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Integrating Global and Local Forecasting Resources and Methods for Flood Warning Systems in Central America and Caribbean Region

José Fidel Pérez
Brigham Young University

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José Fidel Pérez

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E. James Nelson, Chair
Norman L. Jones
Daniel P. Ames
Rollin H. Hotchkiss
Gus Williams

Department of Civil and Environmental Engineering

Brigham Young University

ABSTRACT

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José Fidel Pérez
Department of Civil and Environmental Engineering, BYU
Doctor of Philosophy

Hurricanes and tropical storms occur very frequently in the Central American and Caribbean Region (CA&CR). These extreme weather events produce a lot of rain and consequently a lot of flooding. Damages and loses have been estimated to amount to 13.4 billion dollars in the last ten years. Flood Warning Systems (FEWS) are a key preventive strategy to reduce risk. Technological progress is improving the resources made available for FEWS to be more viable. In spite of the international support for FEWS and the fast development of ICT, there are very few countries in the CA&CR that have succeeded in developing fully operational warning systems that are functioning in a sustainable manner for a long period of time. There is disconnection between the community-based systems and the centralized systems, as well as between the National Meteorological Services (NMS) and the National Hydrological Services (NHS) which tend to work many times in isolation.

The general purpose of this work is to unravel the disfunction/chaos of the way early warning systems are done and provide guidelines to integrate flood warning system at all scales to be used in operational forecasting, particularly for countries in the CA&CR. Flood warning can be seen as a set of sub-systems in which forecasting is only one of those sub-systems. A conceptual framework has been proposed to classify flood warning systems using the spatial and temporal scale at which the flood warning systems operate, subdividing them into Global, Regional, National and Local FEWS. In practice, these systems are not operated in an integrated manner.

Emerging technology is available to allow the integration of global- and local-scale forecasting resources in the CA&CR. The Tethys Platform has a series of online tools applicable to flood forecasting. A workflow is given for the use of four apps in Tethys for flood forecasting: (i) Streamflow Prediction Tool; (ii) Reservoir operation tool; (iii) Hydro Viewer Hispaniola; Flood Map Visualization tool.

Keywords: flood, warning, forecasting, Central American and Caribbean Region, National and local warning systems

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1 INTRODUCTION

This first chapter introduces the topic of the research whose main goal is to define and demonstrate how flood warning systems can be applied in the operational setting of flood forecasting centers as well as in community-based flood warning systems in the Central American and Caribbean Region (CA&CR). The first sections show how weather-related hazards result in great amount of damages and losses of property and lives in the Central American and Caribbean region (CA&CR), which has brought attention and support from the international organizations for flood warning systems and the type of organizations involved at all levels. The other sections go through a list of advances in resources and products that make it easier to develop flood warning systems, but then shows that in spite of this there are problems and limitations in developing countries to make flood warning a mastered art. The general and specific objectives are stated, and then the chapter ends with a brief description of the content of subsequent chapters.

1.1 Weather Related Hazards in Central American and Caribbean Region

Central American and Caribbean countries, located in the path of tropical storms and hurricanes, are often hit by these major events that cause large flooding during the hurricane season that begins in June and ends in November. There are on average 9.3 named storms and 5.8 hurricanes per year in the Atlantic season, but there are very active seasons like the one in 1995 that had 19 named storms and 11 hurricanes (Landsea, Bell, M., & Goldenberg, 1998).

There are other atmospheric events besides hurricanes and major tropical storms, such as cold fronts and tropical depressions that sometimes cause additional flooding, making flood early warning systems even more important. Some authors have demonstrated that there is an increasing number of heavy rainfall events in the Caribbean (Peterson, et al., 2002). Global climate change is predicted to cause increases of average global temperature and sea level rise, and an intensification of the hydrological cycle in a warmer atmosphere (Christensen J. H., 2007). This will increase the risk of extreme weather and climate events such as droughts, floods, heat waves, and stronger storms, making these events more frequent and intense (Kleiner, 2010). Tropical cyclones are expected to become more intense, with heavier precipitation and greater wind speeds according to the Intergovernmental Panel on Climate Change (IPCC) (Salomon, et al., 2007). The climate regime in the Caribbean will be in a process of change in this century and there will be an increasing threat from more extreme weather and the damages and costs will inevitably increase due to the vulnerability of the region (Taylor, Stephenson, Chen, & Stephenson, 2012). Settlements in the floodplains, and increased urbanization as a result of population growth further exacerbates the vulnerability of the population and communities.

The International Disaster Database (EM-DAT) contains comprehensive datasets of disasters all over the world. It is maintained by the Center for Research on the Epidemiology of Disasters (CRED, 2014). EM-DAT reports the number of events, number of fatalities, people affected and cost of damages for natural and technological disasters. The natural disaster category has 5 sub-groups which cover 12 disaster types and more than 30 sub-types. The flood related disasters for Central American and Caribbean countries in the 10-year period 2005-2014 were generated country-by-country from this database for flood related events, and summarized in Table 1-1.

Table 1-1: Cost of Weather-Related Disasters, Period 2005-2014 in C&CA Region

Type of Disaster	# of Events	Killed	Total Affected	Damage (000 US$)
Flash Flood	6	2,032	46,553	$ -
General Flood	87	968	2,426,414	$ 1,244,316
Local storm	1	6	73,122	$ -
Storm surge/coastal	1	-	4,690	$ -
Tropical cyclone	111	4,643	6,142,695	$ 12,143,077
unspecified	4	10	4,533	$ -
T O T A L	210	7,659	8,698,007	$13,387,393

During the ten-year period, there have been 210 events, killing over 7000 and affecting over 8.6 million people. Where no figures are shown, it is because no reports are available for this period. The exact numbers for damage per event are not always available, but even though it is incomplete, the estimated cost for all events in the region is a staggering amount of 13.4 billion dollars in the ten-year period. General floods and tropical cyclones account for 41.4% and 52.9% of the events, and 27.9% and 70.6% of the total affected population. An interesting result is that the category of flash floods has only 2.9% of the number of events, and yet accounts for 26.5% of the total number of deaths as shown in Table 1. This is one category where incremental improvements in flood warning systems could make an important contribution to reducing losses.

1.2 International Support for Flood Warning Systems

The 2005-2015 Hyogo Framework for Action, agreed upon by 168 countries, led to a paradigm shift in disaster risk management from emergency response to a comprehensive approach which also includes preparedness, of which warning systems are a key preventive strategy to reduce risk (ISDR, 2005). This framework motivated many efforts in creating resilience from a variety of research perspectives including those from the hazards/disasters and global change communities, and the identification of standards and metrics for measuring disaster resilience models (Cutter, et al., 2008).

The Organization of American States (OAS, 2018) has promoted the Central American Program for Flood Early Warning in Small Basins, an initiative aimed at developing a Regional Platform of Community-Based Flood Warning Systems (CB-FEWS) in support of Civil Defense or Civil Protection agencies in the eight-member countries of the Central American Integration System (SICA in Spanish) (SICA, 2018) that also includes the Dominican Republic. This initiative has the support of the Global Platform of United Nations for the Promotion of Early Warning (UN/PGPAT) and the International Strategy for Disaster Reduction of the United Nations (UNISDR, 2018). The UNISDR launched in 2006 its Online Platform for the Promotion of International Early Warning Program. As a result of this program, OAS has established the Inter-American Network for Disaster Mitigation (OAS-DSD, 2018) to assists the sharing and transfer of information and knowledge to the development of "best" practices for replication and extension of EWS across the region. An international strategy of the UN, the Inter-American Network for Disaster Mitigation (INDM) supports key priority actions for Risk Management Programs to provide technical assistance in the formulation of public policy on risk and disaster management. The Caribbean Disaster Emergency Management Center (CDEMA, 2018), as well as the OAS, has been providing training workshops following the disaster mitigation efforts in this region.

1.3 Organizations Involved in Flood Warning Systems

Key actors involved in early warning projects in the region include, as described in *Table 1-2*, several United Nation’s Umbrella organizations, international cooperation agencies, humanitarian aid organizations, and many non-governmental organizations which develop projects with funding from International Financial organizations and networks of donors.

Table 1-2: Organizations Involved in Flood Warning in the Region

ACTORS	ORGANIZATIONS	ROLE
research centers	HRC, CRRH, CIIFEN, and CATHALAC, CEPREDENAC, CAPRADE	promoted applied research that benefits EWSs and IT as part of disaster prevention
Emergency Management	CDERA, CNE,	Emergency and rescue operations
International Cooperation agencies	CIDA, USAID, GIZ/GTZ, JICA, AECID	foreign government aid Managed projects
Regional Technical Centers	Caribbean Meteorological Organization	Research,
Regional Weather Monitoring	NHC, Weather Channel	Provide forecast products (hurricane tracking) from prediction models
Donors	European Commission's Humanitarian Aid and Civil Protection Directorate General (ECHO) and its disaster preparedness program (DIPECHO), Sweden (MSB), Germany (GIZ), Norway, Japan (JICA), UK and United States (USAID).	Investment in EW
Financial Institutions,	World Bank, International Development Bank, Caribbean Development Bank, EU,	Loans and grants for training and project development
Non-governmental Organizations (NGOs)	Plan International, Oxfam, Oikos, Trocaire, Care, Solidar, Acsur, Adie et Action, Christian Aid,	Sponsored & manage CB-FEWS projects
Humanitarian organizations	ECHO, International Federation of Red Cross and Red Crescent Societies, Spanish Red Cross, Finish Red Cross,	Help communities and organizations plan for disaster response and Preparedness projects, Assessments on Vulnerability
Meteorological and Hydrological Services (NMHSs)		Monitoring and prediction of weather, climate, water and related environmental conditions, operation met. forecast and flood warning centers.
Civil Defense or Civil Protection	COPECO, SINAPRED, Defensa Civil, CEPREDENAC,	Emergency management, Disaster preparedness,
Armed Forces	National Armies, US Southern Command	Deployment of personnel for Evacuation and rescue, initial response, training for preparedness, distributions o donations.

Some of these organizations like the OAS, GIZ/GTZ and the Red Cross have published manuals for community-based flood warning systems. The Red Cross has developed seasonal forecasts that helps them pre-position emergency stocks and plan early actions for disaster response and preparedness activities based on this longer-range forecast (Braman, et al., 2013).

1.4 Advances in Technological Resources and Product Development

There has been significant progress in the amount and quality of resources made available for flood warning to be more viable. Information and Communication Technology (ICT) is an area that is continually improving, with the processing power of computers doubling every two years (McCarthy, 2017). Some of the most interesting progress in ICT have been high performance computing (HPC), cloud computing, web development, mobile telephony, and telemetry. The internet offers connectivity via the web, replacing or enhancing almost all previous means of communications.

Development in the field of meteorology has paved the way for flood warning, by making the primary input for hydrologic forecasts readily available. Global observations offer many products from rainfall, to evaporation, to soil moisture. Remote sensing and related technologies are now more reliable data collection methods and support if not replace more challenging in situ methods. Weather instruments have become more sophisticated with more precise sub-hourly measurements of weather variables. Real time data transmission is now possible through alternative means such as via satellite radio, and GPRS. Geographic Information Systems and web cartography is another area of growth that creates more possibilities in the development of Flood Early Warning Systems (FEWS). Weather forecasts provide models that extend forecast length to 7 and more days. Global and regional hydrologic forecasts provide wide coverage that includes the location of developing countries now offering numerical or quantitative precipitation forecast. Hydrologic and hydraulic modeling software keeps improving and making it easier to develop models for the purpose of flood warning or evaluation studies for floods or flood maps. Global and regional hydrologic models are available and are made to run simulations automatically.

1.5 Proposed Classification of Flood Warning Systems

While there is a lot of work and progress made in flood warning systems (FWS) in the region, there are also misconceptions and confusing terminology which when taken into practice results in failed projects or ineffective practices.

Flood warning systems are called by different names (Hill, Verjee, & Barrett, 2010), such as these:

LFWS	Local Flood Warning Subsystems (term used by Red Cross and other organizations)
ALERT	Automated Local Evaluation in Real Time (USA) (Dorman, 2013)
IFLOWS	Integrated Flood Observing and Warning System (USA) (Şensoy, Uysal, & Şorman, 2018)
FFG	Flash Flood Guidance Systems (used NWS in the USA)
FFGS	Flash Flood Forecasting Subsystems (Philippines)
FFMP	Flash Flood Monitoring & Prediction (USA) (Gourley, et al., 2017)
GFFGS	Global Flash Flood Guidance System (US Hydrologic Research Center)

GFAS	Global Flood Awareness System (Europe and Japan) (Alfieri, et al., GloFAS-global ensemble streamflow forecasting and flood early warning, 2013)
FEWS	Flood Early Warning System (The Netherlands) (Werner, Dijk, M, & Schellekens,, 2004)
FFPI	Flash Flood Potential Index (USA)
FORTH	Forecasting Operational Real-Time Hydrological systems (Němec, 1986)
CB-FEWS	Community-Based Flood Warning Systems (Gurung, et al., 2014)
IBF	Ingredients-Based Forecasting (Doswell III, Brooks, & Maddox, Flash flood forecasting: An ingredients-based methodology, 1996)

The first clarification needed here is that almost all in this list and most of what is found in practice are actually flood forecasting systems. Flood warning can be seen as a set of sub-systems in which forecasting is only one of those sub-systems. The communication of the alert or threat level is what warning is about, and that is done by the emergency management agencies not by the forecast centers.

A conceptual framework has been proposed to classify flood warning systems using the spatial and temporal scale at which the flood warning systems operate (Perez, et al., 2016), as shown in in Figure 1-1. According to their spatial coverage FEWS are classified as either global, regional national and local. These four types of FEWS overlap spatially and temporally. According to the time scale, each type of FEWS is able to predict different types of weather phenomenon. Forecasts can be long term (years-months), medium term (months-days) and short term (days-hours) forecast. A fourth time span can be added, referred to as “now-casting” (hours-minutes).

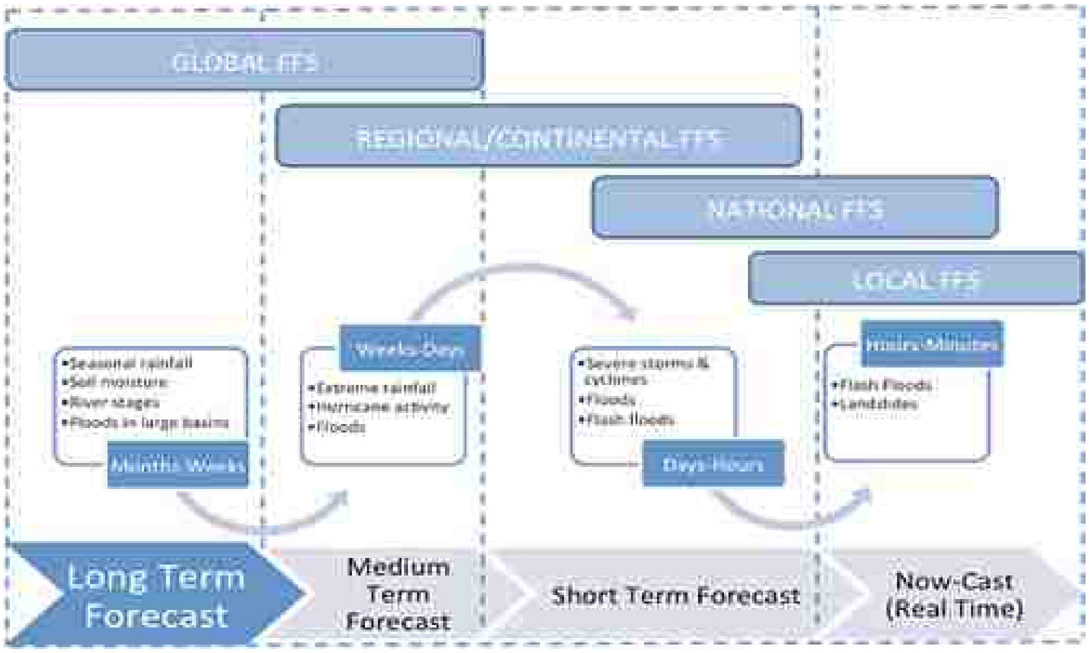

Figure 1-1: The Spatial and Temporal Scale of Flood Warning Systems *(Perez, et al., 2016)*

The geographic nature of insertion of one category into another would suggest that this is the logical way they should operate as it is being proposed here. Bu in practice, these systems are not operated in an integrated manner.

1.6 Objectives of This Research Work

The general purpose of this work is to unravel the disfunction/chaos of the way early warning systems are done and provide guidelines to integrate flood warning system at all scales to be used in operational forecasting, particularly for countries in the Central American and Caribbean Region where the author has experience.

The three specific supporting objectives are:

(i) Assess the present situation of capabilities of NMS and NH in the CA&CR in terms of FEWS, finding out what are the current capacities and limitations;

(ii) Propose how FEWS can work across scales integrating "from Global to Local" and vice versa, to be more effective and to take advantage of the strengths at each level.

(iii) To test/assess the emerging technology that provide online applications for flood warning systems

1.7 Content of This Work

The content of this document is organized using Figure 1-1 as a road map. Chapter Two is related to the first specific objective and contains the results of the assessment and review of flood warning systems in the region. A detailed description from this assessment is contained in separate appendices. Chapter Three and Four are related to the second objective of integrating systems across scales. The third chapter deals with the National and Local scale systems, discussing advantages and disadvantages of each and proposing how they can be linked into a unified system, and how they can contribute to the global scale systems. Chapter Four deals with how two systems that work at Global and Regional Scale, illustrating how these can contribute to the systems at a local scale. Chapter Five is related to the third objective of online applications for flood warning systems. The document ends with conclusions in Chapter Six that summarize the main objectives of how the proposals made here can contribute to improve operation of forecast centers in the hydrologic services of the Central American and Caribbean region (CA&CR), and also suggests what further work should be done in the future.

2 ASSESSMENT OF WARNING SYSTEMS IN THE REGION

This chapter describes the present capabilities in forecasting of the countries in the Central American and Caribbean region. The review aims more at the centralized services of the national meteorological (NMS) and national hydrological services (NHS). There are three appendices associated with this chapter with more detailed country by country report.

2.1 Geographic Context

There are about twenty different countries and a variety of cultures with more than six languages in the Central America and Caribbean region. The region can be divided into the following subregions: Central America, Greater Antilles, Northwestern Caribbean, and the Lesser Antilles or Eastern Caribbean.

Figure 2-1: Map of the Central American and Caribbean Region

The Lesser Antilles can be subdivided into leeward and windward islands, or can be also subdivided according to their status as either British, French, or Dutch commonwealth.

Figure 2-2: Countries in Central America

Figure 2-3: Countries of the Greater Antilles

The countries in the northern part of South America, Colombia, Venezuela and the British Guyana, French Guyana and Dutch-Guyana (Suriname) are integrated and considered to be part of the Caribbean region for trade, commerce, and other purposes. But these countries have not been included in this assessment since the focus of this research is on smaller developing countries.

Table 2-1: Countries in the Sub-regions of Central America and the Caribbean

Sub-region	Group	Countries
Central America	Independent	Belize, El Salvador, Guatemala, Honduras, Costa Rica, Nicaragua and Panama
Grater Antilles	Independent	Cuba, Dominican Republic and Haiti, Jamaica
	US Territories	Puerto Rico
Northwestern Caribbean	Lucayan Archipelago	Bahamas (700 islands), Turk and Caicos,
	Southwestern Caribbean	Cayman Islands (Grand Cayman, Cayman Brac, and Little Cayman)
Lesser Antilles	Leeward Islands	U.S. Virgin Islands, the British Virgin Islands, Anguilla, Saint Martin, Saint-Barthelemy, Saba, Sint Eustatius, Saint Kitts, Nevis, Antiqua & Barbuda (Great Bird, Green, Guiana, Long, Maiden, Redonda), Redonda, Montserrat, Guadeloupe and Dominica.
	Winward Islands	Martinique, St. Lucia, St. Vincent & the Grenadines, Grenada and Trinidad & Tobago
	Dutch Antilles	Aruba, Bonaire and Curacao (ABC islands), and Saba Sint Marteen, St Eustacius, (SSS islands)
	British Overseas Territories	Anguilla, Bermuda, British Virgin Islands (50 islands and cays, Tortola, Virgin Gorda, Anegada, Jost Van Dyke), Cayman Islands, Montserrat, and Turks and Caicos (UK)
	French Territories	Guadeloupe, Martinique, Saint-Barthélemy, Saint Martin, French Guiana
	USA Territories	Puerto Rico, U.S. Virgin Islands (St. Thomas, St. John and St. Croix)
Northern portion of South America		Venezuela, Colombia, Guyanas (British Guyana, French Guyana, Suriname)

Figure 2-4: Countries of the Lesser Antilles and the Eastern Caribbean

The Anglo Caribbean countries that are part of the British Commonwealth, and are integrated also in the Caribbean Community or (CARICOM, 2018). The countries are Antigua & Barbuda, Bahamas, Barbados, Belize, Dominica, Grenada, Guyana, Haiti, Jamaica, Montserrat, Saint Lucia, St. Kitts and Nevis, St. Vincent and Grenadines, Suriname, Trinidad and Tobago.

2.2 The NMS and the NHS in the Region

The National Meteorological and Hydrological Services found in the region are listed in Table 2-2 and Table 2-3.

In most of Central America, the NMS and NHS are unified in a single organization, a pattern which seems to work well. The opposite, separate entities for the NMS and the NHS, is found in the Greater Antilles. The smaller island states of the Lesser Antilles only have the NMS, and that should be sufficient since these are very flat and small territories where the natural drainage systems are not so pronounced to call for nationwide network of streamflow measurements.

Table 2-2: The National Meteorological and Hydrological Services in Central America and the Greater Antilles

	Country	NMS	NHS
1	Belize	National Meteorological Service of Belize (NMSB, 2018)	
2	Panama	Empresa de Transmision Eléctrica, hydrometeorologic direction (ETESA, 2018)	
3	Costa Rica	Instituto Meteorológico Nacional (IMN, 2018)	
4	El Salvador	Servicio Nacional de Estudios Territoriales (SNET, 2018)	
5	Guatemala	Instituto Nacional de Sismología, Vulcanologia, Meteorología e Hidrologia (INSIVUMEH, 2018)	
6	Honduras	Servicio Meteorologico National de Honduras (SNMH, 2018)	
7	Nicaragua	Instituto Nicaraguense de Estudios Territoriales (INETER, 2018)	
8	Cuba	Instituto Meteorológico de la Republica de Cuba (INSMET, 2018)	Instituto de Recursos Hidráulicos (INRH, 2018)
9	Haiti	Unité HydroMétéorologique d'Haïti (UHM, 2018)	
10	Dominican Republic	Oficina Nacional de Meteorología (ONAMET, 2018)	Instituto Nacional de Recursos Hidráulicos (INDRHI, 2018)
11	Jamaica	Meteorological Service of Jamaica (MSJ, 2018)	Water Resources Authority (WRA, 2018)

Table 2-3: The National Meteorological and Hydrological Services in the Lesser Antilles

	COUNTRY	National Meteorological Service	National Hydrological Service
1	Antigua & Barbuda	Antigua Meteorological Office (AMO, 2018)	
2	Barbados	Barbados Meteorological Services (BMS, 2018)	
3	Bermuda	Bermuda Department of Meteorology (BDM, 2018)	
4	Cayman Islands	Cayman Islands National Weather Service (CINWS, 2018)	
5	Dominica	Dominica Meteorological Service (DMS, 2018)	
6	Trinidad & Tobago	Trinidad and Tobago Meteorological Service (TTMS, 2018)	Water and Sewerage Authority (WASA, 2018)
7	Curacao	Meteorological Department of Curacao (MDC, 2018)	
8	Aruba	Departamento Meteorológico de Aruba (DMA, 2018)	
9	St. Marten	Meteorological Department of St Marteen (MDSM, 2018)	

The other interesting observation is that some of the NHS are operated by the national energy or electricity providers, instead of the water resources agency. This is the case of ETESA, the electricity agency in Panama, that has an internal department for hydrometric measurements. The same happens in Honduras where the National Electric Company has a hydrological division in charge of several hydrometric networks located in watersheds.

2.3 Meteorological and Hydrological Services

Real-time data provision seems to be what is interpreted in most countries as an early warning system, and it is certainly an initial step in that direction. There is progress in terms of monitoring networks in many of the countries, and many countries are improving their network moving from old mechanical stations to more modern automatic stations. The Servicio Nacional

Meteorologico de Honduras to give an example, improved in 2014 its monitoring network by adding 14 new automatic weather stations. The NHS in the Dominican Republic has invested millions of dollars with World Bank support in vast network of 120 stations in 1998 and later 68 more stations in 2015. Unfortunately, almost in all cases there is vandalism, theft, and lack of maintenance reduces the number of stations in operations in a relatively short period of time.

The NMS provide public and specialized weather forecasts in most if not all of the countries in the region. Meteorological forecasts are mostly issued for the current day. In some countries, Costa Rica for example, the forecasts are issued for durations of 1, 2, 3 and 15 days, based on numerical models that are able to map precipitation, temperature, wind, speed, evapotranspiration, relative humidity, thermic sensation, and fire indices. There are daily and weekly bulletins for rivers, other hydrologic conditions and for water quality.

The NMS and NHS of several countries in Central America use the Weather Research and Forecasting (WRF) model for numerical weather prediction. WRF is designed for atmospheric research and operational forecasting applications (NCAR, 2018). The Global Forecast System (GFS), used mainly in Caribbean countries, is a weather forecast model produced by the National Centers for Environmental Prediction (NCEP) (NOAA/NCEP, 2018). GFS has a global coverage with resolution of 28 kilometers between grid points, and is used by the operational forecasters who predict weather out to 16 days in the future.

The Regional Specialized Meteorological Center (RSMC) for WMO-RA-IV Hurricane Committee, responsible for tropical cyclone forecast and warnings for Atlantic and Eastern Pacific issues the TAFB products that cover the Caribbean area, America, Mexico Canada and Bermuda. It is based in Miami with the National Hurricane Center (NHC). The RSMC/NHC collaborates with the Caribbean countries and is producing storm surge forecasting with graphical products and storm surge watches and warnings during 2014 and 2015, available now just for the US Gulf and East Coasts. The RSMC however indicated its willingness to provide during the next several years, some centralized storm surge modelling, forecasting, products, and guidance for the benefit of other RA-IV countries, since it would be expensive and challenging for each country to develop its own capabilities in all of these areas.

The meteorological services in several of the island state of the Caribbean get direct assistance and support from the meteorological services of countries in Europe of which the Caribbean countries were, or still are, a colony of. Some examples of these are the following: The Met Office from the United Kingdom is the supplier of weather information and forecast for Anguilla, British Virgin Islands, and Monserrat. The former Dutch colonies are part of the Kingdom of the Netherlands and get support from the Royal Netherlands Meteorological Institute (KNMI) has played a key role in creating and supporting the meteorological organizations in Aruba, Bonaire, Curacao, Saba, St. Marten, St, Eustacius (KMNI, 2013). Likewise, MeteoFrance supports the French Caribbean territories. The US agencies National Weather Services and NOAA support the Puerto Rico, Virgin Islands. Interest in weather services also come from the aviation industry since many of these islands are top tourist destination. Such is the case of Bahamas and Bermuda, Turk and Caicos, and the weather forecasts are commonly included in the area served by countries like the United States and Canada for the purpose of offering weather information for flight operations and to the general public.

2.4 Watershed Flood Warning Systems

This is the second level of FEWS in which there is not only a network of stations for hydrologic monitoring to transmit real-time data, but there is also a hydrologic model that generates predicted values of discharge as a hydrologic forecast. The most recent assessment of flood warning capacities in the region shows that there is still a lot to do to make these systems be part of actual forecasting practices in an operational environment (Perez J. F., 2018). Hydrologic models are used in study of flood vulnerability assessments, and some FEWs have been designed with a hydrologic model such as Hydrologiska Byråns Vattenbalansavdelning (HBV) and Hydrologic Modeling System (HMS). A survey carried out and targeting the NHS in the region revealed that only SNET, the NHS in El Salvador, is known to be using operational forecast at watershed level FEWS (Perez J. F., 2018). The most common hydrologic models found are the HBV and HMS.

The countries of the Lesser Antilles have no experience or little experience with FEWs projects. In the small-island states, the terrain is very flat, the natural drainage network is therefore not very pronounced to call for watershed type FEWS.

2.5 Community-Based Flood Warning Systems

The local level FEWs are usually called community-based flood warning systems. These are low-tech and low-cost systems that rely on the community to operate it themselves. CB-FEWS are preferred by the NGO and non-profit organizations. A more detailed discussion of CB-FEWS is presented in Chapter Three.

The United Nation's Education, Science and Cultural Organization (UNESCO) and Coordination Center for of Natural Disaster Prevention in Central America (CEPREDENAC) jointly published in 2011 an inventory of flood warning systems in Central America, which was useful to the assessment in this work (UNESCO-CEPREDENAC, 2012). This diagnosis and inventory is part of the regional action plans of the Disaster Preparedness Program of the

European Community Humanitarian Office known as DIPECHO. These regional DIPECHOs projects identify hazards and vulnerability of communities as a mean of prevention and preparedness for natural hazards. More than 166 community-based systems are part of this inventory in the six countries of Central America, where the ECHO has invested 10 million Euros.

This DIPECHO VII report, along with other reports were helpful in identifying organizations working in community-based flood warning systems, a required step for the surveys. DIPECHO projects are usually executed by non-governmental organizations (NGOs) and with the participation of the communities and the emergency management agencies in the countries The list of NGO and ICA involved in CB-FEWS in Central America is shown in Table 2-4.

No similar detailed inventory is available for the Caribbean countries. For the case of the Dominican Republic, there are two known projects. Plan International established in 2013 community-based flood warning systems in the Provinces of San Juan de la Maguana, Azua and Elias Piña. The Organization of American States (OAS) contributed in 2009 to the design and installation of similar systems in the watershed of the Yaque del Sur river, and another such system in the Mahomita river for the town of Los Cacaos. All these systems in this country were designed with assistance from INDRHI the water resources agency.

There are nine community-based flood warning systems in Guatemala, installed with low cost technology and operated by the community (RIMD, 2008). The USGS and NOAA gave support after hurricane Mitch to improve these systems with some automatic stations with satellite transmission.

Table 2-4: Organizations involved in projects of CB-FEWS in Central America

Organization	El Salvador	Guatemala	Honduras	Nicaragua	Panama	Costa Rica
AAA Deutsche Welthungerhilfe				X		
ACH		X				
ACSUR				X		
AeA		X	X			
ASB			X	X		
BINACIONAL GOAL (Nic+Hond)			X	X		
CARE	X			X		
CARE France				X		
CARE-Nld		X				
Christian Aid			X			
COOPI		X				
CR-Española	X			X		
CR-FILANDESA			X			
CRIC				X		
CR-Nld		X				
Dan Church Aid			X			
GOAL			X			
IFRC	X	X	X	X	X	X
INTERMON				X		
Intermón Oxfam				X		
Nederland Red Cross		X				
OCHA	X	X	X	X	X	X
OIKOS	X					
OXFAM - GB		X		X		
OXFAM BEL	X					
OXFAM Solidarité	X					
PAHO	X	X	X	X	X	X
PLAN INT- UK	X	X	X	X	X	X
Save the Children Spain				X		
SOLIDAR	X					
Spanish Red Cross	X			X		
Swiss Labour Assistance	X					
TROCAIRE		X				
UNDP			X			
UNICEF	X	X	X	X	X	X
UN-ISDR	X	X	X	X	X	X

2.6 Global and Regional Hydrological Forecast

There are two recent developments that come as a novelty for flood waring in the region. These will be dealt with later in Chapter Five, but for the sake of completeness of the assessment they are introduced here.

The first interesting development to be mentioned is the Haiti and Dominican Republic Flash Flood Guidance (HDR-FFG) developed by the Hydrologic Research Center (HRC, 2018), in San Diego US, with support from the National Weather Service (NWS) and the World Meteorological Organization (WMO) between 2015 and 2018. The first deployment of the Central America FFG was in 2004. Training sessions are being organized by WMO and NWS in the San Diego, and the last one in Santo Domingo (WMO, 2018). The participants are representatives of the National Meteorological and Hydrological Services (NMHSs), which include INDRHI and ONAMET.

The FFG developed by the HRC provides regional and country scales, serving the NMS and the NHS with this operational tool to provide flash-flood watches, warnings and threat.

HRC developers were contacted to participate in the assessment for this research, and suggested that the NMHSs can be asked in the next season after they have had a chance to use the system (Georgakakhos, 2017). Access to the last version is restricted to official organizations from the countries. Calibration is known to be a challenge to be treated in further work to be done by HRC.

The second important development is the tool developed in 2015 by Brigham Young University (BYU), an application called the Stream flow Prediction Tool (SPT), based on hydrologic forecast provided by the European Center for Medium Range Weather Forecast (ECWMF) (Snow, et al., 2016). The resolution of the ECMWF forecast is applicable to very large basins. The SPT produces a downscaling of this forecast, and then applies the method known Routing Application for Parallel computation of Discharge (RAPID) (David C. , 2017) (David, et al., 2011). This is a Muskingum matrix method which STP applies over a network of nodes defined by the layers of stream network and sub-basins. STP runs daily automated and. The SPT runs daily in the BYU Tethys portal and is available for all the watersheds in the Dominican Republic, see **Figure *2-5***, and watersheds in South America (Brazil and Argentina) Asia (Bangladesh and Nepal), Africa (Snow A. D., 2015).

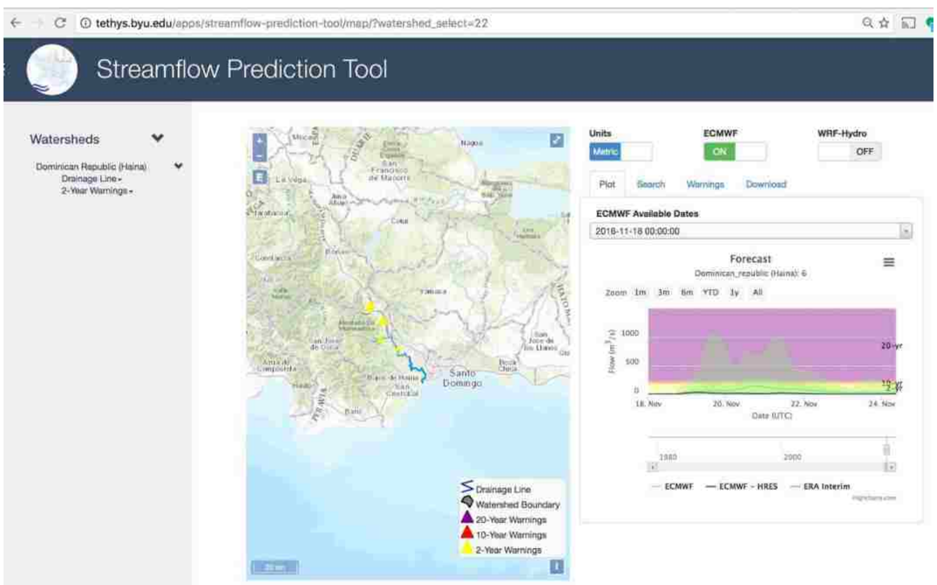

Figure 2-5: Streamflow Prediction Tool for the DR

A flood warning system based on STP tool was developed by Aquaveo and BYU for three watersheds in the Dominican Republic. This project was by the United States Agency for International Development (USAID), with the purpose of creating capacities at ONAMET and INDRHI, the NMS and NHS respectively. The basins for which this warning app is available are the Isabela, Ozama, Haina and Higuamo rivers. This application allows the user to visualize the extension of the floodplain for different levels of the river, and it takes the forecast given by the SPT.

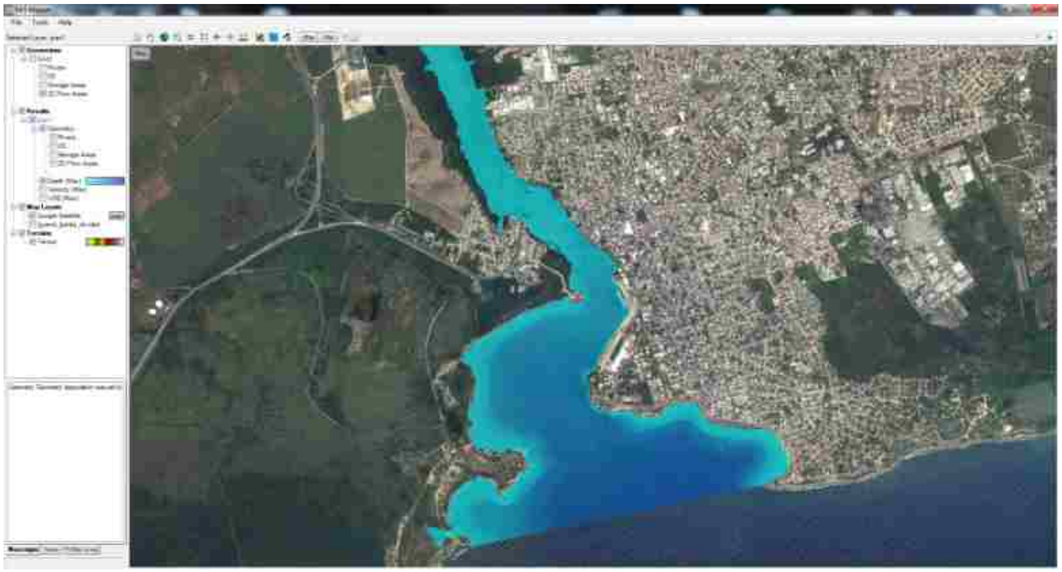

Figure 2-6: The BYU Hydro App for the Rio Haina watershed

2.7 Multi-Hazard Warning Systems

The countries in Central America are in the so called “ring of fire” due the natural threats faced for the seismic and volcano activities and the extreme weather events such as hurricanes and tropical storms. The geographic, geological, and tectonic position make these territories highly vulnerable, and this is further exacerbated due to its social, economic, environmental deterioration and development situation. Warning systems, therefore, need to be developed with a multi-hazard vision. INETER, in Nicaragua, offers meteorological services and seismic and volcano monitoring, as well as weather, maritime and tidal forecast. SNET runs the SATCA, or early wanting systems for Central America, a web page that offers monitoring and warning for drought, floods, hurricanes, earthquakes, volcanoes, tsunamis. SNET also works on climate change studies, seismology, oceanography, volcanology, hydrology. SNET has drawn the attention and support of agencies in the US such as NOAA, NASA, USGS, the Dartmouth Flood

Observatory, and the financing of USAID, European Union, IDB, and other. This country stands out as the leader in the region with its monitoring and multi hazard warning systems. SNET is both the NMS and the NHS in El Salvador and is part of the Ministry of Environment and Natural Resources. INSMET, in Cuba, has also been working on multi-hazard warning systems which includes riverine and coastal flooding, droughts, forest fires, and other threats (Carrasco Diaz, 2013).

2.8 Opportunities for Flood Warning Projects in the Region

There are several initiatives and projects that represent good opportunities to further advance the science and art of flood warning.

The World Meteorological Organization (WMO) is currently working with the Coastal Inundation Forecast Demonstration Project (CIFDP) with pilot countries Bangladesh and the Dominican Republic, two countries in region identified as vulnerable to coastal flooding (WMO/JCOMM, 2018). Flooding in general is known to be the most reported extreme event during 2001-2010, and the most common natural hazard affecting socioeconomic development in the Caribbean. The CIFDP has as an objective to develop and implement a forecast weather system including tropical cyclone characteristics, through the coupling of a wave model, a surge model and a river model. The Project Steering Group (PSG) assigned by WMO started the project in 2011. WMO prefers an island approach while countries in the Caribbean prefer a regional approach. The PSG has recommended the project to continue with the DR as a beta-project instead of a pilot project, where full user involvement is guarantee while Haiti remains uncertain. The CIFDP is now in Phase two of system implementation. Phase 3 of pre-operational testing is scheduled for 2015-2016, and Phase 4 of Live Running & Evaluation is scheduled for 2016-2020.

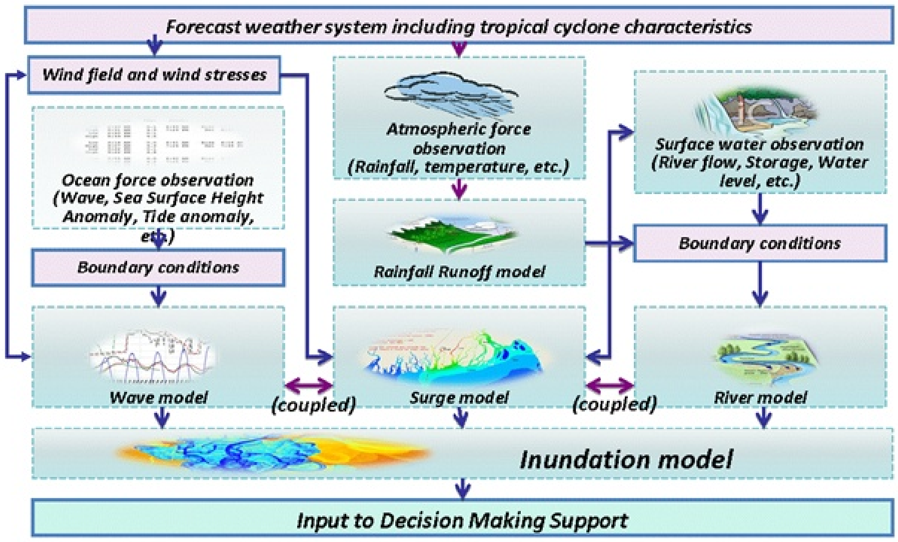

Figure 2-7: System Design for Coastal Inundation Forecasting (CIFDP/WMO)

The GEOSS Caribbean Flood Pilot has the following main objectives:

- To demonstrate the effectiveness of satellite imagery to strengthen regional, national and community level capacity for mitigation, management and coordinated response to natural hazards;
- To identify specific satellite-based products that can be used for disaster mitigation and response on a regional level;
- To identify capacity building activities that will increase the ability of the region to integrate satellite-based information into disaster management initiatives.
- The Caribbean Flood Pilot began its planning activities earlier this year and aims to provide an operational demonstration this hurricane season. The pilot will include activities for every phase of disaster management: mitigation, warning, response and recovery.

Water managers and scientists from several federal, state, and local agencies (USBR, USACE, ERDC, NOAA/NWS), and universities in the US are involved in a project known as Forecast Informed Reservoir Operation (FIRO), the viability of which has been tested for Lake Mendocino in California (Jasperse, et al., 2017). FIRO proposes a reservoir management strategy applicable to water supply and flood control. FIRO incorporates short to mid-range precipitation and 15-day ensemble streamflow predictions (ESPs) made by NOAA's California-Nevada River Forecast Center (CNRFC)to inform the flood operations of reservoirs (Delaney, et al., 2017). Release decisions are based on forecast. FIRO uses the Ensemble Forecast Operations (EFO) alternative, a probabilistic approach to manage forecasted risk of reaching critical operational thresholds (Sellars, Reynolds, Kawzenuk, & Ralph, 2016). Multipurpose reservoirs have been traditionally managed using the guide curve and actual water level in reservoir. FIRO seeks to explore and improve multi-purpose reservoir management, by making a balance between water supply and flood control, and ecological flows. FIRO considers scenarios to operate a reservoir: the existing water control manual operation; the "perfect" forecast; and the hybrid operations. A modified guide curve within the FIRO pool is used to improve water supply availability and flood control reservoir operations. In the case of extreme rainfall events over river basins, the operators can make decisions to allow the safe removal of large volumes of water in the reservoir. Release rates should consider the time it takes to pass vulnerable points downstream, where the river reaches are exceedance in their flow capacities.

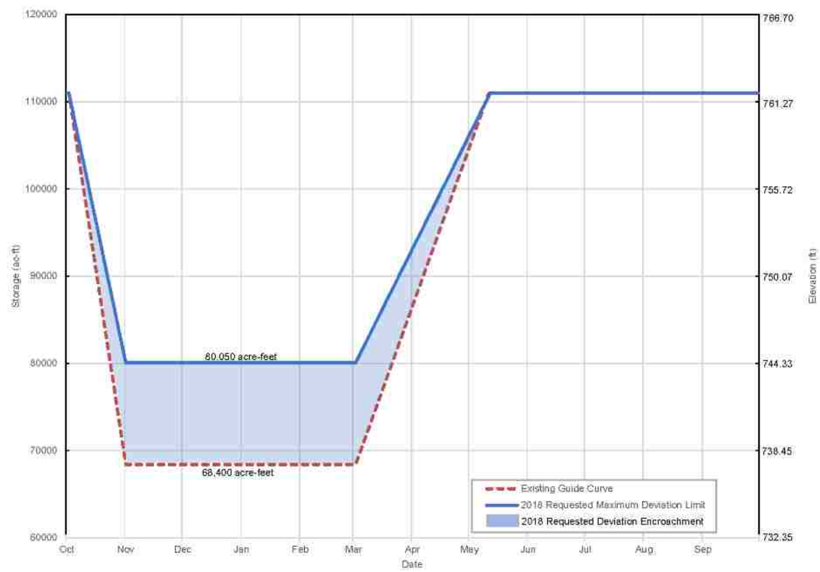

Figure 2-8: Modified Guide Curve for Reservoir Storage and Releases

FIRO can, and therefore tis initiative is an opportunity to continue research and development of flood warning systems. While this concept is starting to be applied in the USA, the precursor of this has been applied in American and European reservoirs under the name of Real-Time Reservoir Operation ration (Che & Mays, 2017).

An important concept that offers more opportunities for flood warning is forecast-based financing, which is promoted by the International Federation of Red Cross and red Crescent Societies (IFRC, 2018). Forecast-based financing has started a new era in disaster management, and the program enables access to funding for early action based on forecast information and risk analysis to promote anticipatory humanitarian assistance in the future to reduce human losses. Early action is triggered by forecast thresholds so that resources are released to provide the assistance (Rüth, Lux, & Scholz, 2017).

Pilot projects are currently being implemented by sixteen National Societies in Africa, the Americas and Asia-Pacific. These are mainly for long-term weather forecast but there are also projects under the program for flood warning systems like on in the Dominican Republic. The forecast-based financing mechanism is a social protection system which integrates early action and preparedness to supports more effective resilience, enhance scalability, timeliness, predictability and adequacy of social protection benefits **Invalid source specified.**.

2.9 Institutional and Management Limitations in Developing Countries

In spite of the international support for FEWS and the fast development of ICT, there are very few countries in the CA&CR that have succeeded in developing fully operational warning systems that are functioning in a sustainable manner for a long period of time. The limitations seen in the flood warning systems are:

(i) Institutional weaknesses: Many agencies do not have enough visibility and often face problems with administrative constraints to maintain quality operations.

a. Administrative constraints: Budget restrictions are commonly found in many national hydrological services (NHS). This limits growth or development since investment is needed continually.

b. Influential role of agencies: priorities are given to other sectors and even though flood forecasting is a matter of saving lives and avoiding economic damage, it would seem that this activity of forecasting centers does not attract the attention of decision makers in governments.

c. Personnel Issues: Staff are not always well trained and personnel turnover is high. Some agencies pay low wages and cannot keep good staff for longer time periods or cannot attract or recruit the more qualified individuals. Hydrology is a specialized field, and people who study it are qualified to gain higher wages.

(ii) Density of Hydrologic Network: There has been a progressive decline in the number of stations that provide hydrologic data. This happens even in developed countries like the United States of America, for a variety of reasons:

a. Budget limitations, especially in developing countries.

b. Occurrence of the climatic hazards themselves destroy and/or damage stations during a hurricane or a flood.

c. Vandalism and theft of monitoring stations is a great limitation to be able to maintain an adequate density.

(iii) Technological gap to keep up to date with emerging technology and improvements

a. High Cost of software, hardware and upgrades;

b. Lack of trained programmers; Many agencies have staff that are very knowledgeable about operational hydrology but have less proficiency in programing skills and IT abilities.

c. Dependency on consultants for specialized modeling

d. Tendency to rely on forecast products provided by regional bodies without comprehension of relative strengths and weaknesses or abilities to do anything about them.

(iv) Disconnection between the different services

a. CB-FEWS and National FEWS are not working together

b. National meteorological services (NMS) and NHS work in isolation and sometimes in competition against each other

It should be stressed that there is a gap between centralized and local FEWS. The community systems are not managed by the centralized forecast centers. An effort by NGOs and organizations promoting CB-EWS is needed to develop systems that are integrated to the national systems. On the other hand, the centralized systems need to be integrated with the global flood forecast services such as GloFAS, and flood monitoring like the Dartmouth Flood Observatory, but the surveys revealed than none of these two services are known by the official agencies in charge of flood forecasting in the region. More promotion and collaboration are needed to take advantage of the services.

2.10 Summary

There are some important conclusions to be pointed out from the above review of the capabilities in each of the countries.

Several projects have been implemented in the Caribbean, Central and South America to establish regional or centralized Flood Early Warning Systems (FEWS) based on networks of automatic stations with satellite or radio telemetry. These are often implemented as part of recovery projects after hurricanes and catastrophic flood events by national governments with the funding of international financial institutions. Many times, the networks deteriorate in a short time due to a number of reasons, like lack of maintenance, vandalism, technology obsolescence, destruction by the natural hazards themselves. The cost of installation of automatic stations with telemetry data transmission are very high. Operational costs are also high. And even if the networks are properly maintained and preserved in operation, most of these systems are not a full flood forecast and warning system. Real-time data provision is only one component of the flood warning systems.

The national meteorological services (NMS) are doing better that the national hydrological services (NHS) in terms of providing forecasts. Practically all the countries have their national meteorological services (NMS) that are capable of operating the weather forecast centers. The NMS get support from WMO and the regional forecasting centers defined by WMO for the region. Some countries get direct support from the meteorological offices of North America and the European countries of which the Caribbean nations were previously a colony of. WMO has supported the NMS in the region, training forecasters, promoting the development of tools and overseen the proper functioning of the NMS. WMO does have a Commission of Hydrology (WMO-CHy, 2018), but efforts are mostly oriented towards the meteorological side.

The tendency in meteorological forecast for the region is to have the better equipped regional agencies and more capable weather services of developed nations assist the developing countries in their NMSs. These regional agencies use coupled global and regional models to provide more accurate information. Given the nature of meteorological phenomena, this is necessary. This approach could be the better solution in the field of hydrological forecast. The developing countries just do not have the resources to consistently develop and improve the models, tools, products or technology needed.

There are initiatives currently developing such global-regional tools that provide forecast for Central America and the Caribbean. The Haiti-DR Flash Flood Guidance Systems (HDR-FFG) and the Central America Flash Flood Guidance Systems (CA-FFGS) are an example. This particular tool is supported by WMO and is at a mature stage of development. Other countries are expected to join soon. Another tool of this type is the Streamflow Prediction Tool developed by BYU (Snow, et al., 2016). It is currently in use in the Dominican Republic and has the potential to be further developed and applied in the region.

Hydrological models have been used in the region in hazard evaluation activities like in the elaboration of flood maps. Only a few of the existing EWS use a hydrologic watershed model in operational flood forecasting. SNET in el Salvador and maybe to some degree the IMN of Costa Rica do have simulations, via a hydrologic model, as part of the forecasting procedure. The small island states in the Caribbean are very flat and are also very small with a poorly defined natural drainage network. In these cases, a watershed model would not be the ideal tool. The FFG approach can provide a better solution. But for the larger countries in Central America and the Greater Antilles, the hydrologic model can offer better resolution in the reproduction of flood behavior than the global-regional models that use coupled atmospheric-land surface models. The last two approaches are explored in the coming chapters.

3 INTEGRATION LOCAL AND NATIONAL FLOOD WARNING SYSTEMS

This chapter describes how local and national level flood warning systems can work in an integrated manner. The national systems dealt with here are the watershed-based FEWS operated by the National Hydrological Services (NHS) or whichever agency is responsible in the country. The local FEWS are usually referred to as Community-Based Flood Early Warning Systems (CB-FEWS), and are operated by volunteers in the communities. This chapters describes the main concepts behind both types and the organizations that are promoting and supporting the initiatives in the region. The advantages and disadvantages of both types of systems are discussed. The chapter also addresses the issues to be improved upon and proposes the integrated operation of both.

3.1 National Level FEWS

The FEWS at national levels are also referred to as "centralized" systems since the FEWS for several basins are operated from a forecast center at the NHS of a given country or region, which monitors the flooding conditions in many watersheds from a single "center" of hydrologic forecast services. These national level systems are based on watersheds, following the conventional territorial divisions used in hydrology.

The national systems have the following four principal components: (i) A network of hydrometeorological stations at key monitoring sites; (ii) Communication channels to transmit real-time data from the stations to the forecast center, usually provided by satellite telemetry; (iii)

The weather forecasting models; and (iv) A hydrologic model used to make simulations to generate the predicted discharge values for the precipitation data.

An example of such systems can be seen in the River Forecast Centers (RFC) of the National Weather Service (NWS) that have been in operation over four decades (Peck, 1976). The NWS operates 13 RFCs in the United States (NWS, 2018). The duties of the RFC are to provide river and flood forecasts and warnings for the protection of lives and property (NWS, 2018). The forecast process used by the RFC of the NWS are summarized in three steps: (i) Data collection - precipitation from several sources including rain gauges (NWS, USGS, USACE), radar, and reservoir levels and temperatures; (ii) Simulations with rainfall-runoff hydrologic models; and (iii) Issuing the 48- and 72-hour forecasts showing river stage and flow at different locations.

There are of course many candidate models to be used in hydrologic analysis. The RFC of the NWS use the well-known Sacramento model (Sorooshian, Duan, & Gupta, 1993). However, the most popular model in the USA for event simulation is the Hydrologic Modeling System developed by the Hydrologic Engineering Center (HEC-HMS) of the United States Army Corps of Engineers (USACE). HEC-HMS has become standard industry practice, known worldwide, and it is also the most widely known hydrologic model in the region of this study. Since it is much easier to use than other models, this suits the capacities of staff at NHS in developing countries. It is used for both event and continuous modeling (Chu & Steinman, 2009). The HEC-HMS model was used in a FEWS in Costa Rica operated by Instituto Meteorológico Nacional (IMN, 2018), for the Sarapiqui, Puerto Viejo and Sucio river basins in the pilot "Costa Rica Early Warning System for the Hydrometeorological Hazards Project" (WMO, 2014). It is not known if this model is still currently used by IMN forecast operations.

Another model used is the Hydrologiska Byråns Vattenbalansavdelning (HBV) model, which can use basin subdivision and spatially distributed data making the model more physically-based, improving its performance (Lindström, Johansson, Persson, Gardelin, & Bergström, 1997). The semi-distributed structure of the HBV-based TUWien model has been applied to ungauged watersheds, by transposing rainfall-runoff model parameters (Neri, Toth, Parajka, & Viglione, 2018). It is used in the forecast operations by the Servicio Nacional de Estudios Territoriales (SNET), the NHS/NMS in El Salvador (SNET, 2018).

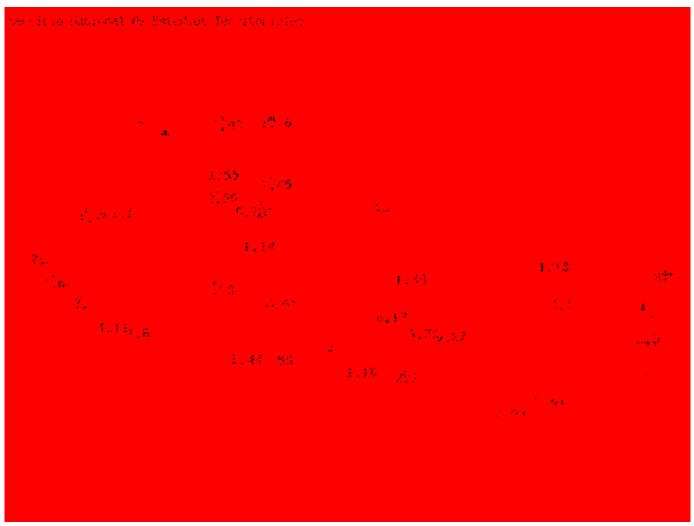

Figure 3-1: Map of Early Flood Warning System operated by SNET in El Salvador

A more advanced model is Gridded Surface and Sub-Surface Hydrologic Analysis (GSSHA) developed by the Engineering Development and Research Center (ERDC) of the USACE (Downer & Ogden, 2004). GSSHA offers the following advantages: (i) preference of distributed, physically-based models over lumped-empirical models; (ii) It is developed and actively maintained by USACE-ERDC and Aquaveo; (iii) it is openly distributed and the source code is made available; and (iv) it was originally developed to allow real time predictions like the ones needed in forecast applications.

HMS is an empirically-based lumped hydrologic model that uses the unit hydrograph concept and the SCS curve number equation. It is also possible to develop quasi-distributed Clark runoff model in HMS, ModClark method, to be able to use spatially varying rainfall with distributed loss methods, obtaining more accurate results of runoff (Paudel, Nelson, & Scharffenberg, 2009). GSSHA is a physically based, multi-dimensional distributed model. These two models have been compared, and GSSHA has been proven to be better simulating land use change scenarios and is able to distinguishing the spatial location of the change and its effects on the watershed response (Paudel, Nelson, Downer, & Hotchkiss, 2011).

While GSSHA is a more advanced model, its implementation in actual forecast operation can pose some issues, one of which is using GSSHA in large watersheds, which can lead to greater computational time to make it undesirable to use in forecast where time is of the essence (Perez, Nelson, & Downer, 2018). Multi-resolution GSSHA models have been proposed for simulations where one resolution is desired for the large watershed and a higher resolution local scale inside the same watershed (Perez, et al., 2016). Two approaches have been demonstrated to be useful to apply GSSHA in large watersheds. One is the small-inset and large-inset models, see Figure 3-2. The other one is the parent/child models as shown in Figure 3-3. This modeling approach was tested in the Esteli River watershed in Nicaragua (Perez, et al., 2016).

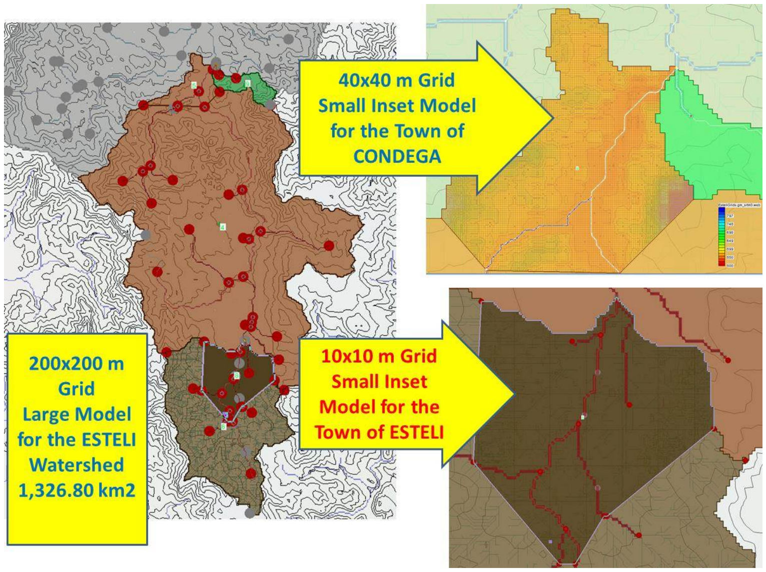

Figure 3-2: Large-Small Inset Models for the Esteli River watershed *(Perez, et al., 2016)*

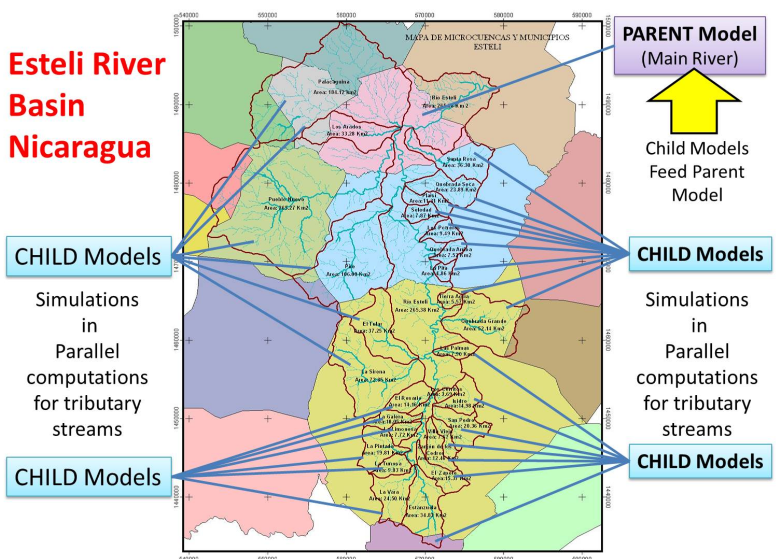

Figure 3-3: Parent-Child Models, Esteli River watershed, Nicaragua *(Perez, et al., 2016)*

Unfortunately, the results of the survey shown in Chapter Two reveal that there are not many of these watershed-based FEWS operating optimally and most projects have failed in attaining the end objective of a FEWS in the region of study.

3.2 Community-Based Flood Warning Systems

Community-Based Flood Early Warning Systems (CB-FEWS) are built with low-cost technology and are operated by the community. CB-FEWS typically go beyond weather monitoring or forecasting, and consider the local technological, social, and political factors. So, while they might be more local and small-scale, these disaster mitigation projects are more comprehensive in their approach, and they include the community organization, analysis of risk/vulnerability and the training required to provide effective emergency response. They are often preceded by a series of Disaster Risk Management (DRM) (Bajek, Matsuda, & Okada, 2008) and Participatory Risk Assessment (PRA) exercises, also referred to as Community Risk Assessments (CRA) (Van Aalst, Cannon, & Burton, 2008).

The key elements in a FEWS centered on the people are: the knowledge of the risk, the alert monitoring and instrumentation, the dissemination, communication, response capacity and organization (Wiltshire, 2006). A community-based flood early warning system for flood preparedness and response consists of five main components (Kuppers & Zschau, 2003), namely:

(i) **Monitoring:** This is done using low-cost instrumentation, sometimes employing non-conventional materials for rain gauges and river staff gauges.

(ii) **Forecast**: This relies on simple observations of local weather conditions. A person in the community would take the decision based on past experience. Since the communities can be isolated from media news, the local expertise needs to be trained to make good judgement, and this is not always the case.

(iii)**Identification** of the Threat: Threshold values for rainfall and river discharge are estimated for each of the 3 or 4-color codes used to define the level of the alert, which is the way a given meteorological event is identified as potentially harmful.

(iv) **Communication:** In a rural setting many times isolated from energy grids, and telecommunication coverage, it is common to rely on radio technology with UHF/VHF band radios, handheld and mobile models (Bin Ali, 2014). Two key issues need to be resolved for these to work effectively. One is that mountain relief may pose a challenge to wave propagation and radio-antennas are required to be placed at key locations. The other important aspect is having this radio communication on a national frequency connected to the national emergency management agency.

(v) **Response:** When the threat is deemed as harmful enough to require actions and response to protect the community, the response mechanism put in place are taken into action which can be, depending on the level of threat, just warning, or evacuation of the population at risk.

Capacity building becomes central with a lot of focus on evacuation plans, flood simulation exercises, and provision of emergency preparedness teams. Having the communities sufficiently capable to handle flood situations by themselves is a good approach as many times during flood events people are left in isolation due to either the damage to roads and communications, or to shortage of national government resources to attend all communities at once in a short time. The people centered approach also brings with its better governance, and a mentality of "don't ask yourself what your government can do for you, but what you can do for your government". By insuring that the people have "skin in the game" or ownership, its operation when properly implemented is more sustainable and effective, even though it may not be built on a foundation of the best technological resources available for making flood forecasts and predictions.

3.3 Comparison of Community and National Systems

Both of these systems co-exist with very little integration most of the time, and do not benefit from the existence of each other. The ideal is for effective CB-EWS programs and initiatives with warning systems that are good enough to provide feedback to the national forecasting centers, while at the same time use the information from those centers. Recent projects in the Dominican Republic, Nicaragua and Costa Rica developed CB-EWS that are integrated to the centralized system and provide a template for how early warning systems in much of the Central American and Caribbean region can be made more effective. Table 3-1 shows a comparison of the centralized and the local flood forecast systems, while Table 3-2 shows the advantages and disadvantages of both systems.

Centralized systems make use of technology for measurement and automatic data transmission, and computers to manage databases and models. A distinct advantage is that they are operated with personnel educated and trained in the science and application of flood forecasting. Lending agencies and some institutional governments usually support them, which means funding is available for the expensive initial investment and ongoing maintenance. A major drawback however is that they are more vulnerable to vandalism and theft than community systems that use simpler stations and instruments. Since the technology is constantly changing, further investment is periodically needed to keep them operational, but the sad truth is that due to budgetary restrictions, once the initial investment is made the maintenance is not adequate. The same story is repeated from country to country, and not long after they are installed the networks are decimated and the systems operate rather precariously.

Table 3-1: Comparison of Regional and Local FEWS

	Regional Systems	Community (Local) Systems
Type:	Automatic EWS	Manual EWS
Technology Level:	High-technology	Simple or basic
	Regional meteorological phenomena, such as hurricanes	Localized storms, or cloud burst, flash floods,
Operated by:	NMHSs	Communities
Monitorin g Network	remote automatic stations equipped with electronic sensors, data loggers, energy sources, and/or conventional stations	Low cots instrumentation; and need not conform to standards used in operational hydrology of NMHSs. Any material (plastic or ceramics) Conforming to usual standards is not required in these systems.
Staffed by:	Employees who permanently manned stations	Volunteers who become active whenever there is a threat or pre-warning condition
Weather forecast	operational meso-scale model quantitative precipitation forecasts	
Weather observations	Radars	In-situ,
Variables measured	Rainfall, river level, and sometimes water quality	Rainfall and river levels or
Data Transmission	satellite telemetry (GOES, Iridium, etc.)	None
Records	Manual reading of paper forms at periodic intervals, or automated databases that store historical time Series	None,
Data processing:	river levels transformed to flow data using the rating curve for the cross section where the site is located	None
Warning Dissemination method	TV, internet,	Horns, whistles, speakers, sirens, bells, megaphones, mobile phones (SMS), radio, band radio,
Reports to:		Community or some civil defense municipal or town group in charge or the response
Communication Means		radio technology UHF/VHF band radio, handheld and mobile models fixed frequency radio receivers
Communication content	Forecast	Warning

Table 3-2: Advantages and Disadvantages of National and Local EWS

	Advantages	Disadvantages
Regional EWS	managed by operational centers that work 24/7 Transmit data in near real time	Expensive to install and maintain Requires well-trained staff for operation and maintenance.
Local EWS	Low cost tech available anywhere Promote a sense of ownership	No systematic data management No standardization of methods, instruments

The following are the salient points in favor of CB-EWS, according to experience in the Philippines (Perez, Espinueva, & Hernando, 2007). First, they empower local government units and communities to protect themselves against flooding, so they are in a better position to take preparedness measures against flooding, and they promote a sense of ownership by the LGU's, and so are easier to sustain. Other advantages of CB-EWS are the following: (i) based on voluntary participation; (ii) strong in response preparedness; (iii) low cost; (iv) take advantage of local knowledge and experience; (v) does not create a dependency of centralized systems; (vi) supported by NGOs and community-minded institutions.

Two important shortcomings are: (i) volunteering does not create long-term commitment; (ii) there isn't systematic recording of measurements that would serve to improve predictions and set alert thresholds that are not fully utilized.

A review in Development of the Regional Platform of CB-EWS, established within the Central American Program for Flood Early Warning Systems in Small Watersheds (SVP) and Reduction of Vulnerability (DSD/OAS, 2009) arrived at the following conclusions:

(i) There is a lack of harmonized methodology for the design and implementation of these systems (multiplicity of methodologies and national and regional manuals);

(ii) Lack of policies, strategy and guide the CB-FEWS;

(iii) Sustainability depends largely on international aid when its discontinued resulting in disruption of operation;

(iv) Most CB-FEWS do not have basic hydrologic studies, resulting in inadequate warning times;

(v) Overlapping of responsibilities in the operation of various components of the FEWS, particularly in communication and preparation of contingency components;

(vi) Lack of coordination between NGOs, which is a challenge to the effectiveness of the systems.

(vii) Limitations on the use of state-of-the-art technologies that could help provide forecasts, warnings and alerts, which in a region where flash floods are predominant with peak times less than an hour, can improve early warnings leading to a more effective response.

3.4 Integrating the Monitoring Networks at National and Local Level

One area where CB-EWS need to make improvements is having better records for the monitoring sites. River levels are measured in staff gages or with color coded bands painted on some fixed object along the river which can be concrete or a rock, indicating the level of warning using green, yellow, orange and red. In some cases, a 3-color ramp, omitting the orange, is preferred. While this color code is useful for flood warning, numerical record of the actual depth or elevation is needed in order to be able to develop and calibrate a hydrologic model.

An example of how to integrate monitoring networks at the national and local level is the CB-FEWS project in the Dominican Republic, carried out by Plan International with the support of USAID, and AECID. Staff gages and rain gages were installed by the NHS in rivers in the provinces of Azua, San Juan and Elías Piña. This project is a good example of resource integration for local and regional systems. Material and organization were provided by this NGO and the donor, but staff gauges installation was done by INDRHI, the national agency of water resources that operates the regional forecast center. In doing so, the stations in this CB-EWS had the same standards as those in the regional system. Figure 3-4 shows how staff gages had both the color code used in CB-EWS and also had the standard staff gages that allow systematic reading of river levels.

Figure 3-4: Example of staff gauges in Rio Tabara, Rio Grande and Arroyo Grande in the Azua province, Dominican Republic

The principles for network design in regards to the location of rain gages (Karasseff, 1986) and staff gages (Brimley, 1990) are common practice in operational hydrology. But in an EWS, the sties need to be strategically located sometimes leading separate sites for flood warning than the previously existing sites. And in developing countries the requirements need to include cost and reliability which creates several interesting problems from factors as diverse as technological, social, and political (Basha & Rus, 2007). In the regular networks, the sites are located for the purposes of water resources evaluation and consideration is given to things like sizes of watersheds, drainage network, and location of future hydraulic infrastructure projects. For EWS the network has to be re-engineered. Sites need to be located having in mind the warning and response, and the population centers that can be affected by a flood. A site is not needed if it is placed at a location that does not provide either enough time, or if there is no population or other target downstream for whom to give the warning.

Another good example of integration of monitoring networks is the FEWS of the Coco the Esteli, Jicaro and Coco rivers in Nicaragua (INETER, 2017). This system combines real-time monitoring with automatic stations and CB-EWS.

3.5 Using Hydrologic Models to Improve Local and National FEWS

A review of CB-FEWS projects developed by non-governmental and non-profit organizations (NGO/NPO) and international cooperation agencies (ICA) reveals that many projects are implemented without having a hydrologic model as the basis of the system. Unfortunately, this also happens in projects of centralized or national level FEWS where the so called FEWS are actually only reporting real-time data.

There are three benefits of using hydrologic models for both national level and CB-FEWS. The model can be used to determine the best location of the monitoring sites, and the minimum/optimal number of stations. Doing this type of analysis, helps reduce the cost of installation of sensors and instruments, but also help identify where persons are needed to manage the stations in the case of stations that are not automatic. Different sites can be tested using a model instead of just “playing by ear” and making errors in site locations. A hydrologic model can be used to develop flood maps which is very important in planning, and also in vulnerability and risk assessments. And the third benefit is to use the model to determine the lead times and warning times.

An example where the above has been done is the CB-FEWS for the Mahomita river in the Dominican Republic installed in 2009 in project sponsored by OAS. Several buildings in the town of Los Cacaos were severely damaged during Tropical Storm Noel in 2007. The project was revisited to use GSSHA, an advanced two-dimensional model, to determine the effectiveness of the three monitoring stations installed in Los Cacaos, and also in Calderon and Benito, located upstream of Los Cacaos (Perez J. F., Nelson, Jones, & Ames, 2018).

3.6 Improving Communication between the Local and National Level FEWS

Results of the survey in the region of this research shows that national level and community level FEWS work in an isolated manner. It has been ideally proposed, but not yet accomplished, that there should be two-way communications between the local and the national flood warning systems. The communities can benefit from the forecast information issued by the centralized system, and at the same time the CB-FEWS can share information about local flood conditions with the national FEWS. To take this to a more complete integration a telephone application was developed for the Haina river in the Dominican Republic (Perez J. F., Nelson, Ames, & Jones, 2018). The app provides a "flood-communication-platform" where the NHS, the NMS, the emergency management agencies, the communities and other key actors interact and share weather and river data, and information about flood conditions. This app also allows communities upstream to warn other communities downstream. This prototype can be applied to other watersheds and other countries.

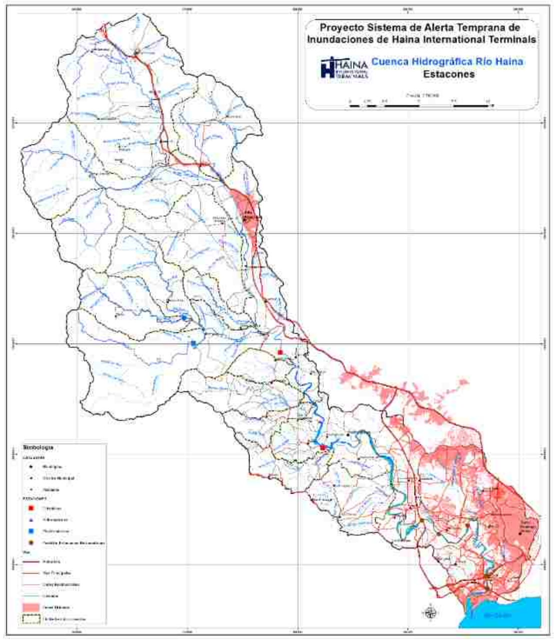

Figure 3-5: Map of the Haina watershed showing the location of monitoring sites

The effectiveness of community–based systems is increased when warnings are handled using the user-centered situation-based approach and context awareness alerting (Meissen & Voisard, 2008).

Another alternative is the use of social media, which has proven to be an effective way to share vital information during disasters. In fact, some of the official agencies do have and use Facebook, Twitter and Instagram and have links from their websites, to allow communication with the general public. A Facebook page has been created for the Yuna river in The Dominican Republic to allow persons to post information and pictures of flood situations in their location (Ernest, 2018). The Facebook page also shows the forecast information from data-driven models previously developed for this watershed using artificial neural networks (Emanueli, 2017). These two research-works cited above for the Yuna river were part of the requirements for M.Sc. thesis at IHE in Delft, The Netherlands. The author of this dissertation acted as supervisor of both of the thesis and as external examiner in one of them.

3.7 Summary of Conclusions about Integration of Local and National FEWS

It is ideal to integrate national and local FEWS so they provide feedback to each other, and leverage on the advantages of each other. The NHMs that operate the local FEWS and the organizations that promote CB-FEWS should work together in planning, designing and operating these systems.

The monitoring system should be integrated. CB-FEWs have a weakness in this regard, because volunteers in the communities usually end when the project are completed. Volunteerism does not crate long-term commitment. One alternative is to use the same field personnel, who ae on the payroll of the NHS, because they are trained to do the work and they are also art of the community. Community field observers at station can report local flood condition to the centralized forecast centers, and these in turn can share information and data with the communities from their more sophisticated weather/hydrologic monitoring systems and the weather as well as their hydrologic forecast

The use of hydrologic models should be applied in the design of both at local and national level FEWS. Models can be used to determine the best location for monitoring sites for the purposes of flood warning. They can also calculate the lead times which is so critical to warn communities downstream. The third advantage is that models can estimate the threshold for the different levels of warning.

Two hydrologic models are known to be used by the NHS at national level FEWS in the region, the HMS and HVB. The Sacramento model has been used by the RBC in the USA for several decades. The more advanced GSSHA model can be used, but the concern is that it requires better trained staff not always available at forecast centers in developing countries. The next issue is that since it is physically-based model, it requires more data to estimate parameters, and this is not always possible to have that all over a watershed to take advantage of its distributed nature. Rainfall is not uniform spatially nor temporarily, so more automatic rain gages data are needed and that is definitely a big challenge for the NMS and the NHS in developing countries. Other issues with GSSHA are running it for large watersheds and the computer power to make simulations with GSSHA simultaneously for many watersheds. Solutions have been found for these two last issues. In the end, the "best" model is not necessarily the one that is more scientifically sound and produces the more accurate and precise results. The "better" model is one that can be applied consistently and one that users are capable of mastering.

There should be integrated communication between NMS and the NHS, the emergency management agencies and the key-personnel who manage the CB-FEWS. An app that achieves this integrated communication and sharing of data and information been developed as pilot for the Haina river watershed in the Dominican Republic. The use of social media has been proven to be affective as a means of warning. A Facebook page has been developed for flood in the Yuna River basin.

4 GLOBAL AND REGIONAL FLOOD FORECASTING SYSTEMS

This chapter describes forecasting systems at global and regional scale, whose development have offered flood forecasting possibilities that can be used in the Central American and Caribbean region. The first part of the chapter goes through a list of global observation systems and the products derived from them. The main part of the chapter is describing the two most promising global/regional tools in forecasting that are being used in the region of this research. The chapter ends with the challenges in the application and further development of these tools.

4.1 Organizations in Space Observation

A number of organizations are continually developing technology for earth and weather observations, and in global and regional weather forecast and flood monitoring/forecast. The Committee on Earth Observation (CEOS) is a senior space agency that coordinates space-based earth observations programs, combining resources from a number of space organizations in different countries like ESA, NASA, NOAA, JAXA, EUMETSAT, CNES, SCIRO, USGS, NSC and METX. The leading space observations agencies that provide information for the region are listed in The Group on Earth Observation (GEO, 2018) is an intergovernmental organization with 79 members and 56 participating organizations whose strategic guidelines are: (i) to coordinate enhancing and interlinking existing systems in order to form coherent global networks; (ii) to ensure access for all to integrated interoperable data sets; and (iii) to develop end-to-end services for disaster management projects. GEO has created a Disaster Management Clearinghouse which is a centralized source of information for disaster management that provides vulnerability/risk assessment, crisis management, and forecast services. One of GEOSS contributions is the flood pilot project for the Caribbean and Namibia, by NASA, SCA, CEOS, UNOOSA. These and other technological resources are described below.

4.2 Global and Regional Weather Observations

Meteorological forecast or weather forecast products are the essential input to an early warning system. Several meso-scale and regional scale models have been developed by US agencies under the NOAA system. While some products are for the use for regional EWS, the dissemination of the information they provide reaches even rural locations through TV and radio news feeds that can help prepare communities anticipate a weather event. The Weather Forecast products that can be used in FEWS are listed in Table 4-2. The National Hurricane Center (NHC, 2018) is a NOAA organization operating at Florida International University (FIU) of Miami, Florida, designated as the WMO Regional Specialized Meteorological Center (RSMC) for the North Atlantic and Eastern Pacific (WMO, 2018).

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Table 4-1: Space Agencies in Global Weather Observations

Acronym	Organization's Name	Website
CEOS	Committee on Earth Observation	www.ceos.org
NASA	National Aeronautics and Space Administration (US)	www.nasa.gov
NOAA	National Oceanic and Atmospheric Administration (US)	www.noaa.gov
JAXA	Japan Aerospace Exploration Agency (Japan)	http://global.jaxa.jp/
ESA	European Space Agency	http://www.esa.int/ESA
GEO	Group on Earth Observations	
GEOSS	Global Earth Observation Systems of Systems	

Table 4-2: Weather Forecast Products for the Region

AGENCY	FORECAST PRODUCTS
National Weather Service (NWS)	Produces a range of products Meso-scale analysis in real time (Real-Time Mesoscale Analysis - RTMA).
The National Hurricane Center (NHC) http://www.nhc.noaa.gov	Hurricane watches. It is also available through NOAA Weather Radio. The Tropical Analysis and Forecast Branch (TAFB), of the NHC provides support on the NHC during the hurricane season, and also makes the estimates of position and intensity of tropical cyclones derived from satellites. Associated estimates of precipitation.
The International Research Institute for Climate and Society (IRI) **http://iri.columbia.edu/**	Includes seasonal climate forecast, status of ENSO conditions, and sea temperature. It also provides maps of temperature, precipitation and 500mb-geopotential height forecasts from Individual Atmospheric General Circulation Models. The maps are longer term (3 months) forecasts and would serve for anticipated provision.
The Tropical Rainfall Measuring Mission (TRMM) **http://trmm.gsfc.nasa.gov/**	TRMM is a NASA-JAXA joint mission that monitors rainfall through multi-Satellite precipitation analysis (MSPA). The RSS TMI product data files contain: sea surface temperatures, surface wind speeds, atmospheric water vapor, liquid cloud water, and rain rates. TRRM and its products provide real time tropical rainfall monitoring with forecast every hour and each seven days.
National Center for Environmental Prediction (NCEP) (NOAA)	**Products Inventory.** Real-Time Mesoscale Analysis (**RTMA**) Products **http://www.nco.ncep.noaa.gov/pmb/products/rtma/#PRRTMA**
Center for Ocean-Land-Atmosphere Studies (COLA) and Institute of Global Environment and Society (IGES) are dedicated to climate research **http://wxmaps.org/pix/avnsr.pw.html**	Online weather forecast maps like the ***GFS Short Range Forecasts of Convective Available Potential Energy and Precipitable Water*** available for the Caribbean and Central America. The Forecasts for each 12-hour interval from 0 to 72 hours.

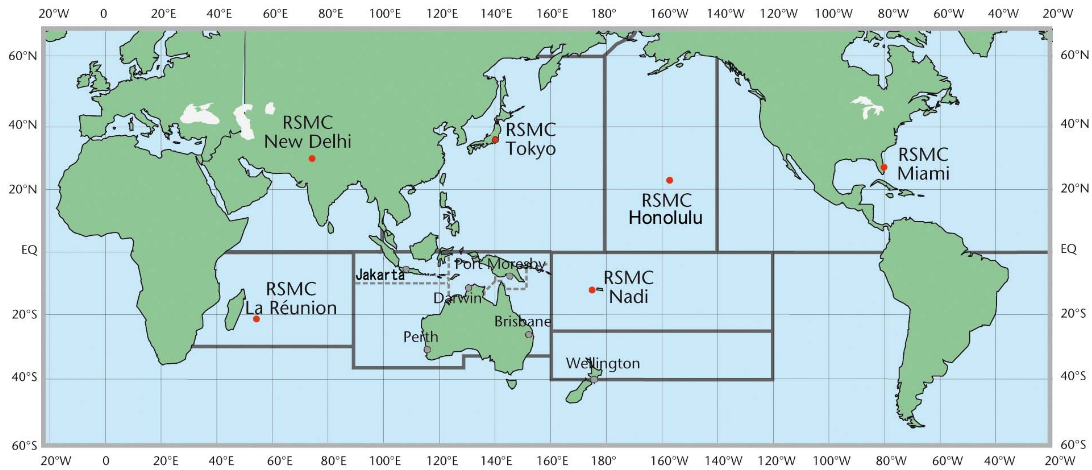

Figure 4-1: Regional Specialized Meteorological Centers and Tropical Cyclone Warning

The NHC issues hurricane watches and warnings via web containing information likely behavior of tropical depressions, tropical storms and hurricanes and hurricane conditions expected during the next 72 hours. All of the Central American and Caribbean region is serviced by the NHC. The NMS and NHS in this region cannot produce this type of forecast themselves.

4.4 Global and Regional Flood Monitoring and Flood Forecasting

Global EWSs use remote sensing technology to detect rising river levels or flooded area. There are already in operation flood information products that provides forecast or now-cast of inundated areas, or of river levels and discharges. The work of the research centers in developed countries makes an invaluable contribution to the agencies charge of EWS. Table 4-3 shows a list of flood information products that cover the region.

Table 4-3: Flood Forecast Services/Products Available Online

SERVICE	DESCRIPTION
GloFAS	The Global Flood Awareness System (GloFAS) http://gfas.internationalfloodnetwork.org/gfas-web/
Flood Observatory	Dartmouth Flood Observatory developed by the Dartmouth College and the University of Colorado http://floodobservatory.colorado.edu/
GFAS	Global Flood Alert System
GFMS	Global Flood Monitoring System, at the University of Maryland, provides http://flood.umd.edu/
FFG	Flash Flood Guidance, developed and operated by the Hydrologic Research Center https://www.hrcwater.org/
ECMWF	European Center for Medium Range Weather Forecast, operating the Copernicus Earth Observation program of the European Union. https://www.ecmwf.int/

The Dartmouth College and the University of Colorado have developed online dynamic maps of Surface Water Record which is a comprehensive map record of the Earth's changing surface water f*or research, humanitarian, and water management applications*. It is for public use and can be used as "River Watch" tool to know when a flooding is currently occurring This remote sensing surveillance tool (Brakenridge, Anderson, & Caquard, 2009) can be used with hydrologic models to predict inundation (Khan, 2011).

A flood early warning is provided by the Global Flood Awareness System (GloFAS) for large river basins and large-scale flood events. It is based on distributed hydrological simulation of numerical ensemble weather predictions with global coverage (Alfieri, et al., GloFAS–global ensemble streamflow forecasting and flood early warning, 2013). Streamflow forecasts are compared statistically to climatological simulations to detect probabilistic exceedance of warning thresholds. It has been tested in actual flood predictions and has been successful in detecting floods up to one month.

The Global Flood Alert System (GFAS) is an attempt to make the best use of global satellite precipitation estimates in flood forecasting and warning. GFAS is promoted both by Ministry of Land, Infrastructure and Transport of Japan (MLIT) and Japan Aerospace Exploration Agency (JAXA), under which Infrastructure Development Institute(IDI) -Japan has developed this Internet-based information system. GFAS converts the satellite precipitation estimates which National Aeronautics and Space Administration (NASA) makes public on its website into useful information for flood forecasting and warning, such as global, regional rainfall maps, text data, and provides heavy rain information by precipitation probability estimates. This system is currently running on a trial basis, posted on the website of International Flood Network (IFNet) in order to verify the satellite precipitation estimates by comparing with surface-based observations.

The satellite precipitation estimate GFAS utilizes is "3B42RT", a product of Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis computed in Real Time (TMPA-RT). These estimates are developed and computed in near real time at NASA Goddard Space Flight Center as a contribution to TRMM (Huffman, et al., 2006), a joint project of the NASA and JAXA, and are publicly available subject to the "data access policy" in (ftp://trmmopen.gsfc.nasa.gov/pub/merged/3B4XRT_doc)

The Global Flood Monitoring System (GFMS), operated by the University of Maryland, provides flood detection/intensity estimates, and calculates stream flow, surface water storage, inundation variables. This system is funded by NASA. Precipitation-input data used in GFMS is the real-time TRMM Multi-satellite Precipitation Analysis (TMPA) and Global Precipitation Measurement (GPM) Integrated Multi-Satellite Retrievals for GPM (IMERG) precipitation information. Real-time quasi-global hydrological calculations at $1/8^{th}$ degree and 1 km resolution. GFMS displays 1-day, 3-days and 7-days maps of instantaneous precipitation and totals.

4.5 Ensemble Prediction Systems

There are two main weather forecast products made available in the Central American and Caribbean region. These are the Global Forecasting System (GFS) developed by the NOAA, and the Ensemble Prediction systems by the European Center for Mid-Range Weather Forecast (ECMWF).

The ECMWF Ensemble Prediction System have been tested over decades, as shown in a work that describes how dynamically defined perturbations were added to validate the ensembles, and model performance was found to be satisfactory, although the performance was found to be potentially poor in winter (Molteni, Buizza, Palmer, & Petroliagis, 1996). The ability of ECMWF to predict sub-daily rainfall have been to the tests and the findings show that further improvement is needed in the representation of subgrid-scale processes to avoid overestimating precipitation in the tropics, and to obtain better representation of the diurnal cycle (Kidd, Dawkins, & Huffman, 2013). The ECMWF is actively developing new approaches to account for uncertainties in model simulations, and tests are conducted routinely for global numerical weather medium-range and long-range predictions to assess the impact of resolutions and sub-grid-scale variability by contrasting the operational performance on seasonal time scales during the retrospective forecast (Weisheimer, Corti, Palmer, & Vitart, 2014). Dynamical downscaling of ECMWF ERA-interim reanalysis and ECMWF seasonal hindcasts show that ERA-interim and ECMWF are good in reproducing the spatial and temporal rainfall variability well, but EMCWF can be found to overestimate the mean and variability over certain regions, but also perform better on grid point by grid point comparison (Diro, Tompkins, & Bi, 2012). The multi-model forecast of ECMWF outperforms other similar single model forecasts (Landman & Beraki, 2012).

Performance of ECMWF's medium-range ensemble forecasts of precipitation was tested on a 270,000 km2 river basin in China, and the study showed that the performance varies with sub-basin properties, between flooding and non-flooding seasons, and with the forecast properties of aggregated time steps and lead times (Ye, et al., 2014).

4.6 Flash Flood Guidance

As stated earlier in chapter two, the Hydrologic Research Center (HRC, 2018), based in San Diego, CA, has developed flash flood guidance systems at global, regional and country scale. A flash flood is a rapid developing flood event that occurs in a short time frame, from cero to six hours. The FFG integrates satellite-based and in-situ observations of precipitation and land-surface hydrology models to generate real-time assessment of hydrologic conditions and the possibility of flood occurrence (Modrick, et al., 2014). FFG combines the satellite and radar precipitation estimates with mesoscale weather prediction models, and physically-based hydrologic modelling. Resolution is in the order of 150-200 km^2 (or 25-50 km^2 for radars).

FFG is also in line with the approach called Ingredient-Based flood warning, (IB-FW) that makes a forecast of the potential for flash flood-producing storms using the notion of basic ingredients (Doswell III, Brooks, & Maddox, Flash flood forecasting: An ingredients-based methodology, 1996). The ingredients of the meteorological process are precipitation amount, duration of the event, and size of the system. This is the standard operational practice in Flood

Warning of the National Meteorological Services, but the NHS are also using this operational tool to provide flash-flood watches, warnings and threat.

The DRH-FFG (Dominican Republic and Haiti Flash Flood Guidance) and the Central America Flash Flood Guidance (CAFFG) system (Shamir, et al., 2013) have been operation for some years. HRC has received support from WMO, NOAA/NWS, and the USAID Office of Disasters, to spread this technology which is now is now globally available (Georgakakos, 2018). HRC has gotten international attention and support from its partners and the FFG system. Other regions specifically serviced with FFG forecast are: Southern Africa, Black Sea/Middle East, Southeast Asia, Southeast Europe, Central Asia, South Asia, Pakistan/Afghanistan, South Eastern Asia Oceania, North West South America (Colombia, Ecuador, and Peru), and the following individual countries: Myanmar, Romania, Mexico, Oman, Viet Nam, and the Republic of South Africa.

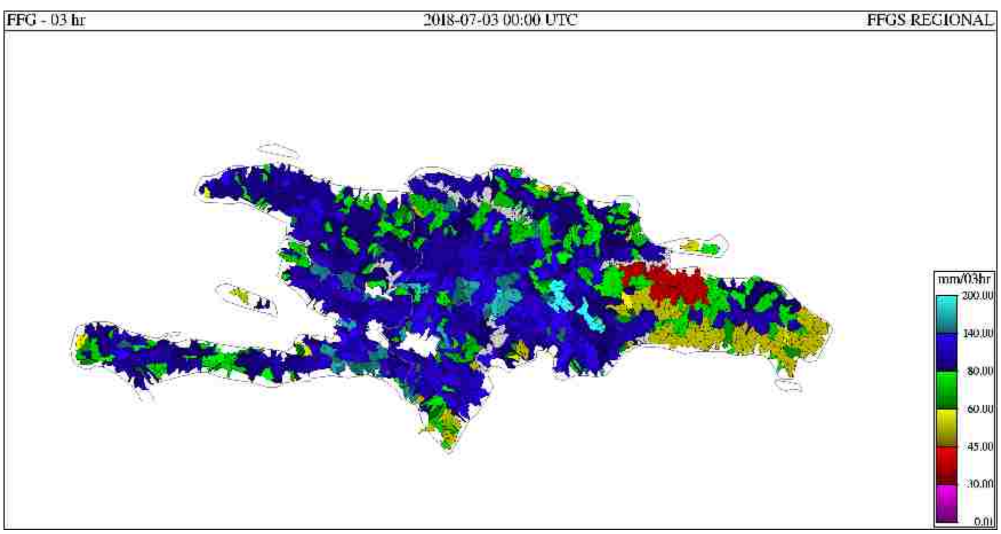

Figure 4-2: Haiti Dom. Rep. Flash Flood Guidance System by HRC

The DRH-FFG and the CAFFG produce in real time flash flood relevant information based on satellite rainfall estimates and telemetered precipitation data, and produces 1-, 3- and 6-hour estimates of mean areal precipitation, 6-hourly estimates of depth-integrated soil moisture, and 1-, 3- and 6-hour flash flood guidance. The information is transmitted to the national forecast agencies to assist with the short-term forecast of flash floods. This FFG provide operational forecasters and disaster management agencies with real- time informational guidance products pertaining to the threat of small-scale flash flooding. This latest FFG by HRC uses satellite and radar precipitation estimates, mesoscale weather prediction models, and is said to use also physically-based hydrologic modelling. Resolution is in the order of 150-200 km^2 (or 25-50 km^2 for radars).

4.7 Downscaling Global Forecast Through the Streamflow Prediction Tool

ECMWF has several forecast products including a global surface and sub-surface runoff that is the basis of the EFAS and GloFAS systems. The resolution of the ECMWF Global-scale flood forecast produced by the ECMWF is applicable to very large basins needs to be downscaled to apply in smaller watersheds of the countries of the region of this research. This downscaling has been achieved in the Streamflow Prediction Tool developed in 2015 at Brigham Young University (BYU), based on hydrologic forecast provided by the ECWMF (Snow, et al., 2016).

The SPT produces a downscaling of this forecast, and then applies the method known Routing Application for Parallel computation of Discharge (David C. H., 2017) (David, et al., 2011). RAPID is basically a river network model that can be run at regional and local scales, with thousands or rivers (David, Yang, & Hong, Regional-scale river flow modeling using off-the-shelf runoff products, thousands of mapped rivers and hundreds of stream flow gauges, 2013). RAPID is able to perform the routing computations when used in combination with land surface models that provide runoff at continental scale. RAPID uses the matrix version of the Muskingum method of stream routing to route water through a drainage network. It has been applied to large watersheds in France (David, Habets, Maidment, & Yang, 2011) and the US (Fay, 2014). RAPID can be applied regionally (David, Yang, & Famiglietti, 2013). RAPID is an effective way to downscale a flood forecast since it gives flood hydrographs at every node of a river network in a short time.

STP uses the RAPID model an approach to downscale these global forecasts to a high-resolution stream network such as is provided by the NHDPlus. A flood forecast is generated by the STP daily in the BYU Tethys portal (BYU, 2015) and is available for all the watersheds in the Dominican Republic and is being used on many other watersheds globally, including Central and South America.

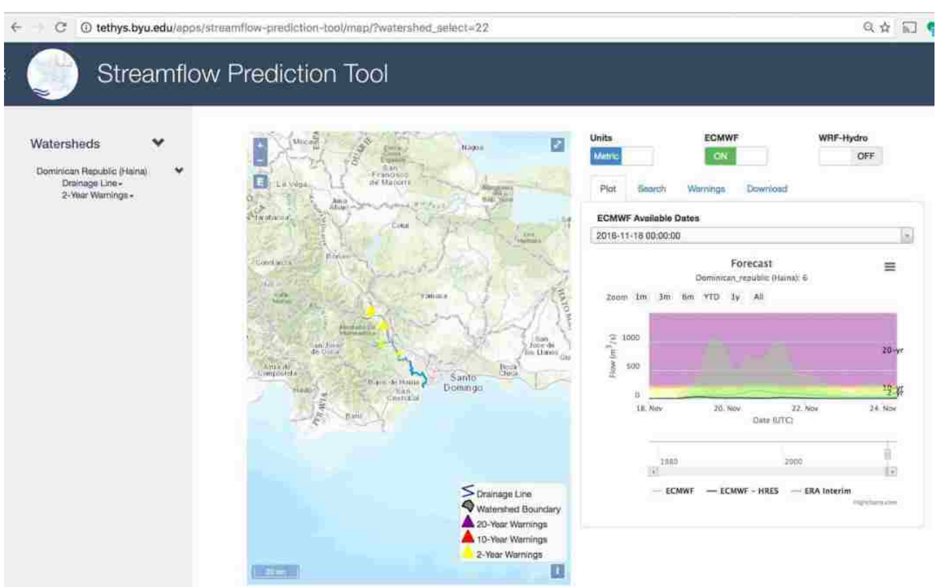

Figure 4-3: Streamflow Prediction Tool for the DR

4.8 Limitations and Further work with the FFG-HDR and STP Tools

Some issues need to be solved in the two most promising technologies of the FFG and the STP app, as their development continues.

With the Flash Flood Guidance System, one issue is calibration. HRC developers were contacted to participate in the assessment for this research and suggested that the NMHSs can be asked in the next season after they have had a chance to use the system (Georgakakhos, 2017). Access to the last version is restricted to official organizations from the countries. Calibration is known to be a challenge to be treated in further work to be done by HRC.

The RAPID-ECMWF application is dependent on the meteorological forecast provided by ECMWF, and the uncertainties can be propagated into the flood forecast itself. A word of caution is therefore necessary about model performance. Rigorous validation processes are carried out before a model can be used for operational weather forecasts. Model predictions are compared with surface observations and with other models and products. Advances in research deal with issues like the impact of horizontal resolution and grid spacing on the forecast, and great improvements are under way (Kumar, Kishtawal, & Pal, 2014). One important issue is downscaling the forecasts which is more useful in local flood forecasting. The RAPID-ECMWF App uses a flood forecast from EMCWF. An alternative would be to downscale the weather forecast and using a hydrologic model to generate the flood forecast.

The next big challenge with both the FFG and SPT, besides calibration, is giving a forecast for hurricane events. ECMWF is known to forecast up to about 15 days in advance. But improvements are needed for hurricane conditions and localized flash flooding which it does not detect well.

One issue with ECMWF is that the precipitation products is not made available, and there are costs for the services they provide. Even the NMS have to pay.

The final issue commented here is how to incorporate reservoirs operations during a flood event in the forecast exercise. SPT with the RAPID-ECMWF combination does not do reservoir routing yet. And it is not known either how the FFG takes this into consideration.

4.9 Summary and Limitations of Global and Regional Flood Forecasting

The international organizations engaged in earth and weather observations, and the global/regional weather forecast and flood monitoring/forecast are improving both the duration, resolution and accuracy of forecast for the region. Several meso-scale and regional scale models have been developed by US agencies under the NOAA system, with special focus on the Caribbean. These forecast products can be used in FEWS. The National Hurricane Center is appointed by WMO to offer prediction of the track of hurricanes over the Atlantic region. This forecast product is reliable and consistently in operation for many years. The NMS in the CA&CR use this forecast of the NHC.

The two main weather forecast products made available in the CA&CR are the Global Forecasting System (GFS) developed by the NOAA, and the Ensemble Prediction systems by the European Center for Mid-Range Weather Forecast (ECMWF). Global flood forecast is available from the following sources: Global Flood Awareness System (GloFAS), The Flood Observatory, Global Flood Alert System (GFAS), Global Flood Monitoring System (GFMS).

The most promising developments already available for the CA&CR are the Flash Flood Guidance, developed and operated by the Hydrologic Research Center, and the Stream Flow Prediction Tool developed by BYU. The FFG is in use at forecast centers of the region. The SPT downscales the ensemble products of the ECMWF, using a routing methodology called RAPID. The SPT has been in use at the forecast center of the NHS in the Dominican Republic. These two tools continue to be applied and tested. There are some issues to be improved, the main ones are calibration of the hydrologic forecast and predictions under hurricane conditions which produce rapidly changing weather patterns. Recently, the SPT was modified to use the same watershed subdivisions utilized by the FFG of the HRC. Although the two are not to be compared lineally, they are generating detection of flood problems in the same areas.

Just as it has happened in meteorological forecasting, that the forecast service for the region is offered by global and regional models, the same is expected to happen with hydrologic forecast services. The FFG and the SPT are the best proof of this.

5 EMERGING TECHNOLOGY FOR FLOOD WARNING SYSTEMS

The purpose of this chapter is to bring together all the concepts and technology described in the preceding chapters, and to propose how to the NMS and the NHS can integrate global and local resources to produce a forecast. This is related to the third specific objective of this research: To assess emerging technologies that provide online applications for flood warning systems in Central American and Caribbean region. The solutions advocated here are the online tools that provide calculations applicable to flood warning and forecasting available for this region. The first section describes the conceptual framework for flood warning as decision support systems composed by several subsystems. The next section describes the forecasting sub-system. In the final section explains how hydrologic models and online tools fit together in a flood warning system.

5.1 Conceptual Framework for Flood Early Warning Systems

A view of flood warning as a decision support system (DSS) composed by several subsystems, provides a better understanding of what they really are. This conceptual framework is useful to clarify some of the confusion and improper use of terminology found in the assessment of flood warning systems in the Central America and Caribbean region and elsewhere. The number of subsystems could vary, but in the proposed framework in this research is composed of the following five sub-systems:

(i) **Monitoring Subsystem:** This includes network of weather and hydrometric stations, and the data management which in turn includes measurements, transmission, processing, storage and display of hydro-meteorological data. The stations can be automatic transmitting real-time data, but also simple stations as the ones found in CB-FEWS. Transmission of data is provided through satellite, radio or GPRS. One key element for FEWS operations is to be able to view water data at any given time.

(ii) **Forecasting subsystem:** This is subdivided into meteorological and hydrological forecast products and models. This work proposes the integration of forecasting at global, regional, national and local scale.

Weather forecasting is mostly done at global and regional scale due to the nature of weather systems, and also due to the fact that technological resources and development needed in meteorological modeling is just outside the capacity of developing countries. NOAA and the NWS and the NHC in the United States offer invaluable service to the Central American and Caribbean region.

Hydrological forecasting can be done through hydrologic models of the rainfall-runoff type, data-driven models, or hybrid models (Corzo Perez, 2009). Common hydrological models can be lumped models, like HMS, and distributed models, like GSSHA, and the semi-distributed category in between, referring to the way model parameters are estimated over an area. Data-driven models are also subdivided into lumped, semi-distributed and fully distributed models. Artificial Neural Networks (ANN) are among the Data-Driven techniques. A hybrid model can be used having the data-driven model with different roles. ANN are useful to achieve the difficult task of calibration and model optimization. The resolution or scale of the hydrologic model is another important issued when FEWS are considered. Global atmosphere land surface models provide hydrologic forecast to the region. The FFG and the ECMWF-RAPID combination are examples of this.

(iii) **Information and Communication Technology sub-system:** A sub-system is needed to connect all the other sub-systems, and this is done with ICT. This means hardware and software, internet and intranet, telemetry and any means of data transmission, and all the applications developed to manage view data. Tethys would be part of this sub-system.

(iv) **Communication and Dissemination sub-system:** Once there is information available of a potentially hazardous and imminent flood event, this needs to be communicated. This sub-system includes internals communications among national meteorological and hydrological services, emergency response agencies, and any institution that is part of the risk management system in a country. But the information needs to be also publicly available to the general population and particularly to those at risk, and to vulnerable communities. The use of mass media (TV, radio, newspaper) and social media are part of this sub-system, as well as any means of communication that is important to make people aware of the emergency.

(v) **Emergency response or Action sub-system:** This sub-system is under the domain of the organizations that are responsible of orchestrating the response actions which include voluntary or mandatory mobilization of population when there is a condition of emergency officially declared. The mobilization many times are not only mandated but forced by military personnel since people are reluctant to leave their home and properties. Rescue teams and actions are needed to save persons who are trapped in situations provoked by the floods. Shelter management is critical to reduce the impact of mobilizing persons to these safe locations, previously defined to be used for this purpose.

A general view of the five sub-systems is shown in Figure 5-1.

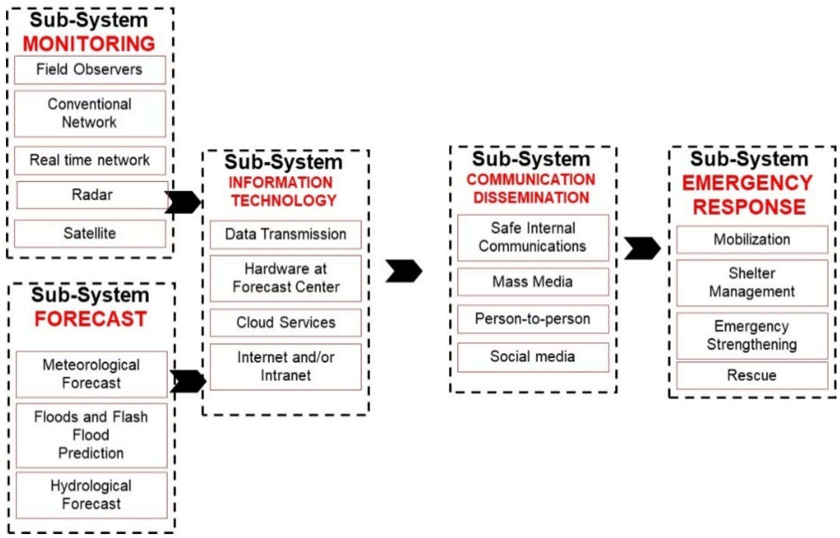

Figure 5-1: Conceptual Framework of Flood Warning as a Decision Support System

5.2 The Forecasting Subsystem

The forecasting sub-system, which is interconnected to all the other sub-system of FEWS, can be conceived with a four-step workflow shown in Table 5-1.

Table 5-1: Proposed Workflow for Flood Forecasting

DATA FEED	SIMULATIONS	OUTPUT:	SYNTHESIS
Data feed (real-time automated stations Manual input Field observations Radar Meteorological Forecast (GFS, others) downscaling	Tethys tools (SPT (ECMWF-RAPID), Reservoir, HANDS, Hydrologic, Hydraulic, reservoir operation models in cascade, Data Driven models, Artificial Neural Networks,	Hydrographs, flood maps, HVH Android App	Impact Information Lead and Response Times Stock – Inventory of Resources

Step 1 - DATA FEED: This would be all the hydrometeorological data needed for hydrologic and hydraulic simulations. This includes the rainfall and discharge data measured in the network of stations, whether the data is transmitted via satellite or through telephone messages. The main data is the precipitation data used as input in the models. Real-time data is good, and it represents water on the ground. Radar data can provide water in clouds before it actually falls which would mean having a greater lead time. A quantitative precipitation estimate in a 7-day forecast is even more desired to feed the model. It is also useful to know antecedent moisture conditions (AMC), which can be provided through satellite-derived products and models. Precipitation accumulated over a period of time is an alternative indicator of AMC.

Step 2 - SIMULATIONS: Three different simulation options can be used for simulations. One is to use hydrologic models of the rainfall-runoff type to transform predicted rainfall from the Data Feed, into forecasted discharges. The second one is Data Driven model based on Artificial Neural Network (ANN). Which are models that do not need a watershed representation. Hybrid models using both hydrologic models and ANN have been used as part of flood warning.

Step 3 - OUTPUT: This next step in the process refers to the display of information through several types of graphs tables, flood maps. It is important to share output data with emergency managers but also to the general public. The time and manner and amount of information made public is sometimes “strategic”, but the more information the better, if the population has been trained and is instructed about what to do. The output of river levels and rainfall amounts should be compared with the threshold levels and color-coded level of threat to trigger the appropriate response actions.

Step 4 - SYNTHESIS AND INTERPRETATION: Emergency managers need information beyond graphs and tables of data that they might not understand well. The key information to be used for decision making are: impact of a flood over an area, response time left to execute emergency actions, and resources available to deal with the situation. The impact information can be flooded area and depth, roads blocked, communities isolated, amount of people displaced or affected, names of towns and location where the flood has heavy impact. Response time is perhaps the most critical piece of information needed by all. This can be expressed as the lead time or time ahead of a given action and also the duration or time affected. The third information the emergency manager needs is what resources are in stock and at disposal to be able to face the approaching threat. This can be number of shelters and their capacities, number of responders and their current location, and transportation capacity to mobilize people, number of ambulances, amount of food and medication in stock, water and food supplies stored for the emergency.

5.3 The Model Cascade for Simulations

Flood predictions at watershed scale can be generated with hydrologic models. But many times, a single hydrologic model is not enough to be able to make a forecast for a watershed, especially if it is large watershed with hydraulic infrastructure. A combination of models, called here the “model cascade” is needed. See Figure 5-2.

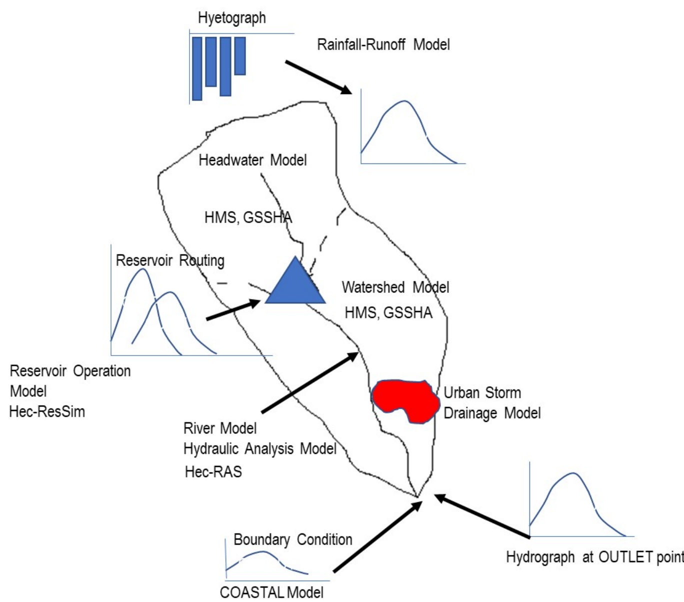

Figure 5-2: Model Cascade for Hydrologic and Hydraulic Simulations

A hydrologic model is needed to characterize the rainfall-runoff behavior in watersheds upstream of dams and will generate the hydrograph at the outlet of the basin. A reservoir operation model, such as Hec-ResSim, is needed to simulate the routing and flood control operation, if there are reservoirs that regulate the flow of water in a river. The reservoir operation model can be useful because it can represent the process the operation decisions on what is the outflow from a reservoir during a flood. A Hydraulic model can then be used, knowing the discharge, to define the water surface profile associated to a flood event. Another hydrologic model is then used for simulations in the -sub-basin downstream of the dam. A hydraulic or river model, such as Hec-RAS, is needed to predict the water-level profile in a river reach. A coastal model is needed when the outlet of the watershed is at the estuarine area where the river flows into the sea or ocean. An example of such model is the "Sea, Lake and Overland Surges from Hurricanes (SLOSH) numerical model used by the NWS to compute storm surges in coastal areas. The GSSHA can represent watershed processes and river analysis, and can also incorporate reservoirs, integrating the analysis done by more than one of the models in the model cascade.

5.4 Proposed Solution of Global and Local Scale Forecasting

The preferred and proposed solution is to use online tools for hydrologic simulations that make use of global forecast and downscales it to the local level. This relieves the NMS and the NHS from the problems associated with applying advanced modeling, and instead use tools safely running in a reliable cloud service.

The flow chart in Figure 5-3 shows the two alternatives explored here for hydrologic simulations. The left side of the graph refers simulations at watershed scale starting form a weather forecast. The right side of the graph shows how online tools in Tethys can be used.

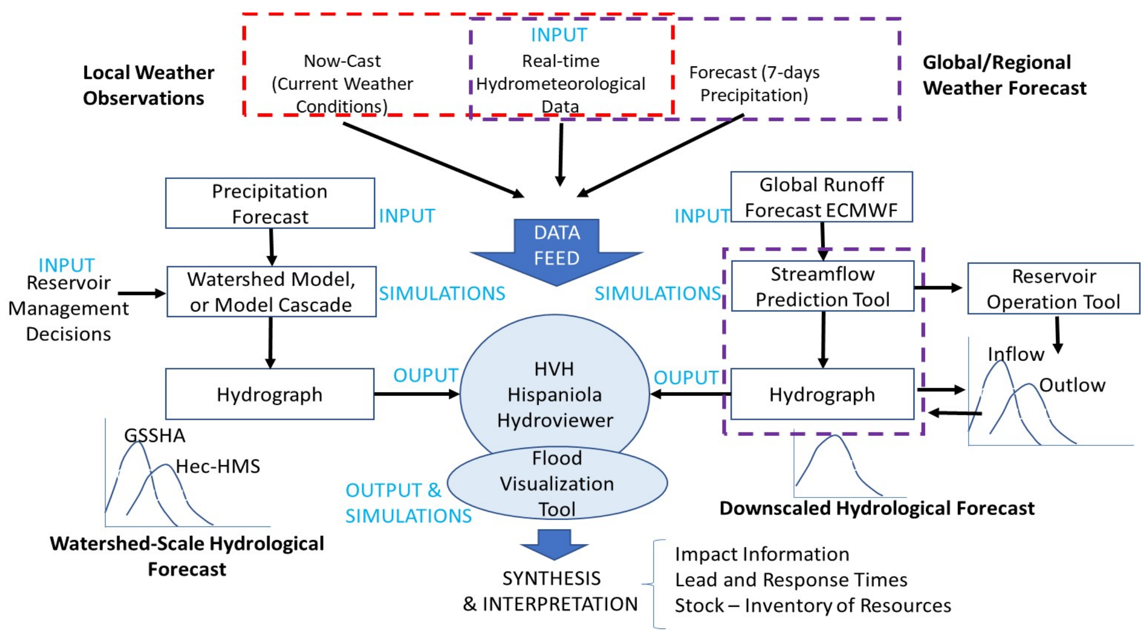

Figure 5-3: Flow-chart for Simulations with Tethys

Tethys is one of the results of the CI-WATER Project, that provided funds for his research work, under an NSFG grant involving work in four universities in Utah and Wyoming

(Ci-Water, 2014). One of the objectives of this project is to enhance access to data- and computationally-intensive modeling and the use of advance high-resolution multi-physics watershed modeling. The Tethys software stack can be used to develop cloud-based modeling applications to drive generic hydrological models and identify data models/servers to populate HPC models. This chapter describes the use of the Tethys platform to develop apps to be used in flood warning. (Swain, et al., 2016). This software framework is an aid in the creation of web-based water resources modeling applications (Jones, Nelson, Swain, Christensen, & Dash, 2014). The four tools in the Tethys platform that are part of the forecasting solution are as follows:

SPT: Streamflow Prediction Tool gives 15-day streamflow predicted estimates, by using EMCWF runoff predictions routed with the RAPID program. Return period estimates and warnings flags aid in determining the severity”

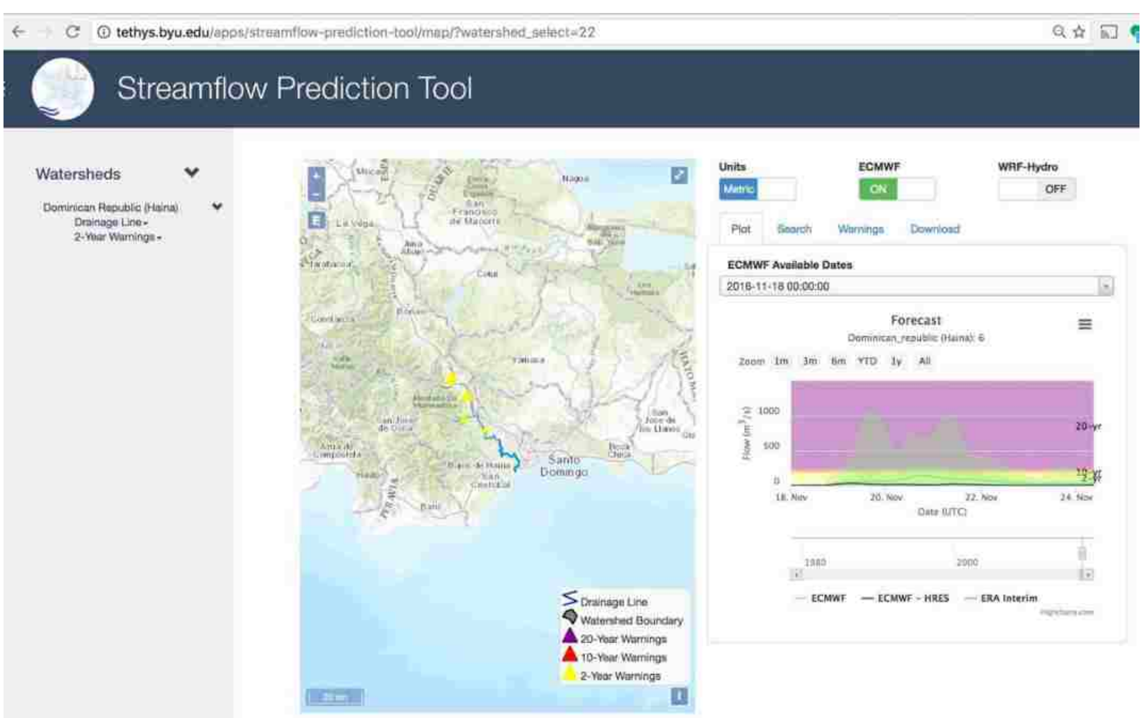

Figure 5-4: Streamflow Prediction Tool for the DR

ROT: Reservoir operation tool used perform reservoir routing calculations. The runoff of the watershed above dams can be generated with SPT. That produces the INFLOW hydrograph. The ROT then routes that hydrograph and produces the OUTLOW hydrograph. This tool was designed initially by BYU for the Dominican Republic.

HVH: Hydro Viewer Hispaniola is a web application designed to visualize streamflow forecast through intelligent hydrographs and dynamic flood maps. HVH can be customized to a given country, rebranded, and adjusted according to their needs. HVH is a “light-weight” application that uses APIs to retrieve and integrate data from different sources. HVH is used to display both INPUT and OUTPUT data. The input can be real-time precipitation and discharge data. Output can be the discharge hydrographs of the channel routing, and also maps of flooded area.

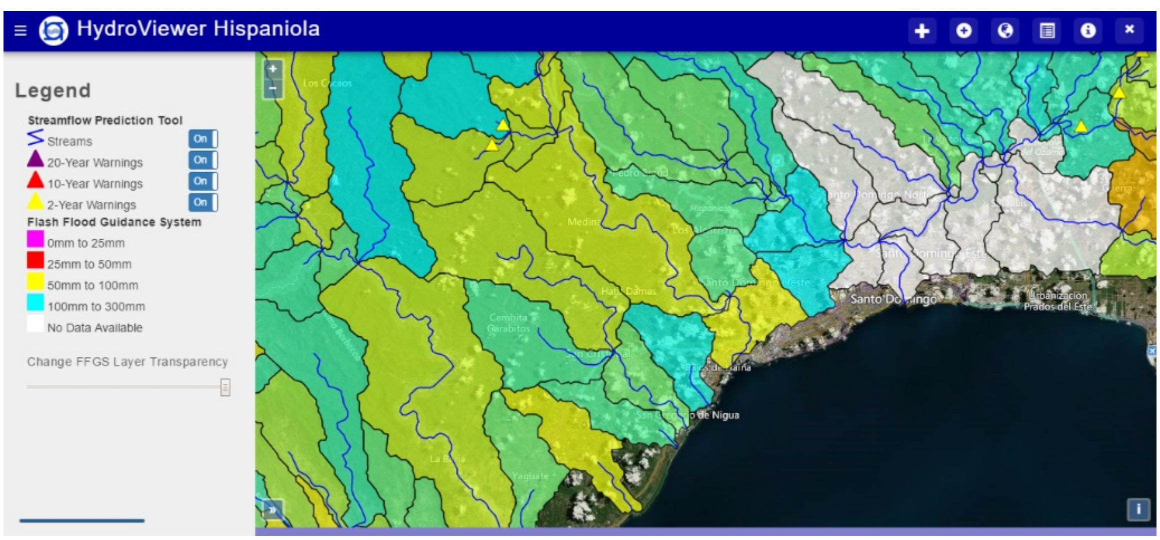

Figure 5-5: HydroViewer Hispaniola for the Dominican Republic

The **Flood Map Visualization tool** is a GIS technique for flood plain delineation called HAND (Height Above the Nearest Drainage (HAND). It is a simple approach for mapping the potential extent of inundation that does not depend on flood observations, and works as an effective distributed predictor of flood potential, which is directly related to the river stage-height (Nobre, et al., 2016). This application allows the user to visualize the extension of the floodplain for different levels of the river. It has already been applied as part of a flood warning system in the Hana River.

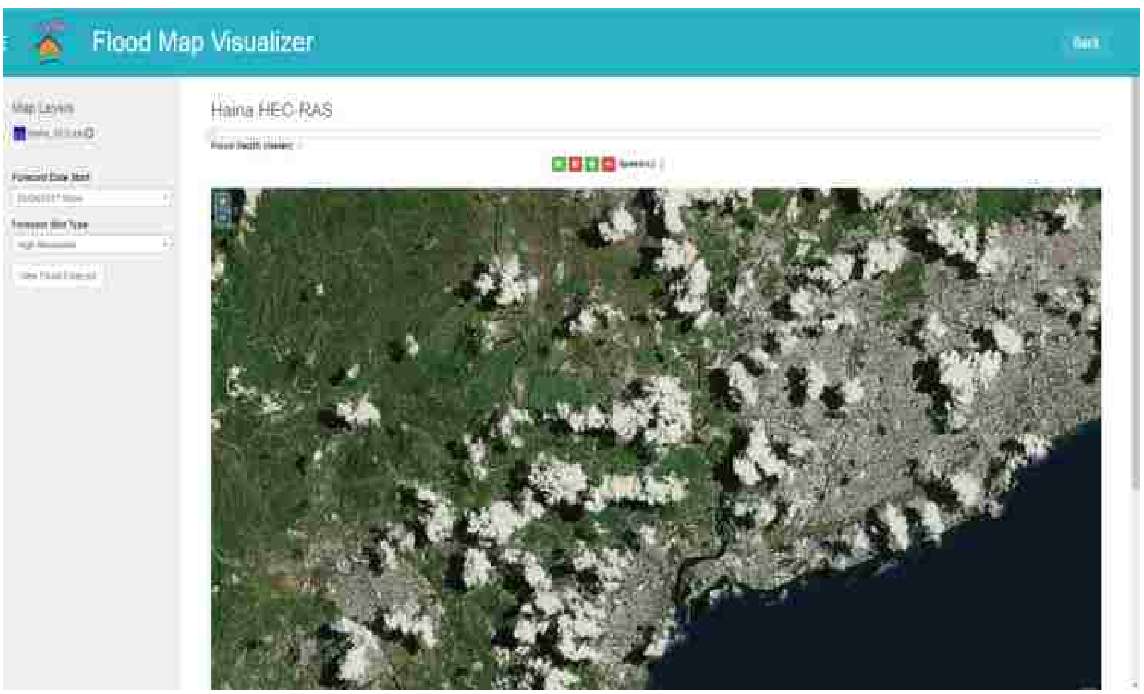

Figure 5-6: Flood Map Visualizer for the Dominican Republic

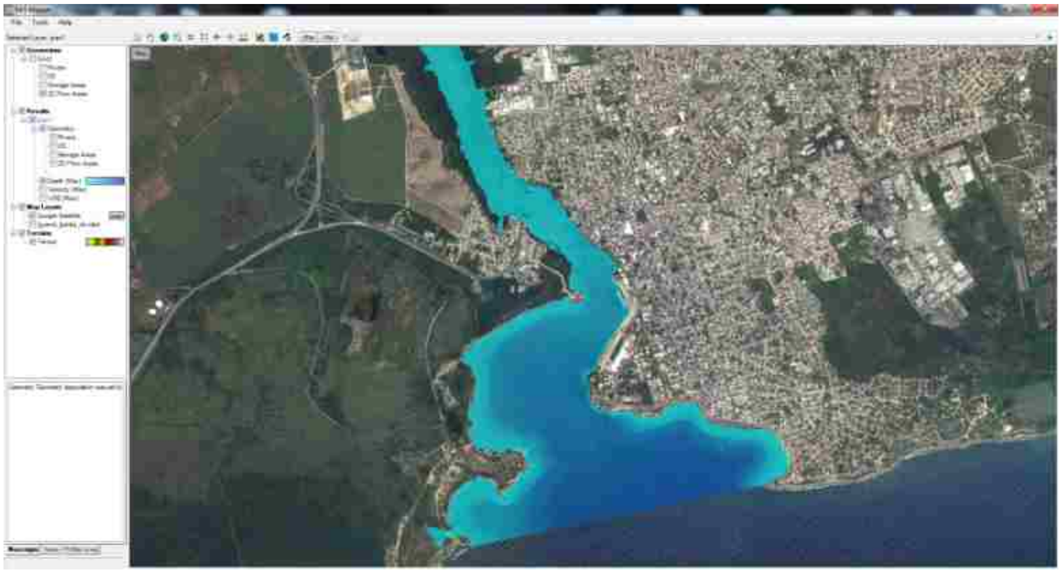

Figure 5-7: The BYU Hydro App for the Rio Haina watershed

5.5 Apps in Tethys for Hydrologic Simulations at Watershed Scale

Two options were tested in this research, hydrologic models and online simulation tools. Both could be part of the model cascade used in the development of a flood warning system, and the Tethys platform has applications for both options, as shown in Table 5-2. Considering the limitations in developing countries, the freely available Tethys tools can provide the right solution for the NMS and the NHS to provide forecast.

Table 5-2: Comparing the Model Cascade for Hydrologic Simulations

Hydrologic Models	Apps in Tethys for Hydrologic Models	Apps in Tethys for Automated Online Simulations
Headwater model or hydrologic model (HMS, GSSHA) Reservoir Operation Model Hydraulic or river Model (Hec-RAS) Urban drainage models (XP, SWMM) Coastal model (SLOSH)	CANNED GSSHA HTC Condor GSSHA py	Data Feed Streamflow Prediction Tool (STP) Reservoir Operation Tool (ROT) HAND

The development of Tethys has progressed to the point of enabling model runs of GSSHA, and other apps that are described here:

Dataset to store GSSHA Models: This app allows a developed and calibrated GSSHA model to be ready to run for a given set of input data. Models for different watersheds and scenarios to be used in flood forecasting can be stored here. These models can be tested under Tethys and can later be deployed to be used in the operation of a forecast center. The Tethys portal has the capacity to store the GSSHA Models and provide web service to run GSSHA models remotely, and a Map Viewer to visualize GSSHA Results using hiCharts for graphical display of hydrographs.

The following additional apps would still be needed for the support of flood forecasting: (i) App for web access and viewer of current and forecasted weather conditions that feeds real time observations and manages weather forecast raster images; (ii) App to manage different forms of precipitation files in GSSHA; (iii) App to manage model simulations that would allow the scheduling of simulations and manage the distributed computing resources where the simulations are run; and (v) Flood Forecast Viewer to allow the visualization of river stage and discharge forecast, and flood maps and flood wave propagation associated to the forecast.

There are two additional tools developed under the CI-Water project that can be useful in forecast applications. One particular is CANNED-GSSHA, a tool that stores precomputed results from simulations with the GSSHA model (Dolder, Jones, & Nelson, 2015). Thousands of simulations are done for a large set of combination of input data. The results can be easily retrieved when there if a flood threat by looking for the hydrographs and flood maps corresponding to the set of input variables that ore closely matches the present or forecasted weather condition.

The other useful tool that can be used where there is need to run many simulations that require a lot of computer power. This would be the case when there is a very large weather system covering many watersheds and a simulation is needed for each one of them. A solution has been developed to facilitate the use of distributed computing resources through high-throughput computing (HTC) and cloud computing in modeling workflows and web applications (Christensen S. D., 2016). A good portion of the time of this research work was dedicated to explore how to process simulations with the GSSHA model in large watersheds by subdividing into sub-basin models. Some of the complexities of this distributed GSSHA model and the challenge to develop stable models, gave an indication that this is maybe not the best resource to use in developing countries where expertise is not readily available in all the NHS.

5.6 Summary of Emerging Technology for Flood Warning

The NMS and the NHS can integrate global and local resources to produce a forecast. By using emerging technologies that provide online applications for flood warning systems in Central American and Caribbean region.

A flood warning system is a decision support system composed by the following five subsystems: Monitoring, Forecasting, Information and Communication Technology, Communication and Dissemination, and Emergency response. The forecasting sub-system, which is interconnected to all the other sub-system of FEWS, can be conceived with a four-step workflow: (i) Data Feed, (ii) Simulations, (iii) Output, and (iv) Synthesis and Interpretation.

Flood predictions at watershed scale can be generated with hydrologic models, or a combination of models in cascade, or with online tools. The Tethys platform has tools for both alternatives explored for hydrologic simulations: (i) simulations at watershed scale starting form a weather forecast; and (ii) Online tools that downscale the forecast. This second option is the proposed and preferred solution for the NMS and the NHS in the CA&CR, given the complexities of applying models correctly. A workflow is given for the use of 4 online tools in Tethys for flood forecasting: (i) Streamflow Prediction Tool; (ii) Reservoir operation tool; (iii) Hydro Viewer Hispaniola; Flood Map Visualization tool.

6 SUMMARY AND CONCLUSION

This final chapter summarizes the findings and conclusion of this work, with brief statements of what has been achieved, what are the current limitations and what challenges are foreseen in developing countries for the implementation of the proposed integrated system for flood forecasting. The last section of the chapter describes other on-going developments that can help improve the practice of flood warning. At the end of the chapter there is a list of the publications that are in progress and will be part of the outcome of this work.

6.1 Focus of This Research

Hurricanes and tropical storms occur very frequently in the Central American and Caribbean and region. Meso-scale weather systems, such as cold fronts and tropical depressions, also produce a lot of rain and consequently a lot of flooding. Vulnerability is increased by settlements in the floodplains, and increased urbanization as a result of population. The cost of damages has been estimated to amount to 13.4 billion dollars in the last ten years. The international disaster management community is shifting from pure emergency response to a more comprehensive approach which also includes preparedness, of which warning systems are a key preventive strategy to reduce risk. Several organizations such as OAS, AECID, USAID, GTI, IFRC and others, are actively promoting flood early warning in small basins. There is an international Global Platform of United Nations for the Promotion of Early Warning

(UN/PGPAT) and the International Strategy for Disaster Reduction of the United Nations (UNISDR).

Technological progress is improving the resources made available for flood warning to be more viable. Information and Communication Technology, high performance computing (HPC), cloud computing, web development, mobile telephony, and telemetry, and the internet. While there is progress made in flood warning systems (FWS) in the region, there are also misconceptions and confusing terminology which when taken into practice results in failed projects or ineffective practices.

Flood warning can be seen as a set of sub-systems in which forecasting is only one of those sub-systems. A conceptual framework has been proposed to classify flood warning systems using the spatial and temporal scale at which the flood warning systems operate (Perez, et al., 2016), as shown in Figure 6-1 .

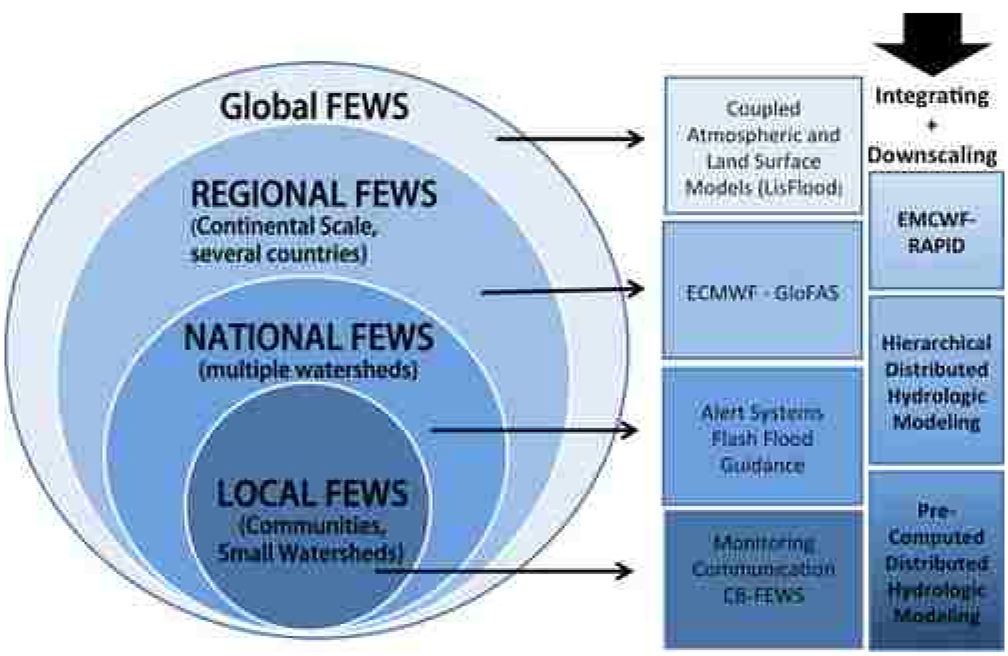

Figure 6-1 Classification of Flood Warning Systems according to Spatial Scale

The flood warning systems should be integrated across the four scales as it is being proposed here. Bu in practice, these systems are not operated in an integrated manner.

The general purpose of this work is to unravel the dysfunction / chaos of the way early warning systems are done and provide guidelines to integrate flood warning system at all scales to be used in operational forecasting, particularly for countries in the Central American and Caribbean Region where the author has experience.

The three specific supporting objectives are:

(i) Assess the present situation of capabilities of NMS and NH in the CA&CR in terms of FEWS, finding out what are the current capacities and limitations;

(ii) Propose how FEWS can work across scales integrating "from Global to Local" and vice versa, to be more effective and to take advantage of the strengths at each level.

(iii) To test/assess the emerging technology that provide online applications for flood warning systems

The relation of the specific objectives and the chapters in this document is shown in Table 6-1.

Table 6-1: Relation Between Specific Objectives and Chapters

Specific Objectives		Chapters	
#1	Assess the present situation of capabilities of NMS and NH in the CA&CR in terms of FEWS, finding out what are the current capacities and limitations;	Chap. 2	Assessment of Flood Forecasting and Warning System in the Region
		Appendices A, B and C	Country by Country Reports for the (A) Central America, (B) Greater Antilles and (C) Lesser Antilles
#2	Propose how FEWS can work across scales integrating "from Global to Local" and vice versa, to be more effective and to take advantage of the strengths at each level.	Chap. 3	Integrating Local and National Flood Warning Systems
		Chap. 4	Integrating Global and Regional Flood Warning Systems
#3	To test/assess the emerging technology that provide online applications for flood warning systems	Chap. 5	Emerging Technology for Flood Warning Systems

6.2 Assessment of Flood Warning Systems in the Region of Study

The second chapter met the first specific objective to assess_the present situation of capabilities of NMS and NHS in the CA&CR in terms of FEWS. The assessment and the results of the survey clearly fulfilled that result. The assessment was conducted to evaluate the present capabilities in forecasting National Meteorological Services (NMS) and the National Hydrological Services (NHS) of the countries in the Central American and Caribbean region. This assessment was based on web sources and literature review, and a survey addressed to the NHS. In Central America there are several countries where both services are unified in a single organization, and they are separate entities in the Greater Antilles. The smaller island states of the Lesser Antilles only have the NMS. There is a move towards more sophisticated monitoring networks with modern automatic stations. The NMS consistently provide meteorological services and forecast on a daily basis, although in most cases this is relying on the forecast products of regional and international weather organizations.

The development of meteorological forecast is far advanced and these services are provided by agencies and research centers in the United States and Europe. Many numerical weather forecast models are available and there is a reliable record of proven success over many years in hurricane and storm tracking.

There have been several projects of flood warning systems at watershed scale and community scale have been popular. The centralized national systems are very sophisticated and expensive to install and maintain, making sustainability a big challenge. With the low-cost community based FEWS the issue is continuity. Multi-hazard warning systems are found in Central America for drought, floods, hurricanes, earthquakes, volcanoes, and tsunamis.

There are several initiatives in the CA&CR that represent good opportunities to further advance the science and art of flood warning. Four specific ones are: The Coastal Inundation Forecast Demonstration Project (CIFDP-DR); the GEO Caribbean project; Forecast Informed Reservoir Operation (FIRO); and Forecast-based Financing.

In spite of the international support for FEWS and the fast development of ICT, there are very few countries in the CA&CR that have succeeded in developing fully operational warning systems that are functioning in a sustainable manner for a long period of time. The limitations seen in the flood warning systems are: Institutional weaknesses, Administrative constraints, lack of an Influential role of agencies; Staff and Personnel Issues; Decline in the Density of Hydrologic Network, Technological gap to keep up to date with emerging technology and improvements Disconnection between the different services of the CB-FEWS and National FEWS, as well as between the NMS and NHS which tend to work in isolation.

It should be stressed that there is a gap between centralized and local FEWS. The community systems are not managed by the centralized forecast centers. An effort by NGOs and organizations promoting CB-EWS is needed to develop systems that are integrated to the national systems. On the other hand, the centralized systems need to be integrated with the global flood forecast services such as GloFAS, and flood monitoring like Dartmouth Flood Observatory, but the surveys revealed than none of these two services are known by the official agencies in charge of flood forecasting in the region. More promotion and collaboration are needed to take advantage of the services.

The quantitative precipitation estimates both for rainfall magnitude and spatial distribution, although sufficiently accurate, are not totally precise for mountainous regions where there are usually differences on the order of 5 to 25 millimeters depending on the storm event.

6.3 National and Local Flood Warning Systems

In Chapter Three, the focus was to show how National and local FEWS should and can be integrated. They can provide feedback to each other. The monitoring system should be common with same standards and field personnel. CB-FEWS can report local flood condition to the centralized FEWS, and these in turn can share information and data with the CB-FEWS. Hydrologic models could be applied in the planning and design at local and national level. Models can be used to: (i) determine the best location for monitoring sites for the purposes of flood warning; (ii) calculate the lead times which is so critical for warning; and (iii) estimate the threshold for the different levels of warning. The HMs and HVB model are known to be used by forecasting centers in the region. GSSHA is a more advanced model that can be also applied. It might not be, however, be used, the best option because it would require better staff, better data distributed over the basins, and denser monitoring network to take advantage if its distributed nature. The "better" model is one that can be applied consistently and one that users are capable of mastering. Communication between NMS and the NHS, the emergency management agencies and the key-personnel who manage the CB-FEWS is very important. A flood warning app for the Haina river has been developed as a pilot in the Dominican Republic, as part of this research work. Applications like this one can be an effective means of warning.

6.4 Global and Regional Forecasting

In Chapter Four, the focus was to show how the very well developed global and regional systems can be integrated with local level. The meteorological forecast for the CA&CR is provided by space and weather observation agencies of developed countries, such as the NOAA/NWS and the National Hurricane Center, the regional forecast center for the region. The forecast of the NHC are used as official forecast given by the NMS in the CA&CR. The global/regional weather models used in the region are GFS, WRF and ECMWF. There is also global flood forecast from GloFAS, GFAS, and GFMS.

There is a scale issue in the global flood forecasting services now available. GloFAS, for example, uses pixels with an area of 16km by 16km, a resolution that needs to be downscaled. For medium term forecast the ECWMF is very successful, but the accuracy for shorter storm events is another issue, especially for what happens after the hurricanes make land fall, a situation for which predictions for the global models need more development. While they predict the event more generally, they do not capture the high variations of rainfall both temporally and spatially.

The flash flood guidance system developed by HRC for Hispaniola and the Stream Flow Prediction Tool developed by BYU, are already available and are used by the NHS and the NMS of the study region. FFG and STP continue to be devloped. These two tools are expected to become the standard hydrologic forecast in the region.

6.5 Emerging Technology for Flood Warning and Forecasting

Chapter Five answered questions related to the third specific objective that has to do with testing/assessing the emerging technology that provide online applications for flood warning systems. This focused on web tools developed at Brigham Young University in parallel with this research. The These tools are proposed as a practical solution to allow the integration across global, regional, national and local scale forecasting. These cloud-based FOOS tools can lower the entry barrier for the forecasting centers, without a burden of cost nor the burden of having to develop the system, something that would require time, and resources and technical know-how not usually found in most countries of the region.

A flood warning system is a decision support system composed by the following five subsystems: Monitoring, Forecasting, Information and Communication Technology, Communication and Dissemination, and Emergency response. The forecasting sub-system, has a four-step workflow: (i) Data Feed, (ii) Simulations, (iii) Output, and (iv) Synthesis and Interpretation. Flood predictions at watershed scale can be generated with hydrologic models, or a combination of models in cascade, or with online tools. The Tethys platform has tools for the two alternatives explored here for hydrologic simulations: (i) simulations at watershed scale starting form a weather forecast; and (ii) Online tools that downscale the forecast. This second option is the proposed and preferred solution for the NMS and the NHS in the CA&CR, given the complexities of applying models correctly.

A workflow is given for the use of four online tools in Tethys for flood forecasting: (i) Streamflow Prediction Tool; (ii) Reservoir operation tool; (iii) Hydro Viewer Hispaniola; Flood Map Visualization tool.

6.6 Extension of this Work

There is work currently underway to add features to the Hydro Viewer Hispaniola app in Tethys to make the app more applicable to the flood warning described in chapter five. This would allow the visualization of real-time data as well as the upload of files and images in jpg or similar format of actual flood conditions. See Figure 6-2.

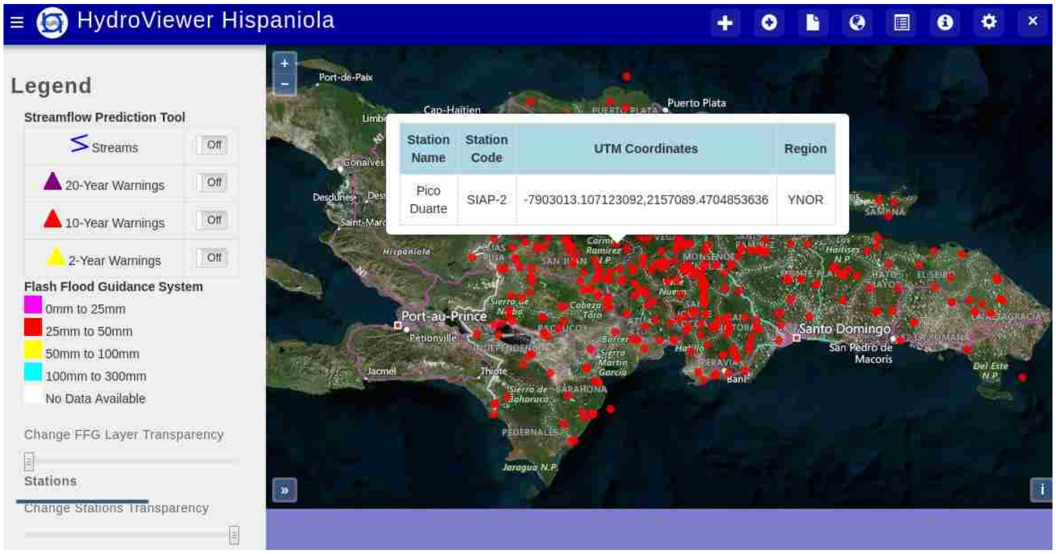

Figure 6-2: Work Currently under progress with the Hydro Viewer Hispaniola

All monitoring sites are shown in HVH has been made to access the link to the “hot folder” where data transmitted via satellite is stored in the servers at INDRHI, in the Dominican Republic. The real-time data is measured at 15-minutes intervals, but are retrieved every hour by the NOAA's satellite services. The data from stations operated by the NMS and private organizations will be also included. Data from non-automatic stations will be obtained by the forecast centers by phone calls or messages and then uploaded to the HVH by the staff managing the forecast.

The label of a site in the HVH map will has a link that will show graphs for the last 30 days for precipitation and discharge values. The cumulative precipitation gives an idea of which watersheds had been receiving lots of rain, which could potentially lead to flooding, if a storm came with an antecedent moisture condition favorable to runoff.

The input/output display in the HVH will include the hydrographs at hydrometric stations showing the measured or observed values and the forecasted or predicted values. The predicted values could be several curves one for each forecasted discharge by different models (GSSHA HMS) for different sources of precipitation forecast like ECMF, GFS or WRF.

This work is going to be extended at BYU continuing the development of free software as a service. More testing and implementation is needed. Most of the applications have been developed with the Dominican Republic in mind. These applications should be tested in other places in the region, as the development reaches a maturity level. Another improvement to be possibly made is to have the telephone applications be enabled to push information, data or pictures to the Hydro Viewer Hispaniola which would link the local FEWS to the Global FEWS.

6.7 Publications and Manuscripts

As a result of this research, one paper was published in 2016, citation provided below:

Perez, J. F., Swain, N. R., Dolder, H. G., Christensen, S. D., Snow, A. D., Nelson, E. J., & Jones, N. L. (2016). From Global to Local: Providing Actionable Flood Forecast Information in a Cloud-Based Computing Environment. *JAWRA Journal of the American Water Resources Association, 52*(4), 965-978.

There are three other potential publications, derived from the research work. These are the unpublished manuscripts, so far:

Perez, J. F., Nelson, J., & Downer, C. (2018). Modeling Large Watershed with GSSHA. *Unpublished Manuscript*, 18.

Perez, J. F., Nelson, J., Ames, D., & Jones, N. (2018). Flood Warning App for the Haina River, Dominican Republic. *Unpublished Manuscript*, 12.

Perez, J. F., Nelson, J., Jones, N., & Ames, D. (2018). Retrofiting a Community-Based Flood Warning System with the help of Advanced Hydrologic Modeling. *Unpublished Manuscript*, 14.

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Alfieri, L., Burek, P., Dutra, E., Krzeminski, B., Muraro, D., Thielen, J., & Pappenberger, F. (2013). GloFAS–global ensemble streamflow forecasting and flood early warning. *Hydrologic Earth System Science, 17*(3), 1161-1175.

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APPENDIX A. COUNTRY BY COUNTRY REPORT OF CENTRAL AMERICA

There are seven countries in Central America, extending from Colombia (South America) to Mexico (North America) in the so called “ring of fire” due the natural threats faced for the seismic and volcano activities and the extreme weather events such as hurricanes and tropical storms. Warning systems, therefore, need to be developed with a multi-hazard vision.

Figure 0-1: Countries in Central America

6.8 Belize

Belize is the country further north of Central America, bordering Yucatan, Mexico. There are more than 1,060 islands that belong to Belize. The country lies in the hurricane belt. Most of the precipitation falls in the rainy season with a pattern influenced by tropical waves and cyclones. Hurricanes and tropical storms affect Belize once every three years (NMS Belize, 2018). A great portion of the terrain is flat or in low lying areas making settlements in those areas vulnerable to flooding. The National Meteorological Service of Belize (NMSB, 2018) operates a network of meteorological stations, a Doppler radar, an upper air observing station. The NMSB provides public and specialized weather forecasts, and several climate-based products and information for a number of sectors like agriculture and tourism. WRF products for rainfall are used in the forecast.

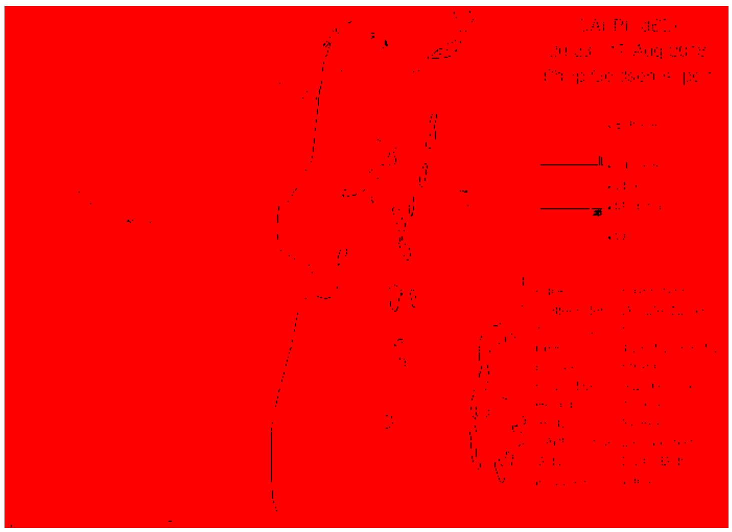


Figure-0-2: Radar Images (50 m) Displayed by the Belize National Meteorological Service

The National Emergency Management Organization (NEMO, Belize, 2018), in coordination with the NMSB provides advice on hurricanes, floods and other forms of severe weather conditions. NEMO declares the alert which activates the National Hurricane Emergency Plan are declared by NEMO, on the advice of the Chief Meteorologist.

NEMO cooperates with the Emergency Management Committees, and all public and private agencies, to preserve life and property in the event of an emergency. There is good progress in the disaster preparedness and risk management. But there seems that there is no actual flood forecasting generated by neither NEMO nor the NMSB. Common Alerting Protocol (CAP) Jump-Start Workshop was conducted in August 2018 in Belize City, to train staff in the provision of providing timely and accurate information to those who are most vulnerable to the effects of disasters (NEMO, Belize, 2018). Stakeholders from different organizations participated in the CAP Jump-Start Workshop.

6.9 Costa Rica

The Instituto Meteorológico Nacional (IMN, 2018) of Costa Rica provides on a daily basis weather forecasts and information about weather conditions with the systematic surveillance of weather to be able to support air navigation and disaster prevention services. The IMN is in charge of operating the monitoring network, and studies extreme hydrometeorological events that cause flooding and damages to water supply and energy generation sectors. INMA also provides forecasts advices and warnings.

The World Meteorological Organization (WMO, 2014) completed in 2013 a pilot project called the "Costa Rica Early Warning System for the Hydrometeorological Hazards Project". Several organizations collaborated with this initiative of the Disaster Risk Reduction Program, including the World Bank Global Facility for Disaster Risk Reduction (GFDRR), the National Meteorological Institute (IMN), the National Commission of Risk Prevention and Emergency Response (CNE) and the Costarican Institute of Electricity (ICE). There are several communities at risk with a population of about 57,000 persons in this watershed (Solano, 2013). Two automatic monitoring stations were installed for the EWS. Cooperation were strengthened among the disaster response agencies (IMN, ICE, and CNE) as well as the collaboration with other national government and non-governmental agencies at the local level. Emergency response communities were organized and trained, and simulation exercises were carried out with 800 participants from 50 communities in this area that became more vulnerable after Cinchona earthquake in 2009 caused extensive landslides that changed the forest cover (El Tiempo, 2013).

This is a model project that WMO promotes as a standard for the region. A hydrologic HEC-HMS model was developed with a DEM for the Sarapiqui (415.59 km^2), Puerto Viejo (385.75 km^2) and Sucio (1,088 km^2) river basins and calibrated using available flood hydrographs and precipitation data from 20 rain gauges.

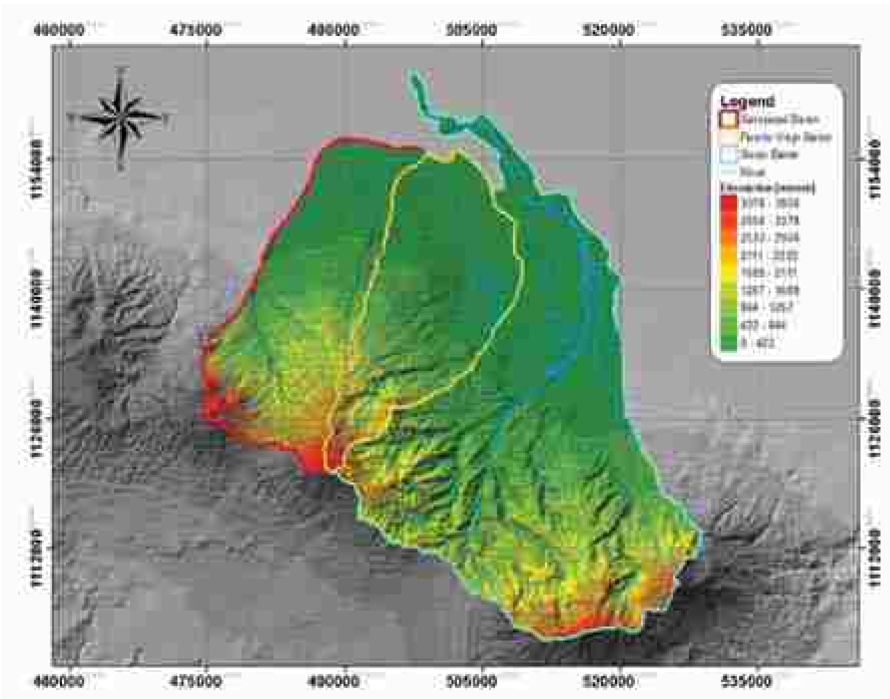


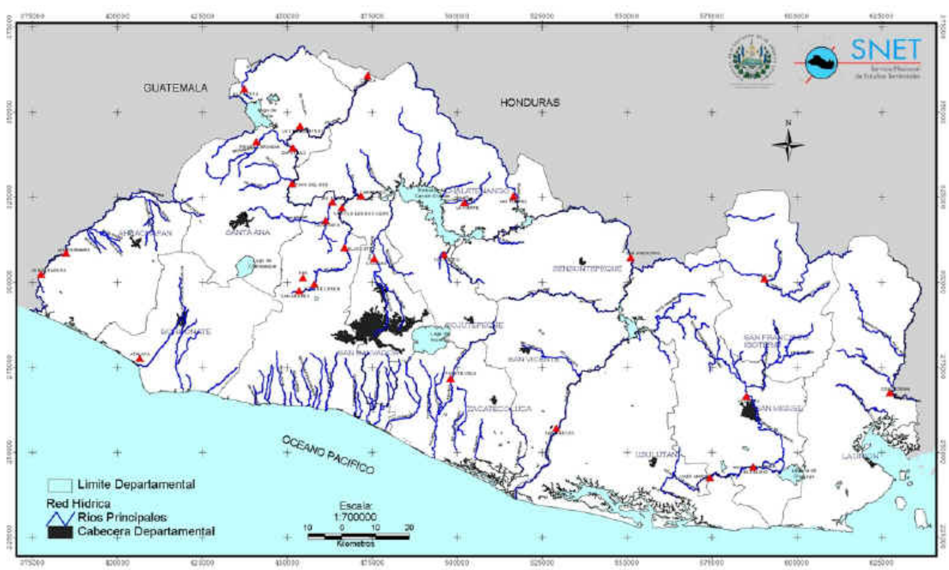
Figure 0-3: Digital elevation model of the Sarapiqui, Sucio and Puerto Viejo rivers

Flood hydrographs were derived for the return periods of 5, 10, 25, 50 and 100 years. Flood hydrographs were routed through flood plains and flood prone areas were determined for each return period.). The improvement on the numerical model used allowed a clearer identification of thresholds, and warnings can now be generated 48-24 hours in advance. Flood maps were elaborated with a hydraulic model.

The International Federation of Red Cross and Red Crescent Societies (IFRC), with funding from the British government, implemented an early warning system for landslides resulting from flooding of the Macho river in Orori de Cartago (IFRC, 2004). The project included installation of sirens and 30 UFH radios to improve communications and to give alert messages to the population, training over 200 persons in first aid and rescue operations and interventions in emergency situations. IFRC has collaborated with the Regional Centers for community education for Disaster Prevention in Costa Rica with support from the Sustainable Development Department of the Organization of American States (OAS), to produce a manual about early warning systems in small basins (IFRC, 2002).

6.10 El Salvador

This country stands out as the leader in the region with its monitoring and multi hazard warning systems. Servicio Nacional de Estudios Territoriales (SNET, 2018) is both the NMS and the NHS in El Salvador and is part of the Ministry of Environment and Natural Resources.



Estaciones Hidrométricas de El Salvador

Figure 0-4: Monitoring Stations operated by SNET

SNET runs the SATCA, or early wanting systems for Central America, a web page that offers monitoring and warning for drought, floods, hurricanes, earthquakes, volcanoes, tsunamis. SNET also works on climate change studies, seismology, oceanography, volcanology, hydrology.

SNET has drawn the attention and support of agencies in the US such as NOAA, NASA, USGS, the Darmouth Flood Observatory, and the financing of USAID, European Union, IDB, and other.

Currently, SNET's Forecast Center operates 5 Early Warning Systems (EWS) with monitoring networks in the following watersheds: Lempa, Río Grande de San Miguel (2/4), Río Paz Basin, Rio Jiboa, Rio Goascorán (SNET, 2015). The Lempa River is a trinational river covering parts of El Salvador, Guatemala and Honduras. This EWS has 10 hydrometric stations with telemetric transmission (2 of them in Guatemala, 1 in Honduras and the rest in El Salvador), 16 automatic rain gauges, and 16 conventional weather stations (7 with daily records and 9 with hourly records wih daily records). The Hydrological Forecast Center (CPH) generates river level forecast, short and long term forecasts for reservoirs and maps of the potential flood areas downstream indicating the level and time that the flood will reach the lower basin and cause flooding.

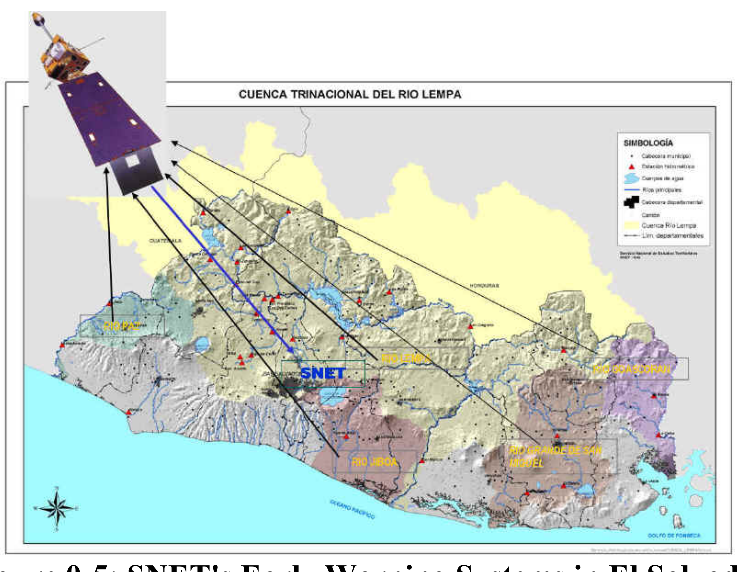


Figure 0-5: SNET's Early Warning Systems in El Salvador

SNET has carried out several FEWS projects (SNET, 2018). Some of these include:

1. Flood Risk Management in the Rio Grande Basins of San Miguel and Río Paz, funded by IDB;
2. FEWs at the AMSS. Also funded by IDB.
3. Strengthening of the EWS of Rio La Paz (2004): hydrologic analysis of the watershed , and river levels at El Jobo y La Hachadura, determining the time and speed of flood wave, response times, discharge computations and hydrographs generation for historic events
4. Rio Grande San Miguel (2007): This is the most important and most documented FEWS project is the one for Río Grande de San Miguel that has real time data transmission, from hydrometric stations the "Villerías" and "El Delirio"; and rainfall stations San Francisco Gotera and Chapeltique. The FEWS uses the HBV hydrologic model, which has been calibrated for hourly intervals, and applied to more than 20 flood events for the purpose of validation. The project was funded by IDB.
5. Rio Acelhuate (2008): Installation of 3 automatic rain gauges with telemetry transmission to provide flood warning to the urban area in the capital city of El Salvador, foreseen future development of hydrologic and hydraulic models as part of the EWS.
6. Social Sustainability of EWS (2008): Analysis of the structure of EWS and the role of mass media, social media, field observers, international technical assistance, and local organizations.
7. Ahuachapán Warning System (2008): Information, monitoring and early warning system in the south of Ahuachapán, with funding from EU – DIPECHO.
8. Early Warning for Central American (2008): Early warning for central American region funded by WFP

9. Risk Management Rio Paz EWS (2009): Study to analyze risk management in the Paz river, funded by IDB

10. Risk Management and Vulnerability to Floods (2009): This project included assessment of the social, physical and economic vulnerability, the improvement of the flood forecasting and improving coordination between the National Emergency Committee.

A thumb up for the smallest and the most densely populated country in Central America, for its work in flood warning systems. Communities are actually saved by the FEWS operating in this country whose name means "Savior".

6.11 Guatemala

The Republic of Guatemala has a high potential of multiple hazards due to its geographic, geological and tectonic position. Vulnerability is also high due to its social, economic, environmental deterioration and development situation. Coordinadora Nacional de Reducción de Desastre (CONRED, 2018) is the national body legally responsible for risk reduction. It was created in 1996 to prevent, mitigate, respond to disasters and also for the rehabilitation following disasters. CONRED's predecessor is the National Emergency Committee (CONE), created in 1969 to assist with emergency actions to the population in case of disasters. Instituto Nacional de Sismología, Vulcanologia, Meteorología e Hidrologia (INSIVUMEH, 2018) is the technical-scientific institution associated with atmospheric, geophysical and hydrological sciences, and acts as technical adviser to the government in case of natural disasters.

The river basins in Guatemala are classified as this: (1) nine basins flowing into the Pacific Ocean; (2) Four basins into The Caribbean Sea; and (3) Five basins into the Gulf of Mexico. INSIMUVEH operates the monitoring systems with a network of 34 hydrometric stations. There are 23 lakes and lagoons, and 119 smaller lagoons, covering an approximate area of 950 square kilometers. INSIMUVEH monitors four of these lakes.

INSIMUVEH got support from NOAA and the USGS through USAID to improve the climate information services and products it provides. Meteorological forecasts are issued for durations of 1, 2, 3 and 15 days, based on numerical models that are able to map precipitation, temperature, wind, speed, evapotranspiration, relative humidity, thermic sensation, and fire indices. There are daily and weekly bulletins for rivers, other hydrologic conditions and for water quality.

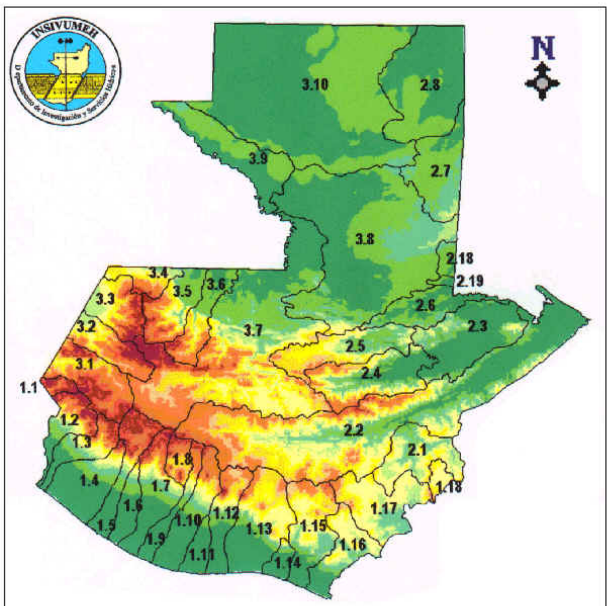


FIGURA No. 1
MAPA DE CUENCAS Y VERTIENTES DE LA REPUBLICA DE GUATEMALA
DEPARTAMENTO DE INVESTIGACION Y SERVICIOS HIDRICOS - INSIVUMEH

Figure 0-6: Map of Watersheds in Guatemala

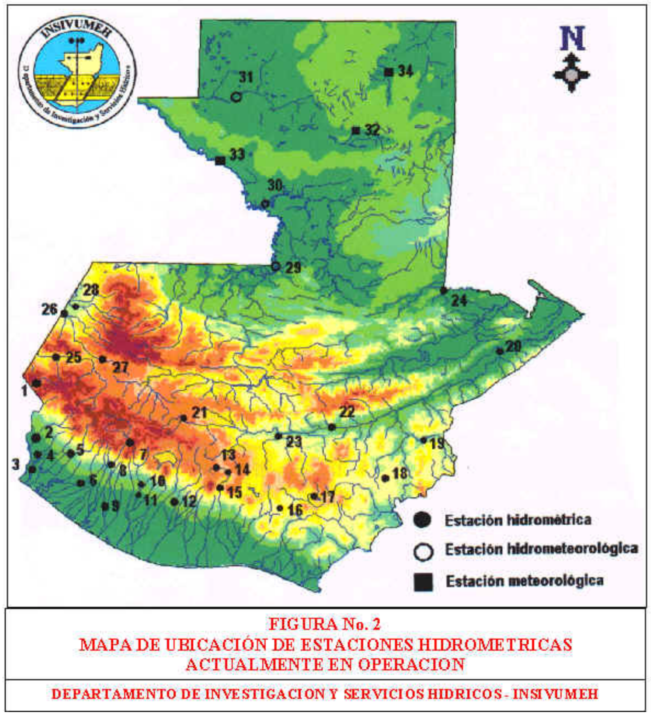


Figure 0-7: Location of Hydrometric stations operated by INSIMUVEH

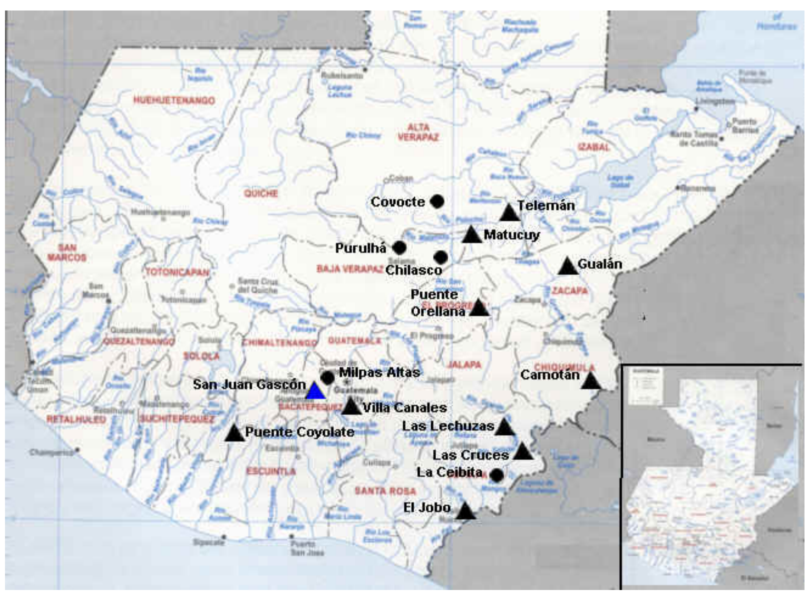


Figure 0-8: Location of weather stations and stream gauges at CB-FEWS

INSIMUVEH publishes on its web site a daily bulletin showing river alert levels, by comparison to minimum and maximum levels at the cross sections of these 12 rivers: Sís, Madre

Vieja, Grande Sacapa, Los Esclavos, Motagua, Polochic, Chixoy, Machaquilá, La Pasión, Lago Petén Itzá, San Pedro, Usumacinta (INSIMUVEH, 2018).

Based on information provided by INSIMUVEH, CONRED issues two types of alerts: the institutional alert for staff of institutions belonging to the CONRED systems and the public alert for the general population. The public alert has a four-color code depending on the intensity of the natural phenomenon, which can be Green, Yellow, Orange or Red.

A flood early warning system (FEWS) was installed in 1997 in the Coyolate river basin, located on the Pacific Ocean side of Guatemala, and since then it has operated properly and has served as a model for other systems installed in the Central American region (OAS, 2009). The success, is due to the active participation of the inhabitants of the basin in the monitoring of rainfall and river levels in the different stations. CONRED and other organizations such as Action Against Hunger (AAH, 2018) have supported this FEWS.

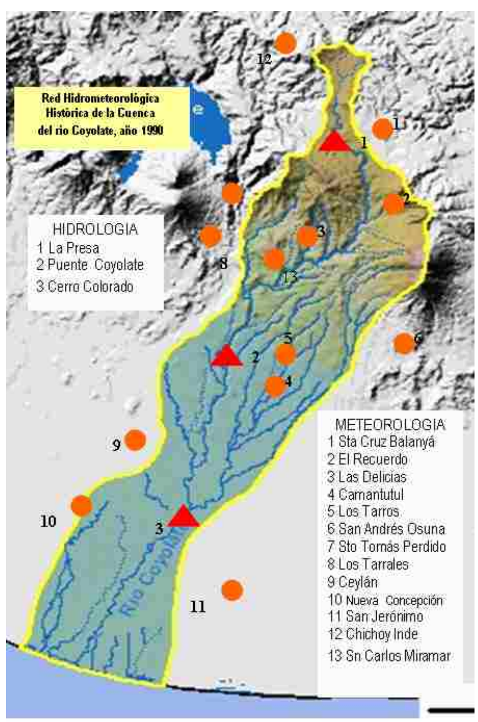


Figure 0-9: Location of rain gages and hydrometric stations in the FEWS of Rio Coyolate

A detailed hydrologic study was conducted in 2009 (OAS, 2009). The frequency analysis was done to define precipitation thresholds with return periods of 1 and 2 years, and for durations of 2, 4, 6, 10 and 24 hours. A Hec-HMS model was applied to generate the hydrographs and peak flows for the threshold levels. Calibration was possible since there were sufficiently long streamflow records. A flood map was to be generated at a later stage with support of the University of Florence Italy.

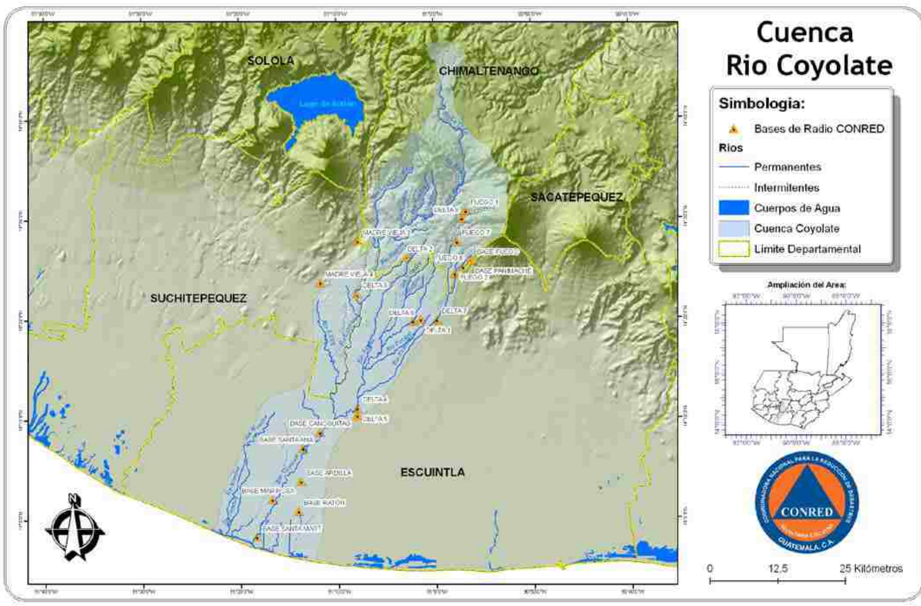


Figure 0-10: Location of Emergency Response Units in Rio Coyolate with UHF/VHF Radios

There are 9 community-based flood warning systems in Guatemala, installed with low cost technology and operated by the community (RIMD, 2008). The USGS and NOAA gave support after hurricane Mitch to improve these systems with some automatic stations with satellite transmission.

Other FEWS have been established in the María Linda, Los Esclavos and Achiguate rivers as a result of inter-institutional coordination between the University Galileo, CONRED, ACH and ICC within the structure of the DIPECHO VIII project, financed by the European Commission

(ICC, 2011). Flood monitoring and alert for the downstream population were located in 5 strategic points for each basin. A calibration phase to define the alarm levels was to follow this project.

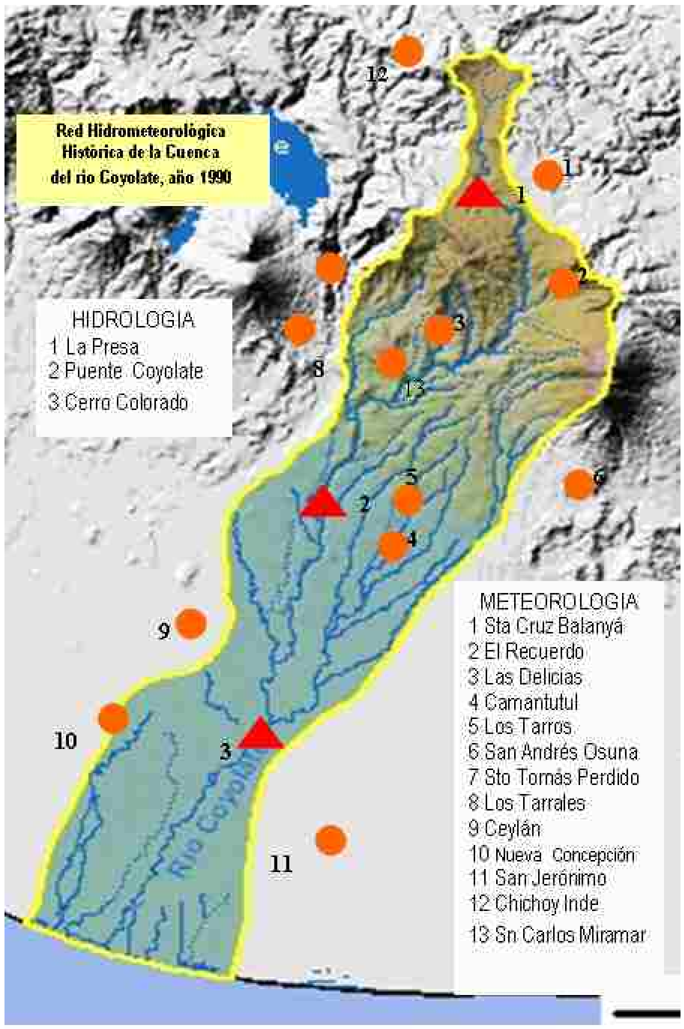


Figure 0-11: Historical Network of Stations a Rio Coyolate

Figure 0-12: Watersheds with FEWS in Guatemala under the USGS-NOAA project

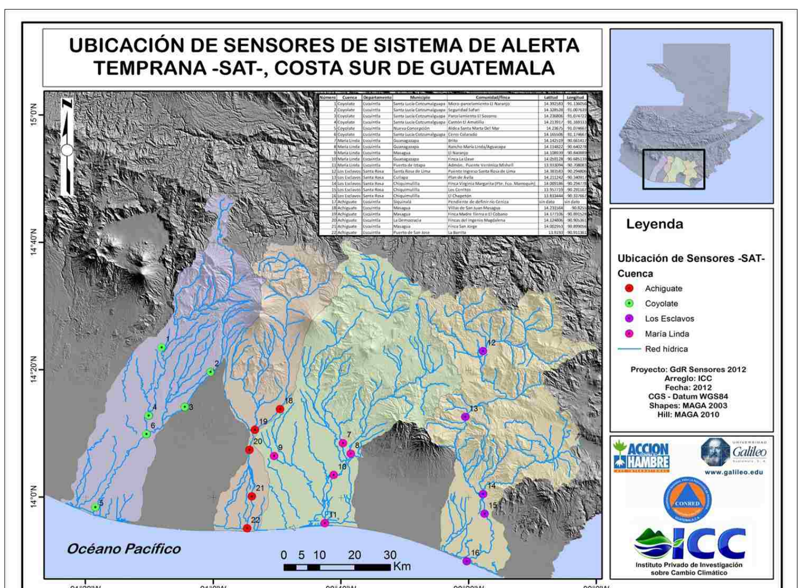


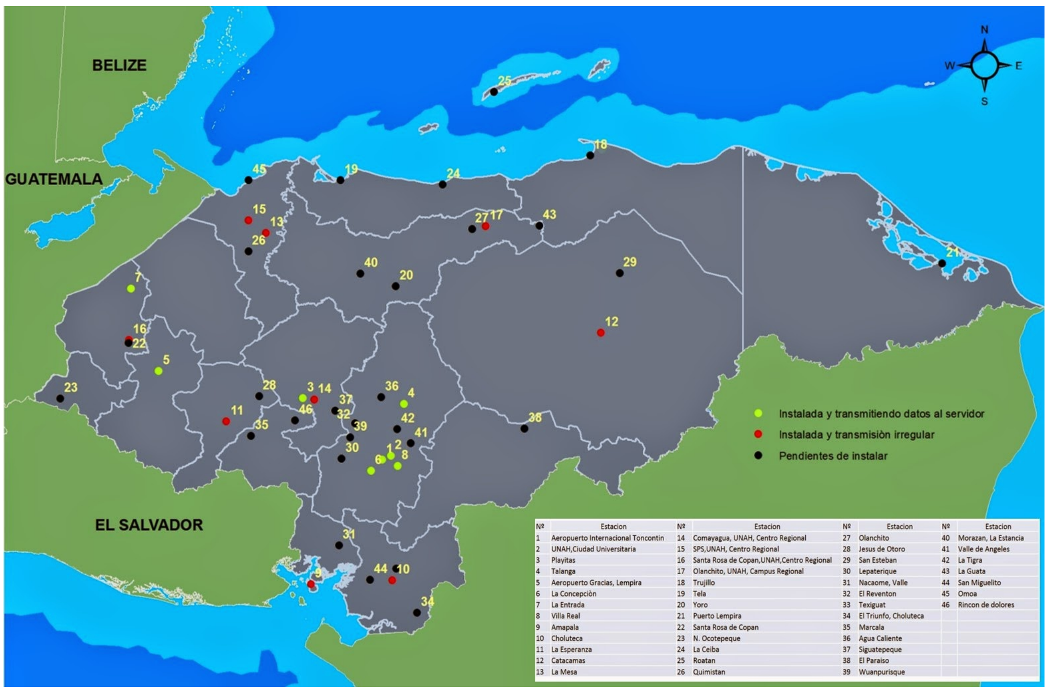
Figure 0-13: Location of Monitoring Sites for FEWS in the ICC project

The country is now covered 36.3%, mostly on the northern part, which explains why most FEWS are in basins that flow towards the Pacific Ocean. Guatemala in the original Nahuatl language means "Forest", or “the place of many trees”.

6.12 Honduras

Hydrometeorological services are carried out by three national institutions in Honduras (FMI, 2015). The Servicio Meteorologico National de Honduras (SMNH, 2018) is responsible for the management of the meteorological information. The Head Office of Hydrological Resources is in charge of the management of surface water and has also a network of climatological stations at national level. The National Electric Company has a hydrological division in charge of several hydrometric networks located in watersheds, with hydropower development projects under way. The Permanent Contingency Commission (COPECO, 2018), is in charge of early warning systems and has received recognition in Central America for its comprehensive risk management including organizing, directing, adopting preventive and coordination measures and integrating participatory efforts to protect the life, property and environment of the inhabitants of the national territory. COPECO offers real time weather information in its website both for meteorological stations and from two radars. The Sistema Nacional de Información Territorial (SINIT, 2018)was created in 2003, integrating in one single information system, the census, statistics, cadastral, property and territorial reference databases managed by different government institutions and partner institutions that feed this platform. COPECO and the SNM are members of SNIT.

The Servicio Meteorologico de Honduras (SNMH, 2018) improved in 2014 its monitoring network by adding 14 new automatic weather stations. The Finish Meteorological Institute (FMI, 2018) has collaborated with projects in Honduras to improve the quality of meteorological and climatological services of SMN by 50% and the Head Office of Hydrological Services by 15%, through the establishment of two-way satellite telecommunication system. This 100% improvement is based on a large increase in the number of products available to meteorologists. Greater effectiveness was also achieved in international telecommunications. In addition, quickened preparatory measures in synoptic and aeronautical meteorology resulted in better weather forecasting. Honduras, whose name means "depths" referring to "deep water", has to sustain he progress so far to be able to face the extreme meteorological and hydrological events that cause almost 150 million dollars in losses per year in Honduras, which represents 1.66% of the DGP.



Nº	Estacion	Nº	Estacion	Nº	Estacion	Nº	Estacion
1	Aeropuerto Internacional Toncontin	14	Comayagua, UNAH, Centro Regional	27	Olanchito	40	Morazan, La Estancia
2	UNAH,Ciudad Universitaria	15	SPS,UNAH, Centro Regional	28	Jesus de Otoro	41	Valle de Angeles
3	Playitas	16	Santa Rosa de Copan,UNAH,Centro Regional	29	San Esteban	42	La Tigra
4	Talanga	17	Olanchito, UNAH, Campus Regional	30	Lepaterique	43	La Guata
5	Aeropuerto Gracias, Lempira	18	Trujillo	31	Nacaome, Valle	44	San Miguelito
6	La Concepciòn	19	Tela	32	El Reventon	45	Omoa
7	La Entrada	20	Yoro	33	Texiguat	46	Rincon de dolores
8	Villa Real	21	Puerto Lempira	34	El Triunfo, Choluteca		
9	Amapala	22	Santa Rosa de Copan	35	Marcala		
10	Choluteca	23	N. Ocotepeque	36	Agua Caliente		
11	La Esperanza	24	La Ceiba	37	Siguatepeque		
12	Catacamas	25	Roatan	38	El Paraiso		
13	La Mesa	26	Quimistan	39	Wuanpurisque		

Figure 0-14: Monitoring Network of Honduras National Meteorological Service

World Bank collaborated with COPECO with over 10 million dollars to strengthen the weather information services and warning systems, and to modernize the Centro Nacional de Estudios Atmosféricos, Oceanográficos y Sísmicos (CENAO, 2018), COPECO's center for atmospheric, oceanographic and seismic studies. The project established a national platform that facilitates the exchange of data and the development of hydrometeorological and climatic services, redesign and installation of the observation networks with acquisition of equipment for monitoring and forecasting of atmospheric and environmental conditions; the improvement in the provision of services; and creation of a committees and data providers and hydrometeorological and climatic products. It seems, this did not include a total FEWS that would issue forecasts of river levels and discharges.

The World Bank funded a project in 2016 to improve the climate, meteorological and hydrological services in support climate-resilient development in Nicaragua and Honduras (NCAR, 2016). This project had two components: (i) assessing the current status of climate, meteorological and hydrological services including Early Warning Systems; (ii) and development of a national Modernization Plan.

6.13 Nicaragua

INETER or Instituto Nicaraguense de Estudios Territoriales, (INETER, 2017) offers meteorological services and seismic and volcano monitoring. INETER offers weather, maritime and tidal forecast. INETER has some basins with flood forecast projects.

A hydrometeorological forecast system was established for the **Rio Coco** with technical cooperation support from NOAA and WMO (El Nuevo Diario, 2016). The Coco river is the largest in Central America, flowing between Nicaragua and Honduras (EcuRed, 2018). The main tributaries are the Comalí river in Honduras and the Tapacalí river in Nicaragua. The river length is 680 km, and the watershed area is 24,767 km^2. On the Nicaraguan side, there are 70 communities with an indigenous population of more than 50 thousand, who will be benefited from the operation of the EWS. Similar monitoring systems are expected to be installed in the Escondido, Prinzapolka, Wawa and Grande de Matagalpa rivers (El Nuevo Diario, 2015).

This EWS of the Coco river combines real time monitoring and community based EWS. The EWS with automated stations are at Esteli river, Jicaro river and Coco river itself.

	EWS Esteli River	EWS Jicaro river	EWs Coco river
Rain gauges	Esteli, Tisey Condega and Ocotal	Jalapa, Jícaro, Quilalí	Wiwili, Piedras
Hydrometric stations	Esteli, Pire and Coco rivers (confl with Esteli)	Río Jícaro, Río Jícaro at Mata de guineo, Rio Coco Confluence with Jícaro)	Río Cuá; Río Coco at Wiwilí; Río Coco at Piedras;

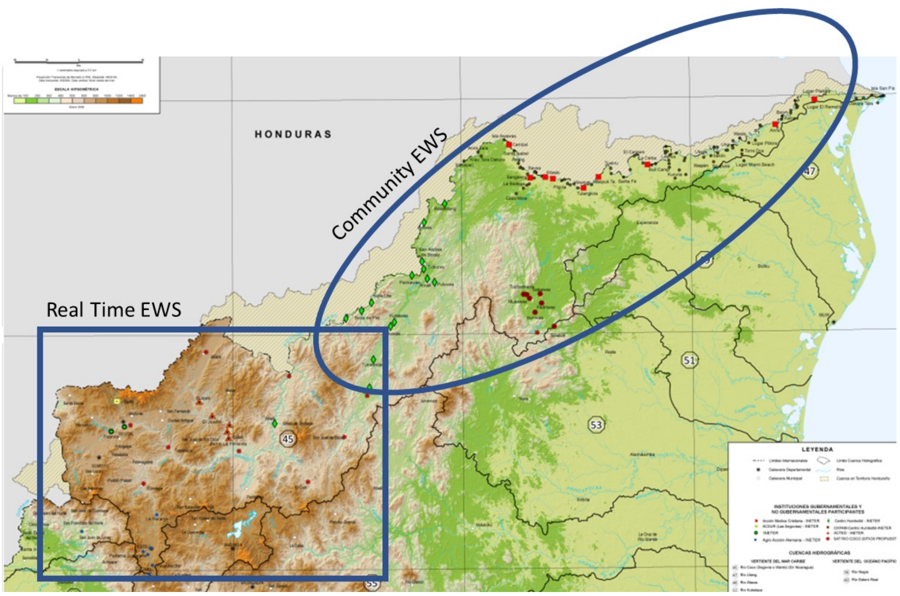


Figure 0-15: Early Warning System of the Coco River in Nicaragua (INETER)

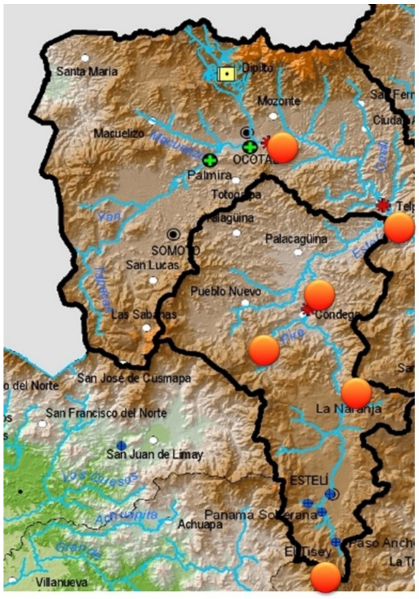


Figure 0-16: EWS of the Esteli River

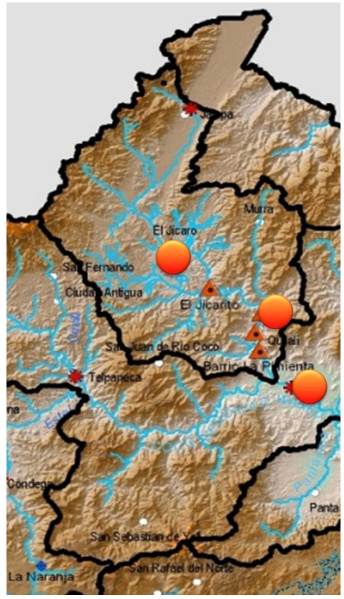


Figure 0-17: EWS of the Jicaro River

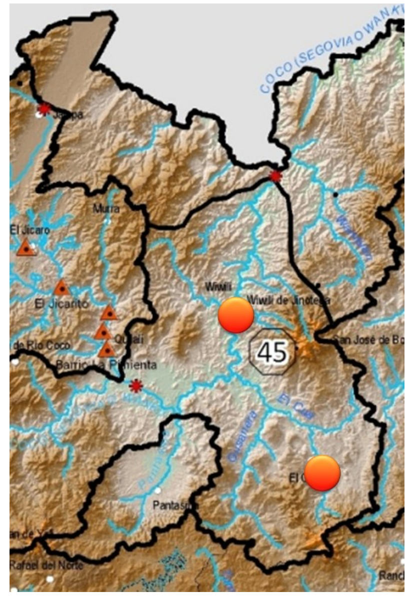


Figure 0-18: EWS of the Coco River

Another hydrometric monitoring system for flood warning is that of **Bocay river,** in the reach between Tunawalang and Peñas Blancas (Prep Consulting, 2013). This system is based on the rainfall forecast provided by INETER, and six hydrometric stations along the Bocay river. A four-level alert scale has been qualitatively defined for different hydraulic conditions: Normal (no-threat), Green (nearing bank full), Yellow (potentially hazardous), and Red (critical flooding). Threshold levels were determined based on analysis of historical flows, and level of threat represented for the communities. A protocol for evaluation and communication has been elaborated for institutions and communities, based on the alert scale and weather conditions.

A Community Flood Early Warning System (CB-FEWS) has been implemented in the lower part of the **Escondido River** basin, in the South Atlantic Autonomous region (RAAS) (IFRC, 2015). It was developed by the Nicaraguan and International Red Cross within the framework of DIPECHO plans for Central America. INETER provided technical support for the installations of the EWS. There are over 17 thousand direct beneficiaries, 90% of whom are exposed to floods and 100% to the collateral effects of tropical cyclones.

Nicaragua is home of a multiethnic, multilingual and multicultural population. The name of the country means “land of lakes and volcanoes”, and as such has to be permanently on guard against natural disasters.

6.14 Panama

ETESA (Empresa de Transmision Eléctrica) has established flood warning systems in Rio Cabra and Pacora rivers in Panama. A hydrological and hydraulic analysis project for the design of an early warning system against Floods in the Pacora River was carried out in 2016 by the Center for Hydraulic and Hydrotechnical Research (CIHH) and the Electrical Engineering Faculty of the Technological University of Panama (UTP) (UTP, 2016). The FEWS has three monitoring sites for the levels of the Pacora River at readings intervals of 15 minutes. and facilitate early warnings before the danger of possible flooding. In addition to including adapted responses that allow people with special abilities to know when there is a flood warning. The IRHE (Instituto de Recursos Hidráulicos y Electrificación) operated hydrologic monitoring networks from 1955 to 1998, when the operation of a network of 165 climate stations and 72 hydrometric stations were transferred to the then newly established ETESA.

The hydrometeorologic direction at ETESA is in charge of the installation and operation of the FEWS (ETESA, 2018). Flooding of the Cabra river affects 25 communities and has generated in different flooding events damage to more than 700 homes, with 12 casualties, and losses estimated in millions of dollars. The FEWS of the Cabra river consists of one weather stations at Cerro Pelón, and a hydrometric station at Racho Café, both automated sensors with telemetry transmission via satellite; and in addition, there are three strategic sites with staff gage for manual operation (ETESA, 2016).

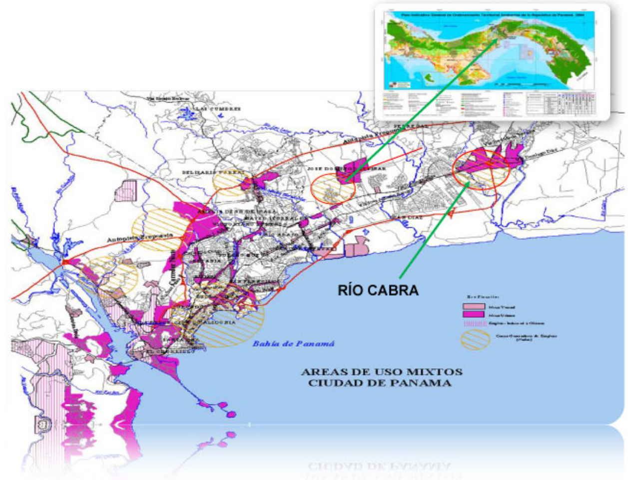


Figure 0-19: Location of Rio Cabra in Panama

The FEWS of the Pacora river is very similar and consists of one automatic weather station in the upper part of the basin, and an automatic hydrometric station at Cariazo using satellite telemetry, and a staff gage at San Miguel that uses radio telemetry (ETESA, 2015). The watershed has an area of 361.20 km2, with 49 populated places in the Pacora and San Martín region of the District of Panama and the province of the same name (ETESA, UniónEuropea, DefensaCivil, 2009). Several entities are involved in the operation including the San Martín Communal Board, Civil Protection agency known as SINAPROC (SINAPROC, 2018) and ETESA.

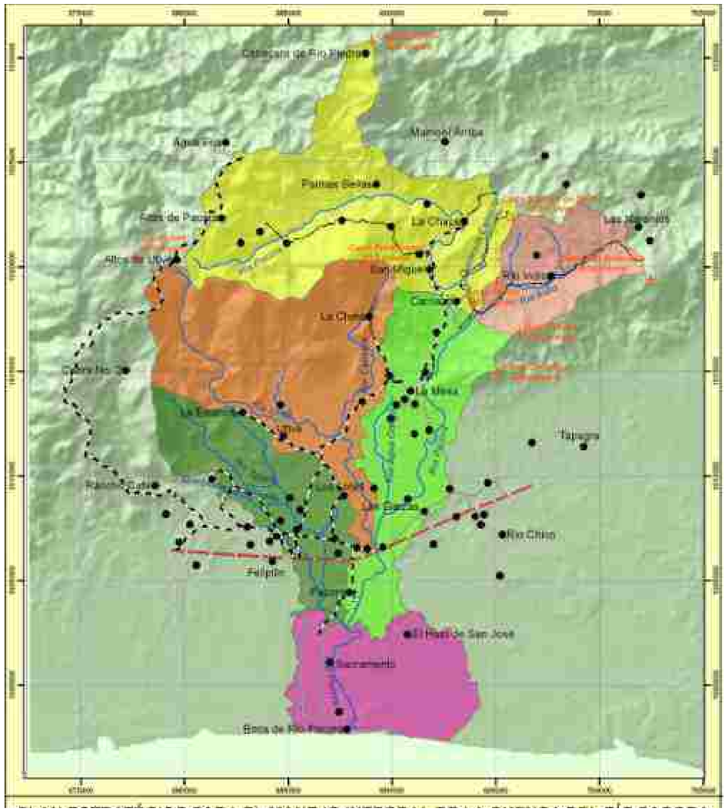


Figure 0-20: Watershed of the Pacora River

An operation manual for FEWS (UNESCO, 2011) has been published by several agencies in collaboration MEDUCA (MEDUCA, 2018), UNESCO (UNESCO, 2018), CEPREDENAC (CEPEDRENAC, 2018), SICA (SICA, 2018), and DIPECHO (DIPECHO-LAC, 2018).

APPENDIX B. COUNTRY BY COUNTRY REPORT OF GREATER ANTILLES

The Greater Antilles are composed by the major islands in the Caribbean that include Cuba, Dominican Republic and Haiti, sharing both the Hispaniola island, Jamaica and Puerto Rico.

Figure 0-1: Countries of the Greater Antilles

Although is kept in this chapter as part of this group of countries, Jamaica, a former colony of Great Britain, is integrated with the Anglo Caribbean, or countries that are part of the British Commonwealth. It is integrated also in the Caribbean Community or CARICOM (CARICOM, 2018) countries (Antigua & Barbuda, Bahamas, Barbados, Belize, Dominica, Grenada, Guyana, Haiti, Jamaica, Montserrat, Saint Lucia, St.Kitts and Nevis, St. Vincent and Grenadines, Suriname, Trinidad and Tobago).

6.15 Cuba

The NMS and NHS in Cuba are Instituto Meteorológico de la Republica de Cuba (INSMET, 2018) and Instituto de Recursos Hidráulicos (INRH, 2018) respectively. Both agencies work on warning and forecast over the island. INSMET has been working on multi-hazard warning systems which includes riverine and coastal flooding, droughts, forest fires, and other threats (Carrasco Diaz, 2013). INSMET operates a high-density network of rain gages and eight weather radars.

Figure 0-2: Map of Weather Stations in Cuba

The population in all the communities has been trained to follow safety procedures when there are extreme weather events. Amateur and voluntary radio operators play a key role to disseminate warnings and other information to maintain people safe.

An EWS was installed by the INRH in 2010 for the Guantánamo y Camagüey provinces, and in Bayamo of the Granma province, and Sagua de Tánamo in the Holguín province (PrensaLatina, 2010). The Project was funded by UNDP and included a last generation monitoring and computing technology (Aguilera, 2010). The FEWS in these four cities are directly connected to the risk centers operated by the Civil Defense, the national emergency management agency/ The FEWS for the San Pedro river basin in Camaguey, sends real time data from rain gauges, and staff gauges and also radars. This project is expected to influence the reduction of risks due to floods caused by heavy rains or cyclones, through timely decision making to help protect a population of more than 170,000, which have been in the past affected in flood risk zones by Cyclone Flora (1963) and Ike (2008), among other weather events.

Later in 2015-2017, the European Civil Protection and Humanitarian Aid Operations (ECHO, 2018) conducted the FORSAT project (stands for strengthening of early warning system) installed a FEWS that benefits almost 40 thousand people who live in vulnerable areas of the Agabama and Zaza river basins; in the town of Placetas, in Villa Clara, and in the municipalities of La Sierpe, Fomento, Trinidad and Sancti Spíritus, in the province of Sancti Espiritu (AgenciaCubanadeNoticias, 2017). The project is supported by UNDP, INRH, INSMET, the ministries of Education and Science, Technology and the Environment, Civil Defense, the Red Cross, and the Federation of Cuban Women. Rain gauges and satellite services of INSMET were included in the project. Hazard, Vulnerability and Risk -Studies were previously carried out to support the tool of Threat, Vulnerability ad capacity tool used by the Civil Defense.

While the largest of the Greater Antilles does not enjoy access to the same level of funding as the rest of the countries in the region, they have a very dense network of over 2,000 rain gauges and also leading record for casualty reduction in the region (Diaz, 2003). Cuba is a model for the region in terms of preparedness (Rubeiera & Puig, 2012), and its resiliency is the greatest strength, and recovery is also formidable. A recent example of this was during hurricane Maria in 2017, that affected Cuba and Puerto Rico (Schwartz, 2018). The extent of exposure and level of hazard were the exact same for the two countries, but Cuba's response while Puerto Rico got to the point of not having power re-established even three months after the event (Grant, 2017). To further strengthen the system, Cuba has developed and applies an integrated operation procedure for flood early warning systems (UNISRD, 2015).

The sustained success of Cuba in risk management comes from investing material resources and human capital in the creation and improvement of its early warning system for tropical cyclones and other alert systems (Rubiera Torres & Puig, 2012). The things they have done very well are these: (i) Strengthening the meteorological and hydrological monitoring systems; (ii) Training of specialists at national agencies and local volunteers in the community; (iii) development tools to improve understanding of the hazards; (iv) preparedness plans at national to local levels; (v) rapid dissemination of alert messages though all available means. Cuba also makes use of forecasts by the National Hurricane Center in the USA (Rubeiera 2012).

6.16 Dominican Republic

Warnings of weather conditions are provided by ONAMET (Oficina Nacional de Meteorología) (ONAMET, 2018), the NMS that operates a 24/7 forecast center. The NHS would be Instituto Nacional de Recursos Hidráulicos (INDRHI, 2018) that operates a monitoring climatic and hydrologic networks and has a hydrologic prevision center (HPC). INDRHI installed, in a World Bank (WB) project in 2002, an advanced hydrologic network of 120 stations for the Yaque del Norte (6,893 km^2), Yaque del Sur (5,062 km^2); Yuna (5,258 km^2); and Rio Nizao (1,039 km^2) watersheds, which together cover about 38% of the Dominican territory. This project had telemetry for data transmission via NOAA's well known GOES12 satellite. It also contemplated the use of a hydrologic model to at the HPC, but this component was never developed, and limited the system to visualization of rainfall and climate data in the remote locations. This was part of a recovery project after Hurricane George in 1998 (World Bank, 1998). Nine years later, INDRHI was struggling to keep the last 12 of these stations in operation since vandalism, theft and lack of maintenance ruined the expensive network. The country was hit by TS Olga and TS Noel in 2007, and this led to another recovery project by WB in 2012 (World Bank, 2008) and brad new telemetry monitoring network consisting of 64 stations was installed in 2015 in the first three of the watersheds named above, and another project around the same time installed 18 more stations in the fourth of these watersheds. Again, no provision as made for a hydrologic modeling application at the HPC.

Recently, the Center for Emergency Operations (COE, 2018) developed an app showing which provinces are under green, yellow or red alert levels when there is an extreme event approaching or passing through the territory. However, this is not based on any modeling to produce the maps showing the extent of flooding expected as a result of a hydrologic forecast.

There are three recent developments that come as a novelty for flood waring in the region. The first interesting development to be mentioned is the Haiti and Dominican Republic Flash Flood Guidance (HDR-FFG) developed by the Hydrologic Research Center (HRC, 2018), in San Diego US, with support from the National Weather Service (NWS) and the World Meteorological Organization (WMO) between 2015 and 2018. The first deployment of the Central America FFG was in 2004. Training sessions are being organized by WMO and NWS in the San Diego, and the last one in Santo Domingo (WMO, 2018). The participants are representatives of the National Meteorological and Hydrological Services (NMHSs), which include INDRHI and ONAMET. The FFG integrates satellite-based and in-situ observations of precipitation and land-surface hydrology models to generate real-time assessment of hydrologic conditions and the possibility of flood occurrence (Modrick, et al., 2014).

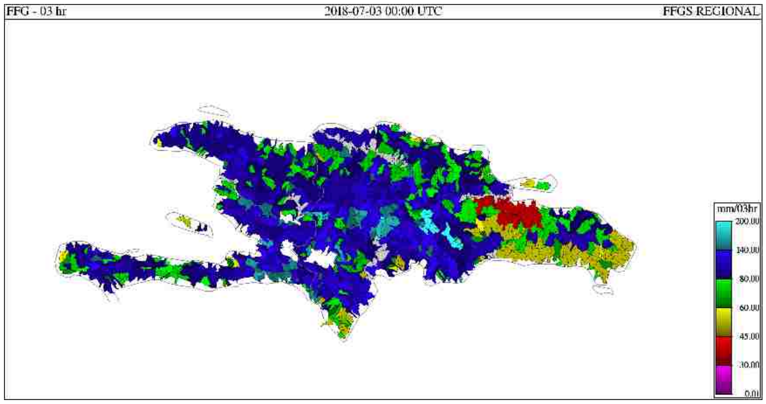


Figure 0-3: Haiti Dom. Rep. Flash Flood Guidance System by HRC

The developers were contacted to participate in the assessment for this research, and suggested that the NMHSs can be asked in the next seas after they have had a chance to use the system (Georgakakhos, 2017). Access to the last version is restricted to official organizations from the countries. Calibration is known to be a challenge to be treated in further work to be done by HRC.

The second one is the tool developed in 2017 by BYU for INDRHI, an application called the stream flow prediction tool (SPT), based on ECWMF hydrologic forecast which covers all the watersheds in the country (Snow, et al., 2016).

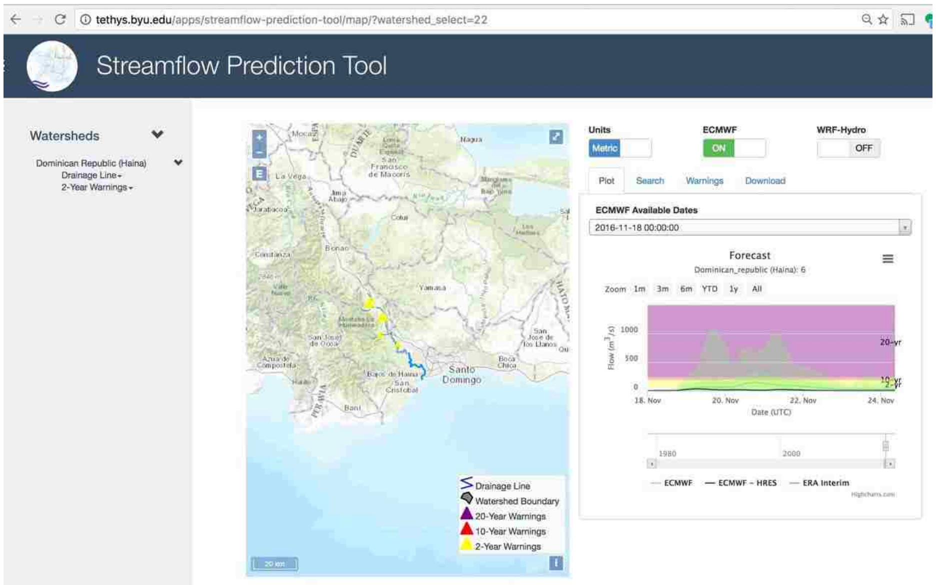


Figure 0-4: Streamflow Prediction Tool for the DR

The second one is a flood warning system developed by AQUAVEO and Brigham Young University (BYU), in a USAID-funded project in 2017, for the Ozama, Higuamo and Haina rivers.

6.17 Haiti

The Ministry of Agriculture of Natural Resources and Rural Development (MARNDR) has a HydroMeteorological Unit of Haiti (UHM, 2018) that provides meteorological information online.

Haiti was on partially approached as the facilities of its national meteorological services were destroyed by the earthquake of 2010 (WMO, 2010). The World Meteorological Organization started actions in 2010 to strengthen the NMHSs in Haiti (WMOb, 2010). This project envisioned The National Flood Early-Warning Programme (PNAP), to be funded by a loan of $5 million from the IDB. Flood Early Warning Systems were to be installed in the 13 catchments that are more prone to flooding. The EWS would have a monitoring network of 84 rain gauges and 40 hydrometric stations, with local and satellite radio transmissions (DVB-RCS) to the PNAP Central

Office. The selected catchments are: Grande Anse river, Port au Prince, Grande Ravine du Sud, Acul river, Torbeck river, Grande and Petite, Rivières de Saint Marc, Maniche/Cavaillon river, Zone des Arcadins, Baraderes river, Artibonite river, Nippes river, Jacmel river, Gosseline river, Trois rivières, La Digue river (Petit Goâve), Rouyonne and Momance rivers. The project progress or performance have not been verified.

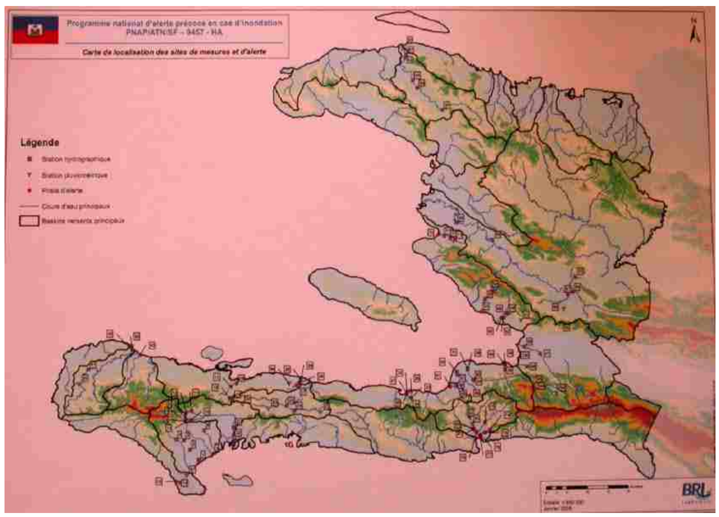


Figure 0-5: Location of PNAP Sites for Monitoring and EWS in Haiti

The World Bank started a project in 2015 with the objective of strengthening the institutional capacity to provide hydrometeorological and climate information services customized to the needs of the civil protection and agriculture sectors, which contributes to increasing disaster and climate resilience" (World Bank, 2018). This also includes the "development of data management tools will focus on the integration of the existing hydrometeorological data collection networks into one national data platform based on an open data approach and accessible across end users in the Government of Haiti and beyond". The project status report (Bradshaw, 2018) shows that this project is just starting, and results are expected by the end of 2020. The National Hydrometeorological Unit under the Ministry of Agriculture is fully operational. The first contract with the consulting firm to support institutional development with a strategic and operational model was signed. The design of the national data platform has started.

6.18 Jamaica

The Meteorological Service of Jamaica (MSJ, 2018) manages observation and forecasting of weather conditions over and around the island, with radar monitors and reports on rainfall occurrence within a range of nearly 500 kilometers; an Upper-Air Station (the Caribbean Rawinsonde Network Section) that monitors the characteristics of the upper atmosphere; a Synoptic Sub-Station operating within the Sangster International Airport in Montego Bay that makes observations and meteorological reports for use in international air navigation; and a National Meteorological Centre at the Norman Manley International Airport that provides weather forecasting services for general dissemination. It also provides a continuous Hurricane Watch during the hurricane season and is responsible for the issuance of severe weather warnings. Data for forecasts are obtained locally from observation points at the surface, as well as from the radar station, and internationally through telecommunication links with regional and international centers and via stationary and polar orbiting satellites.

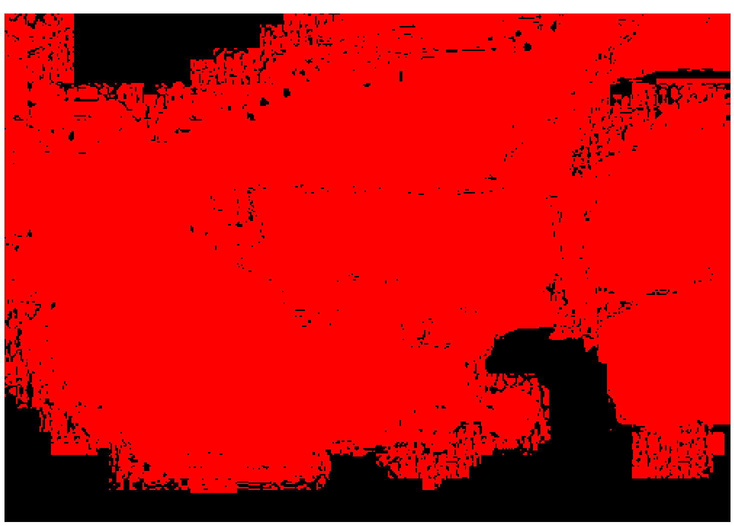


Figure 0-6: Weather Forecast offered by the Meteorological Service of Jamaica

Flood warning systems are operated by the NHS which is the Water Resources Authority (WRA, 2018) for the Cave river, Rio Cobre, and the Annotto and West Town rivers, and over the years has elaborated flood hazard maps for Rio Grande, Yallahs River, Hope River, Rio Cobre, Rio Minho, and Black River (Haiduk, 2004). The NMS is the Meteorological Service of Jamaica (MSJ, 2018). WRA operates a monitoring network and a flood warning system. The watersheds where flooding occurs more frequently are: White River, Milk River, Black River, Great River. Sites that are vulnerable in these basins are: Moneague, Harmons, Newmarket, Forest and Chigwell. Major flood events have been caused by Hurricanes Gustav, Ivan, Dean, Sandy (2012), Wilma (2005), Tropical Storms Lilli and Isadore (2001), and Depression in 1974 over western Jamaica. The monitoring network operated by WRA has been improved in 2017 by retrofitting 10 rainfall stations and 6 hydrometric stations, that now provide real time data (RJRNews, 2017). WRA plans to upgrade 34 stations under the project. A national emergency communication network has been created with the purpose of strengthening early warning systems for disasters at the local level (FloodList, 2017). The funding comes from the national government and the Japan International Cooperation Agency (JICA, 2018), for phase 2 of the Caribbean Disaster Management project (CADM2), which aims at increasing resilience to disasters at the community level. The Office of Disaster Preparedness and Emergency Management (ODPEM) is working on community early warning systems to be developed and rehabilitated by the Water Resources Authority. The Caribbean Disaster Emergency Management Agency (CDEMA) is supporting initiatives for the establishment of robust people-centered early warning systems. CADM2 is developing disaster-risk management mechanisms, including flood plain maps, community disaster-risk management plans and flood warning systems, and recently with funding from the Caribbean Development Bank (CDB) (CDB, 2018), the FEWS for Bogwalk Gorge was upgraded, previously installed in the Rio Cobre where many communities are at flood risk (TheGleaner , 2017). The strength in the development of FEWS for the island of “Wood and Water”, as named by the indigenous Taino habitants, seems to be that the national and local government, and national authorities like WRA have their own initiatives to help communities face flood risks.

Another recent World Bank project will contribute towards the improvement and rehabilitate of hydro-met networks, flood and drought early warning with an investment of about 4 million US dollars (World Bank, 2015). The original network had deteriorated from 23 to only 6 stations. The Doppler weather radar at Cooper’s Hill was obsolete and malfunctioning. The stations needed some relocation since there is some overlap in the network of the Water Resources Authority (WRA) and the Meteorological Service of Jamaica (MSJ). Nineteen of the 27 WRA gauges are within less than 10 km of a MSJ gauge, and 7 are within 5 km of a MSJ gauge. This project has a period of execution between 2015 and 2021 (World Bank, 2015). The projects are justified by the fact that there were 5 major hurricanes and 6 storms between 2001 and 2012 that caused billions in loses, and preparation actions are needed. .

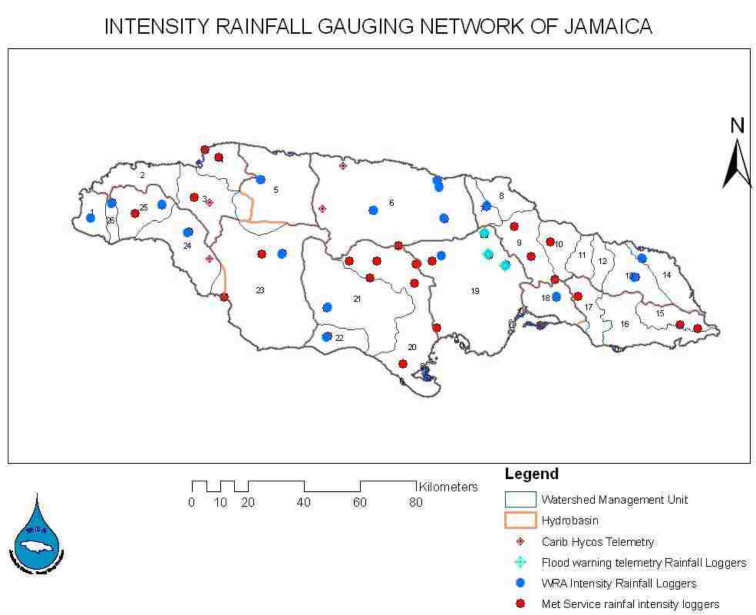


Figure 0-7: Precipitation Monitoring Network in Jamaica (WRA*)*

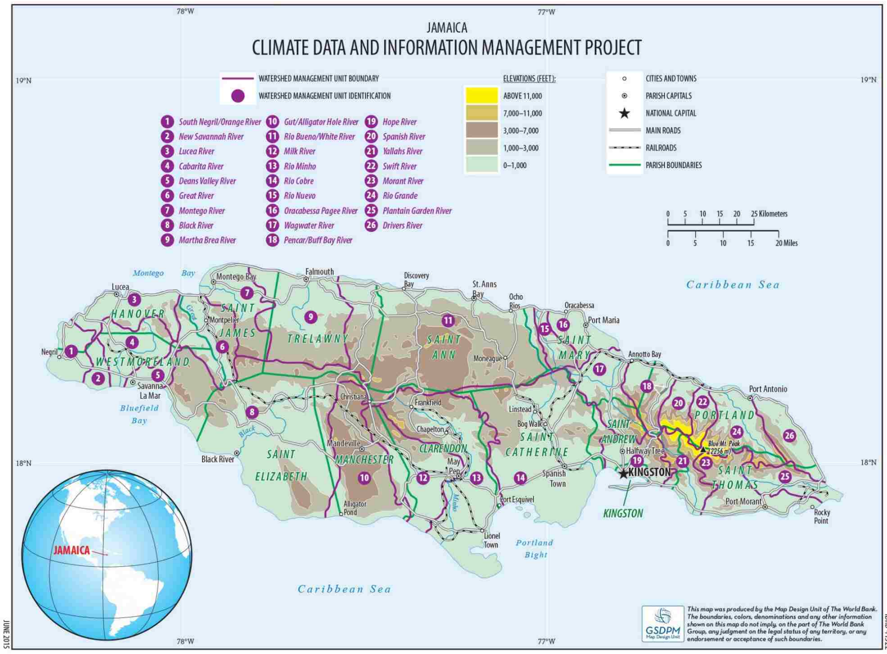


Figure 0-8: Hydrological units in Jamaica

6.19 Puerto Rico

Puerto Rico was excluded because it is considered to be part of the USA where agencies such as NWS, USGS, NRCS, and FEMA have its Caribbean offices and as such, enjoy technology and expertise proper of a developed country. This judgement could be reasonably challenged with in some cases with evidence that proof otherwise, and also by the arguments of the location of the country. In order to be comprehensive, Puerto Rico is kept here in the description did not form part of the list of countries surveyed.

APPENDIX C. COUNTRY BY COUNTRY REPORT OF LESSER ANTILLES

6.20 Northern and Western Caribbean

This subregion includes; (i) the Commonwealth of the Bahamas with its more than 700 hundred islands, cays and islets north of Cuba and southeast of Florida; (ii) Turk & Caicos islands, a British territory located north of the Hispaniola (DR and Haiti); The Bahamas and the Turc and Caicos form part of the Lucayan Lucayan archipelago.

The Bahamas

Information about current weather conditions in the Bahamas can be found in several websites, since it is a travel and vacation destination for many tourists. The three major islands have weather stations issuing data: Nassau Airport in Nassau, Freeport in Gran Bahamas, and George Town in Exuma Bahamas (Bahamas Weather, 2018). Given its proximity to the United States, the needs of weather information and forecasts and hurricane tracking are met by the US agencies like the NWS, NOAA, the NHC and the Canadian Weather service.

The islands are low and very flat, so floods occur by the occurrence of heavy rains and storm surges from hurricanes. Hurricane Joaquin caused damage in the Central Bahamas and the Southeast Bahamas in 2015. The meteorology department of Bahamas is currently in a project to improve weather forecasting for all the vast territory, and will have installed by 2019 the following new equipment: 4 doppler weather radars, 9 automatic weather stations at airports, 16 automatic stations and 1 direct readout ground station (Vaisala, 2018).

Figure 0-1: The Bahamas

The National Emergency Management Agency (NEMA, 2018) of the Commonwealth of The Bahamas, is the official government agency that works on preparedness and mitigation measures, and response and recovery actions. No formal flood warning systems are known. The flat topography and the absence of very defined drainage networks. Flash flood guide dance systems (FFGS) are more suitable.

Turk & Caicos

The Turk & Caicos are a British Overseas territory, and as such it receives support from the Met Office of the United Kingdom (MetOffice, UK, 2018), which gives weather forecasts and warnings for the islands. Again, this is a meteorological and not a hydrological forecast.

6.21 The Eastern Caribbean

The **Leeward** islands includes the group of these islands: the U.S. Virgin **Islands**, the British Virgin **Islands**, Anguilla, Saint Martin, Saint-Barthelemy, Saba, Sint Eustatius, Saint Kitts, Nevis, Barbuda, Antiqua, Redonda, Montserrat, Guadeloupe and Dominica.

The more southerly part of this chain, starting with Martinique, is called the Windward Islands

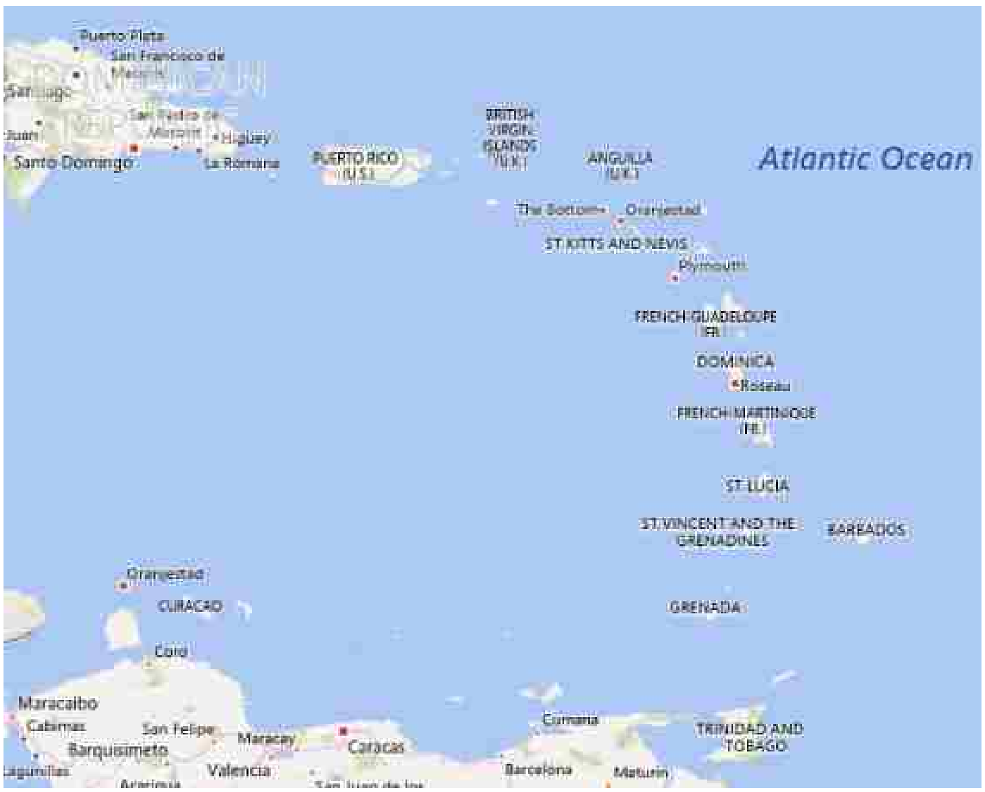


Figure 0-2: Countries of the Eastern Caribbean

6.22 The US Caribbean Territories

The United States territories in the Caribbean are Puerto Rico and the U.S. Virgin Islands. This last includes St. Thomas, St. John and St. Croix. Puerto Rico has been described within the Greater Antilles.

6.23 The Northeastern Caribbean

Antigua & Barbuda

Antigua and Barbuda is an independent country, consisting of two major islands, Antigua and Barbuda, and a number of smaller islands (including Great Bird, Green, Guiana, Long, Maiden and York Islands and further south, the island of Redonda). Hurricane Irma in 2017 damaged or destroyed 95% of Barbuda's buildings and infrastructure. Everyone on the island was evacuated to Antigua (Panzar & Willsher, 2017). The Antigua Meteorological Office (AMO, 2018) provides climate and weather information, weather forecast, watches and warnings for the islands. The forecast extends to the following leeward islands: Montserrat, St Kitts & Nevis, Anguilla and the British Virgin Islands.

6.24 The British Overseas Territories in the Caribbean

There are six British Overseas Territories are: Anguilla, Bermuda, British Virgin Islands, Cayman Islands, Montserrat, and Turks and Caicos. The territory of Anguila consists of the main island of Anguilla, and a number of much smaller islands and cays. Montserrat is called "The Emerald Isle of the Caribbean". The British Virgin Islands consist of over 50 islands and cays, the main ones are: Tortola, Virgin Gorda, Anegada and Jost Van Dyke. Grenada is a sovereign state the southeastern Caribbean Sea, consisting of the island of Grenada and 6 smaller islands at the southern end of the Grenadines island chain, located north of Trinidad & Tobago, and Northeast of Venezuela, and southwest of Saint Vincent and the Grenadines. The Met Office from the United Kingdom is the supplier of weather information and forecast for Anguila, British Virgin Islands, and Monserrat.

Cayman Islands

The Cayman Islands are: Grand Cayman, Cayman Brac, and Little Cayman, lying northwest of Jamaica and south of Cuba The Cayman Islands National Weather Service (CINWS, 2018) of the Cayman Islands offers current weather information and 5-day forecast of general weather conditions. The website shows satellite images by the NWS and NOAA. These islands have the same topography description as most of the small island states. It has been affected by hurricanes Gilbert in 2008 (CINWS, 2013), and Gustav in 1988 (CINWS, 2009). Flood warning is given in a general form in the hurricane forecasts.

Bermuda

The Bermuda Department of Meteorology (BDM, 2018) covers all weather forecast services provides about climate, current weather, weather forecasts, tropical systems as well as alerts, watches and advices. It gives a 7-day weather forecast and a 3-day severe weather outlook. No specific hydrological flood warning is known to be in operation.

6.25 Barbados, Dominique, and St. Vincent

Barbados

The Barbados Meteorological Services (BMS, 2018) provides meteorological, hydrological and marine services, and it is in charge of monitoring observation and data collection of climatological data. The BMS also conducts research in the science of meteorology. Barbados is home of the training center for forecasters in the Caribbean. BMS operates the forecast, warning and advisory services. The BMS provides forecast based on satellite imagery, radar composites, surface and upper air observations, and satellite derived products. Several models are used to develop the forecast: Global Environmental Multiscale Model (GEMS), the Global Forecasting System (GFS) developed by NCEP, WRF, WW3, and UKMET. The coverage of forecast and severe weather advisories (warning and watches) includes Barbados, Dominica, St Vincent, and other Lesser Antilles.

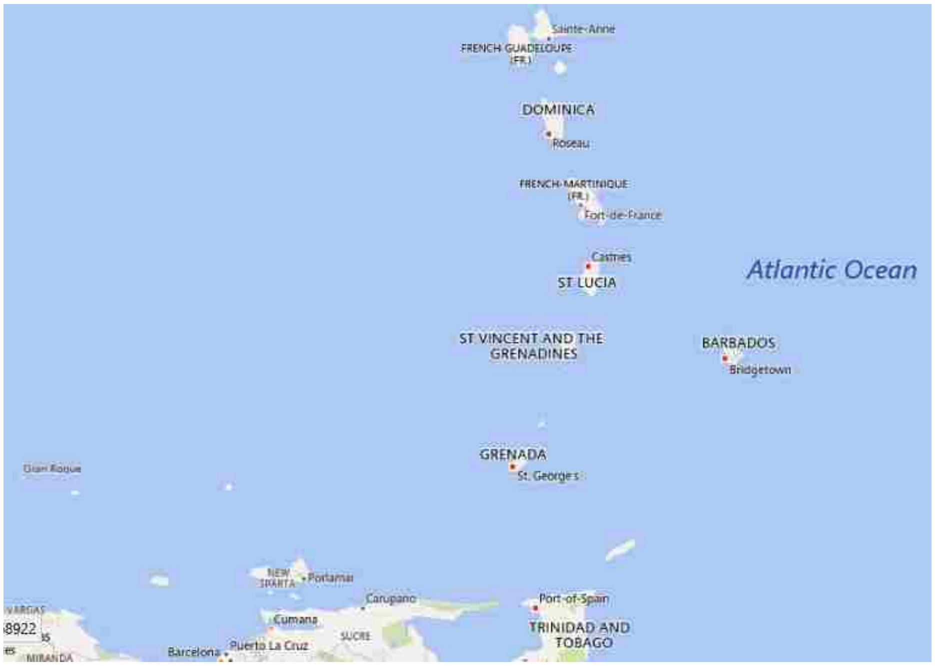


Figure 0-3: Countries of the Eastern Caribbean

The Department of Emergency Management (DEM, 2018) of the Government of Barbados is in charge of the National Disaster Management Programme. The DEM undertakes the preventative and mitigation measures for all possible hazards, and effective warning, response and recovery plans for all sectors.

The European Commission Humanitarian Aid and Civil Protection (ECHO) financed a project called “The Strengthening Resilience and Coping Capacities in the Caribbean through Integrated Early Warning Systems” (DEM, 2018). This project has been implemented in 7 pilot vulnerable communities within 4 countries (Dominica, Barbados, Saint Lucia, St. Vincent and the Grenadines) with the objective of enhancing community resilience. These actions aim at strengthening the national preparedness mechanisms through improved hazard monitoring and alert dissemination. One aspect of this project is to create a regional framework for facilitating multi-hazard Common Alerting Protocol Early Warning System (CAP EWS).

The Intergovernmental Oceanographic Commission (IOC) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) has supported the creation of the Caribbean Tsunami Information Centre (CTIC) in Barbados (UNDP, 2015). The CTIC is an organ of the Intergovernmental Coordinating Group for the Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG/CARIBE EWS).

Dominica

The Commonwealth of Dominica, is an island republic in the West Indies, part of the Windward Islands located near Guadeloupe to the northwest and Martinique to the south-southeast. It was discovered by Spain, and became a French colony and later a British colony, and now it is an independent country. The island has lush mountainous rainforests, and heavy rainfall. The Dominica Meteorological Service (DMS, 2018) offers weather forecasting, climatology, hydrology, agrometeorology, instrument & equipment maintenance and weather observations. It is responsible for issuing the weather warnings, and uses a four-color alert legend: Green for “No Threat”; Yellow for “Low” (Be aware); Orange for “Medium” (Be prepared) and Red for “High” (Take action)

The Disaster Vulnerability Reduction Project (DVRP) is currently under execution (207-2018) and the -objective is to improve data collection capacities, by installing a new hydro-meteorology network of 44 stations. Hazard monitoring systems will reduce vulnerability and will provide real time dissemination of information to include flash flood early warning, through a web portal that will be operated by the Dominica Meteorological Services (Dominica News Online, 2018). The funding comes from the local government, and the World Bank.

Saint Vincent and the Grenadines

St Vincent and the Grenadines is in the arc of the Lesser Antilles, where the Caribbean Sea meets the Atlantic Ocean.

6.26 Trinidad and Tobago

The Trinidad and Tobago Meteorological Service (TTMS, 2018) issues riverine flood alerts, based on current rainfall activity and forecast rainfall expected over the next 24 hours. The NMS closely monitors weather conditions also issues the bulletins with threat, watch or warning for tropical storms. The TTMs displays warnings and forecast on its web site. The Water Resources Agency (WRA) reports significantly high-water levels in major rivers and have defined threshold levels for these. WRA is appended to the Water and Sewerage Authority (WASA, 2018). WRA operates a data collection system that comprises a monitoring network of gauges which measures and reports hydrometeorological data. Data and information to the general public from mechanical and real-time automated stations. WRA, with its telemetry network, provides the TTMS and the Office of Disaster Preparedness and Management (ODPM, 2018) with early warning information on extreme events likely to impact vulnerable communities. ODPM has organized the CORE project (Communities Organized and Ready for Emergencies), and the Flood+ Smart program focusing on flooding and related hazards in preparation for the upcoming rainy and hurricane seasons. The Caroni River Basin is prone to flood events and are kept informed alert for rising river levels and possible overspill, and residents along this river must take measures to preserve life and property. The Canada Caribbean Disaster Risk Management (CCDRM) Fund has supported the Caribbean Disaster Emergency Management Agency (CDEMA, 2018) with projects in Trinidad designed to reduce disaster risk in vulnerable communities. The location of this twin-island state, also known as “the land of the humming bird”, is on guard against the risks from the “trinity of threats” of riverine, coastal and flash flooding.

6.27 Netherland Antilles

The Caribbean Netherlands or the Dutch Antilles are composed by the islands of Aruba, Bonaire, Curacao (the ABC islands) and by St Marteen and Saba and Sint Eustatius (the SSS islands). These are part of the leeward islands.

Figure 0-4: Countries of the Eastern Caribbean

Since these are former Dutch colonies and are part of the Kingdom of the Netherlands, the Royal Netherlands Meteorological Institute (KNMI) has played a key role in creating and supporting the meteorological organizations in these six countries (KMNI, 2013). The Meteorological Department of Curacao issues weather and marine forecast for Curacao and surroundings (MDC, 2018). It also issues watch and warnings for tropical cyclones, and tsunamis, and other natural hazards. The website is impressive and there is also a very good App. MDC has installed eight (8) weather stations in key sites for climate monitoring (MDC, 2016). The Departamento Meteorológico de Aruba (DMA) provides meteorological services and weather forecast for Aruba. DMA also shows on its website the 3-hour precipitation variations based on the NOAA Nam model for the Aruba region (DMA, 2018). The Meteorological Department of St Marteen provides similar monitoring and climate information services including weather bulletins advisories sand warnings for heavy rainfall and severe thunderstorms and winds (MDSM, 2018).

These islands are very small and very flat also, so flooding is mostly urban due to heavy rains and coastal due to storm surges. A strong regional forecasting and early warning system has been stablished based on satellite surveillance, weather data, aircraft reconnaissance flights, weather radar and high-speed communications. The outlook is mostly from the meteorological perspective in service to the general public and for protection purposes with particular attention to navigation given the location of the islands. For example, aeronautical or aviation sector is the major customer of MDC, representing 65% of needs, followed by public weather services with 24%, and marine services with 11% (Martis, 2012). Detection of hazards is accomplished through: land stations, weather radar, upper air stations, satellite imagery and numerical models allowing the NMS to operate an effective early warning system. Communication of hazard is very good with 100% coverage of the population and sectors though mobile telephones, TV, radio and website (Martis, 2012).