 1) Rio Coyolate en Puente Coyolate (in future referred to as Coyolate) and 2) Rio Villalobos at Villa Canales (referred to hereafter as Villa Canales). Table 1 lists the locations of these two basins according to USGS records.

Table 1: Watershed Locations

<table>
<thead>
<tr>
<th>USGS Site number</th>
<th>Site name</th>
<th>Latitude (DMS)</th>
<th>Longitude (DMS)</th>
<th>Datum</th>
<th>Elev. (ft ASL)</th>
<th>Datum</th>
<th>Climate Zone</th>
<th>Drain. area (Km²)</th>
<th>ID - INSIVUMEH</th>
</tr>
</thead>
<tbody>
<tr>
<td>50832-01100102</td>
<td>Rio Coyolate en Puente Coyolate</td>
<td>14°22'39&quot;N</td>
<td>91°08'12&quot;W</td>
<td>NAD27</td>
<td>698.4</td>
<td>NGVD29</td>
<td>Bocacosta</td>
<td>511.88</td>
<td>1.10</td>
</tr>
<tr>
<td>50832-01130645</td>
<td>Rio Villalobos at Villa Canales</td>
<td>14°29'10&quot;N</td>
<td>90°32'10&quot;W</td>
<td>NAD27</td>
<td>3986.4</td>
<td>NGVD29</td>
<td>High Plain</td>
<td>311.52</td>
<td>1.13</td>
</tr>
</tbody>
</table>

The chosen watersheds are within 65 km of each other and are of similar size, but there are important differences between the watersheds. Figure 7 shows a DFO generated flood inundation map over southwestern coast of Guatemala at the time of Hurricane Stan and the location of the two watersheds. The Coyolate gauging station is at the base of a relatively steep-sloped basin in volcanic terrain that faces the Pacific Ocean along the windward side of the Sierra Madre Mountains. It is less than 20 miles southeast of the site of the landslide at Lake Atitlan which decimated the village of Panabaj. The Coyolate watershed is largely unpopulated. The Villa Canales watershed is almost due east of Coyolate, but it is on the leeward side of the mountains in the high plains climate zone. The catchment area is nearly flat and heavily populated, containing the western portions of Guatemala City.
Figure 7: DFO generated flood inundation map for Hurricane Stan showing two watersheds of interest

Method Description
We use an empirical method of converting the rainfall estimates to discharge estimates. Data from the chosen watersheds was difficult to obtain and incomplete. Data was insufficient to estimate the arrival time of a pulse of water from a specific rainfall time. Instead, the Soil Conservation Survey’s Curve Number method (Hjelmfelt et al., 2004) was applied to both the rainfall measurements and the TRMM-based estimates of the rainfall accumulation. This method produces the total estimated discharge associated with a rainfall event. The curve number runoff equation is

\[
Q = \begin{cases} 
\frac{(P-I_d)^2}{(P-I_d)+S} & P > I_d \\
0 & P \leq I_d
\end{cases}
\]

where \( Q \) [L] is runoff, \( P \) [L] is depth of rainfall, \( I_d \) [L] is initial abstraction \( (I_d = 0.25) \) and \( S \) [L] is potential retention

\[
S = \frac{10(100 - CN)}{CN}
\]

where CN is the curve number (taken to be 85).
In situ stream gage measurements were converted to discharge estimates using an empirical relationship

\[ Q = K (h - h_0)^n \]

where \( Q \) is discharge, \( h \) is the gage height, \( h_0 \) is the reference gage height and \( n \) and \( K \) are empirically determined constants.

Using this method, we expect that the total discharge by all methods would be in agreement, but that our rainfall-based discharge estimates will rise more quickly than actual discharge measurements. This relates to the non-linearity and the thresholding of the rainfall-runoff process. In nature it takes time for the rainfall to reach the rain gage, but our method assumes that runoff is immediately measurable. So with this method, the definition for good agreement would be for the total discharge by all methods to be similar, while dismissing the premature discharge estimates that are based on rainfall total.

The limitation of this method is that it does not account for concentrated pulses of water. A rainstorm that lasts 3 days and a rainfall that lasts 3 hours would both yield the same total discharge estimates but may have different flooding results.

**Watershed Data**

The Coyolate station recorded stream gage values every 15 minutes continuously from September 29 through October 6 when the gage broke. It recorded dramatically increased discharge associated with Hurricane Stan in two sharp pulses on Oct. 4-6, 2005. The Villa Canales station was monitored daily from Oct. 1-10, 2005 and recorded a sharp pulse on Oct. 5, 2005. The empirical factors used to generate stream discharge are listed in Table 2.

<table>
<thead>
<tr>
<th>Watershed</th>
<th>K</th>
<th>( h_0 )</th>
<th>( Z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coyolate</td>
<td>1.1826</td>
<td>1.1745</td>
<td>4.5567</td>
</tr>
<tr>
<td>Villa Canales</td>
<td>0.93</td>
<td>1.572</td>
<td>2.722</td>
</tr>
</tbody>
</table>

Both the Coyolate and Villa Canales sites recorded rain gage data approximately every 15 minutes from Sept. 29-Oct.10, 2005. Data was resampled to hourly measurements by using the first measurement of each hour to represent the full hour and converted to units of mm/hr. This method was chosen so that the data would closer reflect the TRMM data.

For the runoff/discharge calculation in the watersheds, a static curve number of 85 was assumed. This high CN is justified because there was heavy rainfall across the end of September leading up to Hurricane Stan and the ground was saturated. The landslide at Lake Atitlan occurred Oct 4, 2005 before the bulk of the rains fell.
TRMM Data

The TRMM Multi-satellite Precipitation Analysis (TMPA) research product 3B42 Real Time (RT) was used for this experiment for dates from October 1 to 10, 2005. The chosen Guatemalan watersheds are smaller than the standard TMPA grid box size. For the time period, the 3B42RT product was Coyolate (185th row, 1074th column) and Villa Canales (185th row, 1076 column).

3B42 RT combines precipitation estimates in mm/hr from multiple satellites, as well as gauge analyses, where available, at a 3-hour time step and 0.25° degree spatial resolution. TMPA is available in real time and after real time products based on calibration by the TRMM Combined Instrument and TRMM Microwave Imager precipitation products, respectively. The after-real-time product (V6 3B42) incorporates gauge data but is delayed by approximately 1 month (Huffman, 2007).

The 3B42-RT product combines microwave, infrared and radar data. 3B42-RT has a temporal resolution of three hours and is published daily with a 6 hour and 40 minute delay. Daily totals compiled by the FEWS NET team at the U.S Geological Survey Center for EROS, are also available (Funk, 2006). The 3-hourly data was resampled at 1-hour increments to match the time step of the rain gage. Missing values were supplied by the previous value.

GPM Data

This experiment explores the potential to convert discharge measurements into a “now-cast” of expected discharge and make that information available to SERVIR following a TRMM pass. The time delay for TRMM would be close to 7 hours after receiving the 3B42RT data and applying an algorithm to generate discharge. GPM data is forecast to be available 20 minutes after acquisition at roughly 3 hour intervals.

4.4 RESULTS AND DISCUSSION

Experiment 1 Results and Discussion

The eighteen regional sites where both AMSR-E and TRMM data, see Figure 3, can be compared in a number of ways. The critical measure described previously the ratio calibration reach/measurement reach, must be compared for both these sensors. While the exact ratio values need not be reproduced with the TRMM sensor, the ratios must be clearly related so that the TRMM data can be calibrated to enable it to make the same measurement of flood hydrographs. One way that these two data sets can be compared is on the basis of the simulated hydrographs. Because this is the first use of TRMM data in this application, the ratio values are compared directly prior to hydrograph calibration. An example of this type of comparison is shown in Figures 8 and 9, where results are shown for Site 1063 for the Hurricane Stan measurement.
The similarity of the two sensor measurements shown in Figure 7 and 8 make it clear that under some circumstances, TRMM-derived flood hydrographs may be as useful as the AMSR-E produced measurements. The timing and strength of signals are similar in Figures 7 and 8, but the magnitude of the flooding differs in the two results. This discrepancy demonstrates that the TRMM-based data must be properly calibrated to reproduce the correct flood description. One
useful way to compare these to signals is to use the correlation coefficient for the ratio values from the two sensors. For Site 1063, the site shown in Figures 7 and 8, the correlation coefficient for these ratios is $r = 0.87$ (out of a possible range of -1.0 to 1.0), demonstrating a strong correlation between the two sensor’s results for the time period 27 September to 25 October 2005.

To present the results of all eighteen regional sites for this same time period, there are a number of methods for presenting and discussing the results. For each site, we compare the band ratio values (using a four day running average). We compared them first as time series for a qualitative assessment of the similarity of the two sensor’s ratio values, where a qualitative comparison was made. We also calculated the correlation coefficient for each of the eighteen regional sites to obtain a qualitative assessment of the similarity of the two measurements. A wide range of results were found, ranging from strong correlation to no (or incorrect) correlation. Examples of this range of correlation results are shown in Figure 10, where Site 69 ($r = 0.85$), Site 277 ($r = 0.5$) and Site 2426 ($r = 0.05$) are shown as time series for the period 27 to 25 October 2005. Another way to show the results is shown in Figure 11, where the approximate linear alignment of the Site 69 results demonstrate the strong correlation, but the cloud of daily measurements reveal weaker correlations for Sites 277 and 2426.

![Figure 10](image1.png)  
**Figure 10:** Shows the four-day running average of the M/C ratio for the AMSR-E and TRMM data sets for a) Site 69, b) Site 277 and c) Site 2426 for the period 27 September to 25 October 2005.
Figure 11: Shows the four-day running average of the M/C ratio for the AMSR-E and TRMM data sets for Sites 69, 277, and 2426. If results from the two sensors matched perfectly, they would fall along the line of equality. Observations that fall roughly along a line (such as the observations from Site 69 in Figure 10a) indicate correlated results. Observations that fall in a random pattern (such as shown in the detailed view in Figure 10b) indicate weaker correlation.

This range of results appeared at first to suggest that we obtained mixed or inconsistent success when assessing the potential of TRMM to replicate the AMSR-E measurement of flood hydrographs. However, we noticed a pattern to the results, when there was a clear flood pulse from Hurricane Stan we tended to obtain strong correlation. In the absence of a clear flood pulse, we had mixed or poor correlation. In an effort to quantify this observation we used three different measures of whether there was a clear flood pulse evident in the AMSR-E hydrograph. The first of these measures was a qualitative assessment of a strong, moderate, weak, or no flood pulse. The second measure of whether there was a flood observed in the hydrograph was the overall standard deviation of the AMSR-E ratio for this time period; the larger the standard deviation, the wider the hydrograph varied over this time. The third measure of whether there was a flood observed in the hydrograph was the overall range (maximum minus the minimum value) of the AMSR-E ratio for this time period; the larger the range of values the stronger the interpreted storm pulse. All three measures demonstrated consistent results (shown in Table 3), where these measures are provided along with the correlation coefficient for the two sensors.

Table 3: The correlation coefficient between the M/C ratio for the AMSR-E and TRMM sensors for the time period 27 September to 25 October 2005. Also included are three estimates of the strength of the storm pulse in the AMSR-E signal (see discussion in text).

<table>
<thead>
<tr>
<th>Site ID</th>
<th>r</th>
<th>Quality</th>
<th>$\sigma_{AMSRE}$</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1060</td>
<td>0.81</td>
<td>Strong</td>
<td>0.393</td>
<td>1.235</td>
</tr>
<tr>
<td>69</td>
<td>0.85</td>
<td>Strong</td>
<td>0.254</td>
<td>1.045</td>
</tr>
<tr>
<td>70</td>
<td>0.68</td>
<td>Strong</td>
<td>0.227</td>
<td>0.703</td>
</tr>
<tr>
<td>2569</td>
<td>0.83</td>
<td>Strong</td>
<td>0.224</td>
<td>0.733</td>
</tr>
<tr>
<td>67</td>
<td>0.75</td>
<td>Mod</td>
<td>0.137</td>
<td>0.480</td>
</tr>
<tr>
<td>1063</td>
<td>0.87</td>
<td>Mod</td>
<td>0.115</td>
<td>0.420</td>
</tr>
<tr>
<td>1066</td>
<td>0.30</td>
<td>None</td>
<td>0.097</td>
<td>0.365</td>
</tr>
<tr>
<td>951</td>
<td>0.83</td>
<td>Weak</td>
<td>0.077</td>
<td>0.265</td>
</tr>
<tr>
<td>277</td>
<td>0.50</td>
<td>Weak</td>
<td>0.074</td>
<td>0.257</td>
</tr>
<tr>
<td>1061</td>
<td>0.60</td>
<td>Weak</td>
<td>0.074</td>
<td>0.282</td>
</tr>
<tr>
<td>1065</td>
<td>-0.42</td>
<td>Weak</td>
<td>0.073</td>
<td>0.242</td>
</tr>
<tr>
<td>1062</td>
<td>0.33</td>
<td>Weak</td>
<td>0.061</td>
<td>0.260</td>
</tr>
<tr>
<td>2501</td>
<td>-0.01</td>
<td>None</td>
<td>0.042</td>
<td>0.185</td>
</tr>
<tr>
<td>2427</td>
<td>-0.40</td>
<td>None</td>
<td>0.040</td>
<td>0.165</td>
</tr>
<tr>
<td>2500</td>
<td>0.20</td>
<td>None</td>
<td>0.040</td>
<td>0.185</td>
</tr>
<tr>
<td>2426</td>
<td>0.05</td>
<td>None</td>
<td>0.035</td>
<td>0.145</td>
</tr>
<tr>
<td>1036</td>
<td>-0.47</td>
<td>None</td>
<td>0.019</td>
<td>0.067</td>
</tr>
<tr>
<td>1035</td>
<td>0.21</td>
<td>None</td>
<td>0.017</td>
<td>0.065</td>
</tr>
</tbody>
</table>
While the correlation coefficient for all eighteen sites range from -0.47 to 0.87, the average value is 0.36 with a standard deviation for all values is 0.46. Such an outcome suggests modest correlation at best with the large standard deviation indicating very inconsistent results. When only the six sites with moderate or strong storm signals are considered to obtain these same measures (the shaded portion of Table 3), the average correlation coefficient is 0.80 with a standard deviation of 0.072. In contrast, the twelve sites with weak or no storm pulse (not shaded in Table 3) had an average correlation coefficient of 0.14 and a standard deviation of 0.414. Thus, when there was a significant flood pulse to measure (as assessed using the established AMSR-E measure), the analogous TRMM ratio is very likely to produce a useful result. In the absence of a significant flood signal, the correlation was inconsistent and commonly weak.

Experiment 2 Results and Discussion

We compared estimated watershed discharge calculated from rainfall accumulation with estimated watershed discharge from calculated from stream gage height measurements. Rainfall measurements came in two forms, 1) in situ rain gages and 2) TRMM real time measurement. Two locations were chosen where TRMM, in situ rainfall estimates and gage heights measurements were available with sufficient measurement for comparison purposes, 1) Rio Coyolate de Pensativo and 2) Rio Villalobos at Villa Canales. The chosen watersheds are located in the southwest of Guatemala, an area subjected to heavy rains during Hurricane Stan, are within 65 km of each other and are of similar size (511 and 311 km2, respectively).

Initially we compared in situ rainfall measurement versus rainfall estimates based on TRMM real time data (using the 3B42RT data product) at both locations. For each of the two sites, the comparison is shown in Figure 12.

![Figure 12](image_url)

*Figure 12. A comparison of the rainfall gauze data in red (measured 1 October 2005 to 10 October 2005) to rainfall estimated using the TRMM 3B42RT product in blue for a) Rio Coyolate de Pensativo and b) Rio Villalobos at Villa Canales.*
These results reveal good agreement at the Rio Coyolate site and poor agreement at the Villa Canales site. In both cases, the measured rainfall is higher than the estimated rainfall. For the Rio Coyolate site the estimated rainfall is 26 to 33% lower than the measured precipitation, while at the Villa Canales site the estimated rainfall is 80% lower than the measured precipitation. There is reasonable agreement across all times at the Rio Coyolate site, with the time of greatest precipitation in agreement between the two rainfall estimates. The Rio Coyolate site supports earlier research that, once properly calibrated, the TRMM data can provide useful estimates of rainfall amounts (Harris and Hossain, 2008). At the Villa Canales site, however, the rainfall estimates do not agree across all time frames. The time of most rapid rainfall accumulation, however, was similar for both estimates. There are a number of human or natural factors that could have caused this discrepancy. Human factors include basin catchment or other parameters of the region that are not properly calibrated for the Villa Canales site or that there was equipment failure on site. The most probable natural factor causing the discrepancy is topography. The Villa Canales watershed is located immediately on the lee side of the coastal mountain range. It is possible that the storm clouds lost much of their moisture crossing the range as they moved inland, but the drop in moisture was not detected by TRMM because of the spatial resolution was too coarse. Rio Coyolate would have been unaffected by this topographic issue because it lies on the windward side of the coastal mountains.

For a time series of discharge based upon the rate of rainfall, we expect that the final total discharge by all methods would be in agreement, but that our rainfall-based discharge estimates will rise more quickly than actual discharge measurements. This is because, it takes time for the rainfall to reach the rain gage, but our method assumes that runoff is immediately measurable. So good agreement, in this case would be for the total discharge by all methods to be similar, while dismissing the premature discharge estimates that are based on rainfall total. When the results for our two sites are considered (see Figure 13), they do not compare as expected.

![Figure 13. Discharge measurements and estimates at a) Rio Coyolate de Pensativo and b) Rio Villalobos at Villa Canales. At each site the stream gage discharge measurement (golden) is compared to the empirical estimate of discharge (using the procedure described above) based on the rainfall gage (blue) measurement or the TRMM 3B42RT product.](image-url)
The comparison at Rio Coyolate de Pensativo was very good. The in situ discharge measurements did not cover the full span of the storm event, but were in good agreement for discharge magnitude. As expected, the discharge estimates based on the SCS method predict an earlier arrival of the discharge than was measured. In fact, it would not have been surprising to find a greater disagreement. After 7 October, 2005, in situ measures became unavailable, and the two rainfall-based estimates of discharge differ distinctly. The difference in rainfall estimations by the two methods is amplified in the discharge estimates. It is not clear why there is such a sharp difference estimated rainfall, and the source of this error is not immediately obvious. It is unlikely to be related to the application of the SCS equation for estimating discharge because the same curve number was used in both cases (CN=85).

When the discharge at the Villa Canales site is examined, a very different result is seen. Here, the in situ measures show much less rainfall and much smaller discharge values than at Rio Coyolate. The low discharge may relate to lowered rainfall (i.e. the in situ rain gauge is more accurate than the TRMM) and may be further reduced by high agricultural usage. Experts familiar with the Villa Canales site report that the gauging station does not have reliable data, due to some external influences, such as: 1) this river receives urban drainage and 2) communities around the river get their water supply for agricultural purposes from this river in some seasons of the year. Agricultural use may lead to discharge measures that were much smaller than would be expected for the observed rainfall.

At this point, the two different results at these sites suggest that the use of TRMM data to estimate rainfall and discharge may be a significant advance, but that the discrepancies at the Villa Canales site indicate that the calibration process may require that additional details.

Our study shows that the planned enhancement of TRMM-based real-time satellite rainfall estimation based on a regional and dynamic bias adjusting scheme (Huffman et al., 2007) may hold promise to overcome the shortcomings observed for Villa Canales.

5. CONCLUSIONS AND RECOMMENDATIONS

The development of this methodology will allow for rapid streamlining of new GPM-generated flood products into an important regional decision support system, SERVIR. GPM rainfall products are expected to be more accurate and timelier than current products from either TRMM or AMSR-E. GPM will continue to provide the information needed for Dartmouth to generated flood inundation maps long after the AMSR-E satellite fails. Dartmouth’s discharge measurements are crucial for calibrating models for discharge of rainfall from select watersheds. The integration of rainfall into the decision support system represents an important first step in the shift from monitoring discharge to anticipating discharge and thereby forecasting flooding events. GPM integration into SERVIR will allow for disaster anticipation, rapid flood response and appropriate allocation of resources. The goal of this research is to mitigate injury and death due to flooding should another heavy rainfall event like Hurricane Stan occur in the future.
The results of Experiment 1 give encouraging results in the continued or improved offering of the Dartmouth Flood Observatory’s flood inundation map. Of the eighteen regional sites where AMSR-E and TRMM results were compared, the six sites with a moderate or strong flood signal revealed a strong correlation (rave= 0.80) with only slight variability between the correlation on these six sites (the standard deviation was 0.072). When the twelve sites without a strong flood signal are considered, the correlation is weaker (rave= 0.143) and much greater variability (the standard deviation was 0.414). These initial results give encouraging evidence that TRMM (and since TRMM is being used here as a GPM proxy) GPM data will give continued flood detection performance. With the transition to a new sensor, however, calibration will be required. While more frequent sampling that is expected to become available with the GPM sensor may be useful, our experiment was unable to address this issue.

The results of Experiment 2 give encouraging results in the improvement in the detection of flooding in Mesoamerica. Our estimates rainfall during 1 to 10 October 2005 at the two study sites revealed good agreement between measured and estimated rainfall at one of the sites and poor agreement at the other site. When we applied an empirical approach to estimate cumulative discharge associated with this rainfall, we found fairly good agreement with stream gage measurement of discharge and estimated discharge at one of our sites and poor agreement at another site. These results shows that the planned enhancement of TRMM-based real-time satellite rainfall estimation based on a regional and dynamic bias adjusting scheme (Huffman et al., 2007) may hold promise to overcome the shortcomings observed for the site with poorer agreement.

Together both experiments suggest that continued availability of the SERVIR flood measurement products will require calibration procedures with the transition to new NASA sensors. The potential for additional products, including the possibility of estimated flood “now casts” may be possible with the continued development of the dynamic bias adjusting scheme using real-time satellite products.

6. REFERENCES


NSIDC, National Snow and Ice Data Center, 2008. AMSR-E/Aqua L1A Raw Observation Counts Digital Media. url address: nsidc.org/data/docs/daac/amsrel1a_raw_counts.gd.html


SERVIR, 2008 url address: www.servir.net.