Flood Prediction using real time sensing Emergency Water Information Networks over mobile phone networks and WiFi

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Abstract

Flooding is a real problem all over the world.

This project seeks to design and implement a real time flood forecasting system using cellular phone networks. With the current and predicted impacts of climate change, flooding has become a global problem and minutes of advance warning can be critical in preserving life and allow local governments to plan growth and development. Unlike the UK that has a mature flood defence system, many developing countries struggle to deploy adequate and appropriate methods to control the devastating impact associated with floods. However, the high information and communication technology penetration in developing countries offers an avenue for environmental agencies to exploit existing cellular phone networks.

Two teams of researchers from the UK and Mexico, supported by small medium enterprises (SMEs) with expertise in water engineering and embedded electronics have come to together to investigate how real time flood forecasting can be implemented using cellular phone technology.

Combined with background research, prototyping of sensors packages and flood modelling, our teams will be conducting a series of highly targeted field trials. These will be small-scale in the UK where rivers and lakes are relatively predictable and medium-scale in Mexico where we will monitor flood events in real time.

Contents

Introduction

Flooding is a global problem and as a representative example, Mexico is currently struggling to manage flood situations which are increasing in regularity and severity. Many developing countries have substandard flood monitoring infrastructure. However, in common with the UK, they have ”state-of-the-art” cellular mobile phone systems. In this research, expertise in water engineering and radio communications from the UK and Mexico have been combined to design a cost effective flood forecasting system based on hydrology sensing and mobile networks.

Recent events such as hurricane Patricia in Mexico (October 2015) has emphasised the need for systems that can predict the dynamic behaviour of large-scale water flows. Currently, management of flood situations in many developing countries is carried out through prediction of water behaviour (Hydro Meteorological Warning System). This system is based on estimates of rainfall, runoff and water levels. In Mexico two central registers and rain measuring stations are used to gather data. The data collected is compared with pre-established risk thresholds which determine whether a warning should be issued.

In general, the rainy season in Mexico occurs during the summer and fall, starting in May and ending in October. Along the main waterways, the change in state is dynamic between dry and rainy both in terms of the water volume in the channels and the vegetation on the banks. Vegetation in Mexico is normally sparse but grows quickly and in abundance during the rainy season. During flood events, new rivers form along river beds that are normally empty. These conditions are typical of flooding in many countries.

To develop a real time flood forecasting system, several areas of research need to be investigated. These include: data sensing at the appropriate location and time, wireless transmission of flood data, sensor data fusion, model generation and prediction at the remote weather station.

Our collaborative research approach is addressing each of these areas by employing UK expertise in Water Engineering and Radio Communications to complement the research base in Mexico.

Background: Colima rivers & Topography

Colima is a small state compared to other states in Mexico. The zone where the study is being carried out is the metropolitan zone of Colima-Villa de Álvarez (Figure 1). It is located north of Colima and has an approximate population of 120,000. The urban area is crossed by several watercourses running from North to South. The most significant rivers are the Pereira brook

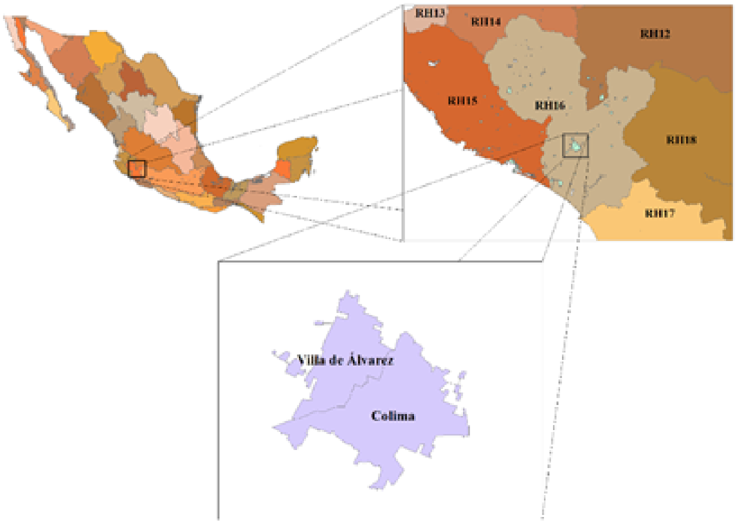

Figure 1: Metropolitan Zone Colima - Villa de Alvarez

Characteristic	Pereira Brook	Colima River	Manrique Brook
Area (km^2)	25.73	56.32	12.87
Main channel length (m)	14,830	27,701	17,776
Channel Slope (%)	2.28	3.41	2.31
Concentration time (hr)	2.27	3.15	2.24

Table 1: Main physiographic characteristics of watercourses

in Villa de Álvarez, the Colima River and the Manrique brook in Colima with only the Colima river having water flowing all year round. In Table 1, a summary of the physiographic properties of these rivers are presented. Around the catchment area, the highest precipitation is recorded between June to October, while November to May can be regarded as dry season. This trend also applies to most states in Mexico [**1**]. The average annual rainfall in the hydrological system of the Colima river ranges between 700 and 1200 mm.

The Problem with Floods

Globally, recorded data shows that between 1900 to 2010, a significant amount of the disasters recorded can be attributed to flooding (Figure 2). An important factor that perhaps has accentuated this condition is linked to the historical development of the prevailing economic system and its models of society. It is important to note that the information presented in the international disaster database ([**2**]) may be influenced by factors of uncertainty. For example, the availability of reliable data for the years prior to the establishment of the database. However, on the criteria established as a classification standard in this database, the global trend reflected in Figure 2 is a significant indicator.

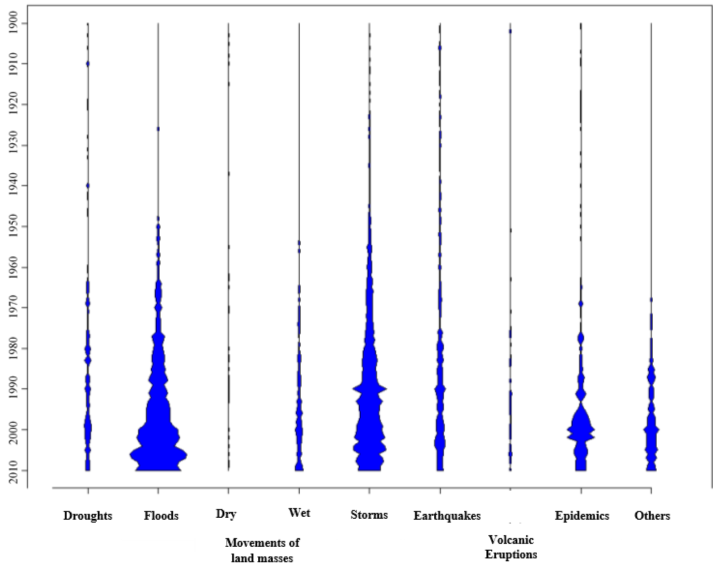

Figure 2: Number of disasters reported in the world for the period 1910 - 2010 classified by the type of phenomenon ([**2**])

Floods in Mexico

Given the Mexican terrain, geographic location and topography, it is frequently affected by cyclone-induced precipitation and tropical storms during summer and autumn as well as by cold fronts in the winter. These conditions generate large amounts of rainfall in different states, such as Chiapas, Colima, Guerrero, Michoacan, Puebla, Tabasco, Veracruz and Yucatan. As a result, most flood events in Mexico are directly attributed to the intense rainfall generated by the tropical cyclones in both the littorals and central region of the country [**3**]. Nonetheless, in highly urbanized areas, additional factors such as land use changes, the urbanization of natural floodplains and the inadequate design of hydraulic infrastructure also contributes to flooding.

While the rainy and dry season is almost the same across that states in Mexico, these periods are clearly differentiated by the Mexican territory hydrometeorological phenomena. This typically leads to anomalies in certain regions. According to these phenomena, there are *cold fronts*, which give rise to winter rains in north-western Mexico. On the other hand, in the summer months, heavy rains are associated with cyclonic action in a large part of the national territory. In addition, the orographic and convective effects which result in high intense storms of short duration also contribute to Mexican rivers having irregular hydraulic regimes. In Table 2, the flood events that have generated the greatest damage in Mexico for a 60-year period (1943 - 2004) are presented.

Year	Event	State	Deaths	Affected population
1943	Cold front	Sinaloa	27	600
1949	Cold front	Sinaloa y Sonora	10	159,000
1955	Gladys, Hilda y Gilbert Hurricanes	Veracruz, Tamaulipas, San Luis Potosí, Yucatán y Quintana Roo	110	—-
1959	Mexico Hurricane	Colima y Jalisco	1,500	1,600
1960	Cold front	Sonora, Sinaloa y Chihuahua	3	96,000
1967	Beluah Hurricane	Tamaulipas, Nuevo León, Yucatán y Quintana Roo	—-	25,000
1967	Katrina Hurricane	Guerrero, Península de Baja California, Sonora y Nayarit	15	30,000
1968	Naomi Hurricane	Colima, Sinaloa, Durango, Coahuila, Sonora y Chihuahua	10	50,000
1976	Lisa Hurricane	Baja California Sur y Sonora	600	10,000
1982	Paul Hurricane	Sinaloa	0	256,800
1985	Cold front	Nayarit	0	47,927
1988	Gilbert Hurricane	Yucatán, Quintana Roo, Campeche, Tamaulipas, Nuevo León y Coahuila	225	139,374
1990	Cold front	Baja California sur, sonora, Sinaloa y Chihuahua	—-	40,000
1990	Diana Hurricane	Veracruz e Hidalgo	139	50,000
1992	Cold front	Nayarit	64	100,000
1993	Lluvias de invierno	Baja California	33	10, 000
		Baja California Sur	3	10, 000
1993	Huracán Gert	Veracruz, Hidalgo, San Luis Potosí y Tamaulipas	40	97,943
1995	Huracán Ismae	Sonora, Sinaloa y Baja California Sur	200	24,111
1995	Huracán Opal	Veracruz, Campeche, Tabasco y Quintana Roo	23	26,874
1995	Huracán Roxanne	Veracruz, Campeche, Tabasco y Quintana Roo	—-	13,860
1997	Huracán Pauline	Guerrero y Oaxaca	228	8,500
1998	Lluvias	Chiapas	229	28,753
		Baja California	92	3,000
1999	Depresión Tropical 11	Veracruz, Puebla, Hidalgo y Tabasco	387	1,904,000
2000	Huracán Keith	Quintana Roo, Chiapas, Tamaulipas y Nuevo León	9	—-
2001	Huracán Juliette	Sonora y Baja California Sur	9	38,730
	Lluvias	Varios Estados	95	126,954
2002	Huracán Isidore	Yucatán y Campeche	4	500,000
	Huracán Kenna	Nayarit y Jalisco	2	374,500
2003	Lluvias de verano	Guanajuato, Jalisco, Michoacán, Nayarit y Zacatecas	14	256,301
2004	Frente Frío No. 49	Coahuila	38	6,692

Table 2: Flood events and associated damage in Mexico for the period (1943-1992) [**3**]

Figure 3: Damage caused to Los Maestros Avenue bridge and Dr. Leonel Ramirez general hospital during Hurricane Jova by the overflow of Colima river. (Source: El Universal newspaper, October 13, 2011

Floods in Colima

The state of Colima is usually affected by the cyclonic activity in the Pacific Ocean. Colima-Villa de Alvarez is the most urbanised area of the state and its proximity to the coastline is evidential in the several tropical cyclones that have resulted into emergency situations. The most recent tropical cyclones that have created enormous damage to infrastructure in Colima were *Jova* in 2011 and *Patricia* in 2015. Specifically, in Colima - Villa de Alvarez, the damages were associated with roads and bridges (see Figure 3 and Figure 4). In Figure 5, the critical zones in Colima-Villa de Alvarez that have experienced flooding is shown. More recently, flooding is becoming more frequent in Colima and in the context of climate change, it is envisaged that this trend will continue in the coming decades. With respect to Colima, the following factors can be linked to the current flood epidemic:

i. Land use changes in the northern zone of Colima-Villa de Álvarez. This is currently affecting the hydrological response of urban watercourses. The increase in urban sprawl is causing an increase in surface runoff, which results into flooding.

ii. Occupation of areas near the rivers. This is one of the main factors that has increased the flooding risk in recent years. This presents obstruction along the river banks which reduces hydraulic capacity.

iii. The lack of instrumentation in the hydrological system of the Colima river. This has led to a lack of knowledge of the hydrological regime. Moreover, the meteorological network in Colima is substandard. As a result, critical information about storm patterns are absent.

Figure 4: Damage caused to 20 de noviembre Avenue by the overflow of Manrique brook. (Source: El Diario de Colima newspaper, August 3, 2018

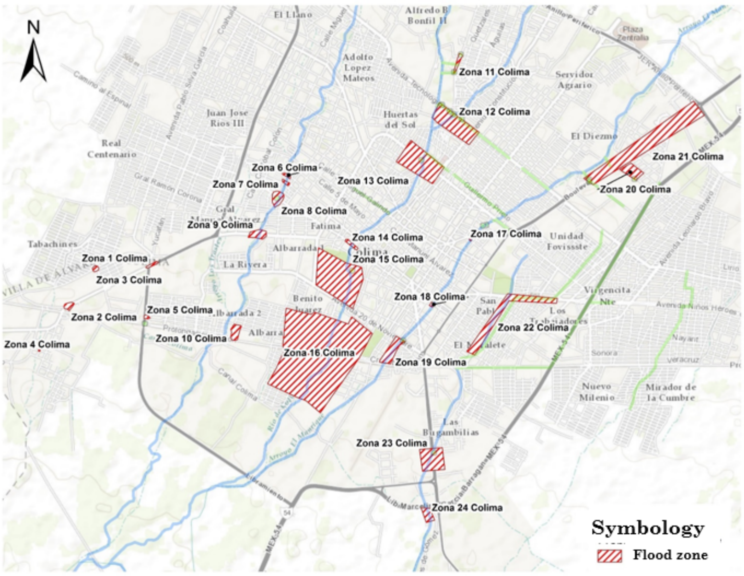

Figure 5: Flooding areas in Colima-Villa de Alvarez [1]

Flood Monitoring and Forecasting

Flood forecasting (FF) is one the main components of any flood management system. It can be defined as a process of estimating and predicting the magnitude, timing and duration of flooding based on known characteristics of a river basin, with the aim to prevent damages to human life, infrastructure, the economy and the environment [**4**]. With the development of information communication technologies, developed countries around the world have been able to develop sophisticated sensor network systems for flood monitoring and forecasting.

Flood Forecasting Components

Generally, an operational FF model can be subdivided to three main components:

1. Data collection and transmission: Data availability during the different stages of a FF design and operation is essential. These could be hydrological, meteorological or parameters characterising the hydrological catchment area.

2. Forecasting: This is the core component of any reliable FF model. It involves data analysis and model prediction.

3. Dissemination: This relates to how information from the government/environmental agencies is communicated to people inhabiting the affected areas.

Flood Forecasting Models

There are different criteria for FF model classification [**5**, **6**, **7**]. FF models can be classified by the way the catchment area processes are represented (i.e. deterministic or data-driven); or by the way the catchment is spatial discretized (i.e. lumped or distributed). Deterministic models solve a set of equations representing the different watershed processes and produces a model output for a given set of parameters. A data-driven model provides the capability to simulate the random and probabilistic nature of the inputs and responses that govern a typical river flow. While each of these models have their advantages and disadvantages, there are hybrid FF models that optimally combine the model parameters and the modelling process. Rather than providing a single deterministic forecast, an ensemble prediction system (EPS) offers an ensemble prediction of hydrological variables such as streamflow or river level. In contrast to the above classification approach, Devia *et al*. [**5**] proposed a classification strategy where FF models can be grouped as empirical, conceptual and physical as shown in Figure 6.

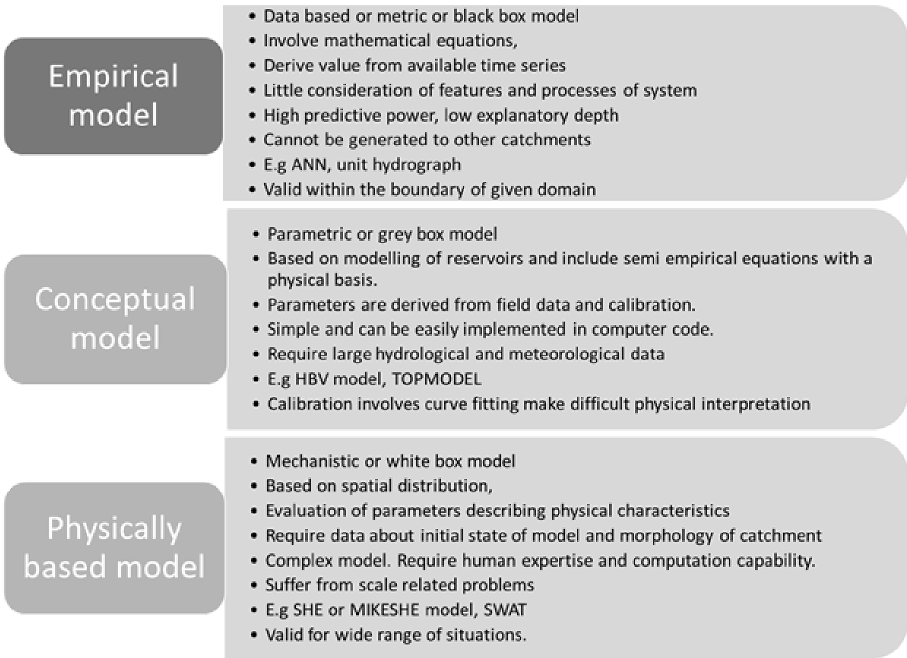

Figure 6: Flood forecasting classification

Wireless Communications for Flood Forecasting

Sensor Node Networks

The flood detection system in Colima is made up of a network of distributed sensors over a wide area. These sensors are capable of recording both climatological and ambient data such as temperature, air pressure, precipitation, water flow rates and river depth if installed close to a river. These devices can relay recorded data to another node via telemetric data exchanges or via a cellular phone connected to a mobile network. In a real life wireless communication channel, there are obstructions between the transmitting and receiving device. These obstructions could be mobile or fixed and they typically impair the performance of the wireless/radio link. Depending on the properties of the radio link, i.e. the transmission frequency, the likelihood of the message getting through from source to receiver will depend on the terrain and vegetation present between the transmitter and receiver. If for example there is a hill, clump of trees or dense forest in between, it is possible that the radio signal is blocked and not usable. In an ideal scenario, a line-of-sight (LoS) is required for radio communication between the transmitter and receiver. However, in scenarios where a LoS is not available, the signal can still arrive via a phenomenon known as *multipath propagation* (depicted in Figure 7). In a multipath propagation scenario, it is possible that the reflected signals (also referred to as echoes) arrive at slightly different times. If these echoes arrive too close together in time, it may affect the ability of the receiver to correctly decode the transmitted data. Consequently, the challenge for the radio network engineer is to assess the topography and environment in order to select the most suitable radio transmission parameters. Some of these parameters include transmit power, transmit frequency, antenna gain and receiver sensitivity.

Channel Sounding

In order for a radio engineer to evaluate the design parameters selected for transmission between two devices, channel sounding is carried out at the site. This is analogous to field trials carried out by communication service providers and mobile network operators. A typical channel sounder consists of a transmitter, transmit antenna, receiver, receive antenna, spectrum/network analyser, power meter as well as active electronics such as amplifiers in long distance scenarios. With regards to this project, the following parameters can be obtained from a measurement campaign using a channel sounder:

1. The received signal strength of the main LoS component.

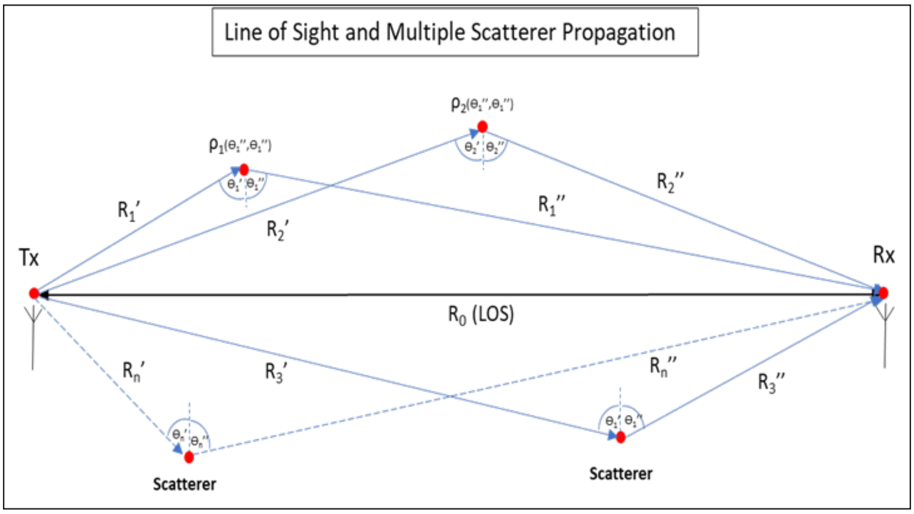

Figure 7: Schematic of typical Radio Channel showing the direct Line of Sight (LoS) and reflected propagation components.

2. The residual spread in time of the delayed multipath components (i.e. delay spread).
3. The differential attenuation applied at different frequencies (i.e. dispersion).

The aim of this measurement in this project is to determine power decay with distance as well as the time spread introduced by multipath propagation.

EWIN Solution

This section outlines the approach taken within this project. A novel approach has been adopted in addressing flood prediction and forecasting for developing countries like Mexico. The flood prediction system in this project consists of four building blocks:

1. Sensors nodes: Non-contact ultrasonic sensor are adopted for measuring water level in this project. These sensors are attached to the underside of bridges to measure distance to the water surface. If the cross section, channel depth and height of the bridge are known, then the water depth can be calculated.

2. Data capture and storage: This project will be utilising a bespoke system called RiverCore. This system offers more flexibility than off-the-shelf logging systems. It can collect and store data from each of the different hydrological sensors in one unit and can connect to the forecasting server to adapt the data collection rate.

3. Wireless data transfer: The position of the gauging sites was determined by the presence of wireless communication signals. Data was collected at all the specified sites and used to optimise the radio network. Consequently, gauges could not be positioned further upstream.

4. Machine learning (ML) for flood forecasting: With ML, data from the distrusted sensor network can be analysed and used to forecast downstream water levels in a short period of time. In this project, statistical and physically-based models will be adopted within the machine learning framework.

EWIN Wireless Sensor Network

In this project, a modular approach has been adopted for the sensor nodes. With this approach, the design can be modified to include more sensors as the need arises. Two types of sensor nodes are used in this project, they are fixed nodes and drifters.

1. Fixed nodes: The fixed node is referred to as RiverCore. The RiverCore node uses a MaxBotix MB7066 ultrasonic sensor to sense parameters such as river width, flow speed and water height. In Figure 8, the schematic of the RiverCore is presented. The RiverCore is made up of four blocks, these are: microcontroller-based processing unit, communications unit, sensors and a power supply unit. The RiverCore is powered by a regulated power supply and a solar charge controller. With a 12 V 80 Ah backup battery and a 75 W polycrystalline 12 V solar panel, constant power is available to the fixed node. The communications unit has a

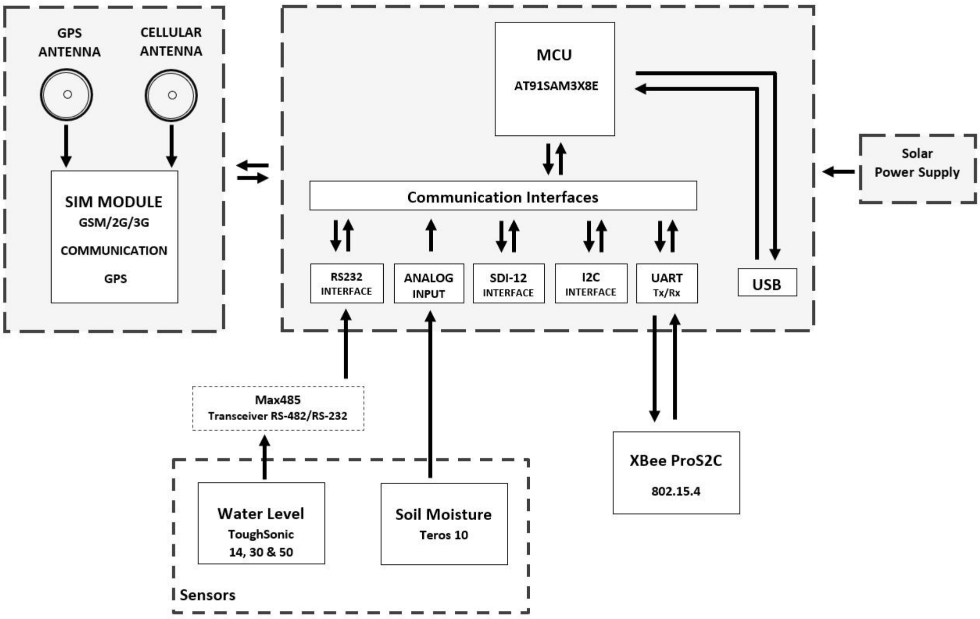

Figure 8: Schematic of RiverCore Node.

GPS module for obtaining location and timing information as well as a cellular module for radio communication. In order to ensure the design is suitable for harsh outdoor conditions, the RiverCore is enclosed in an IP65 enclosure.

2. Drifters: These mobile nodes are used in this project to characterise the dynamic behaviour of a river as the water flows downstream. These nodes provide information relating to surface speed, turbulence and temperature. The drifters used in this project are made up of the following interchangeable component blocks. These are: sensor module, GPS module, processing unit, inertial measurement unit (IMU), data logger and a power supply. The IMU allows the drifters to acquire distance and time information, which can be used to model the river flow rate. In order to ensure that the drifters are in constant operation, a similar rechargeable power supply unit as described in the RiverCore is used. Also, in a similar way to the fixed nodes, the drifters are enclosed in IP65 enclosures.

Radio Communication for EWIN Drifters

In order to provide real time information to a flood forecasting system, the drifters need to be able to reliably transfer water data to a remote server. In order to achieve this, the drifters will be primarily operating on available 3G/4G long term evolution (LTE) networks. As an alternatives, drifters can also use internet of things (IoT) over LTE. This is commercially available as enhanced Machine-Type Communication (eMTC), Narrowband IoT (NB-IoT) or extended coverage Global

System for Mobile Communications (GSM) IoT (EC-GSM-IoT). Unlike the standard GSM and 3G/4G LTE networks, these IoT wireless technologies are optimized for low power consumption and wide coverage. eMTC uses a 1.4 MHz channel bandwidth while NB-IoT provides a 200 kHz channel bandwidth. In México, the major cellular operators (TELCEL and AT&T) now provide eMTC services in some areas. It is anticipated that NB-IoT services will be available mid 2020. Contrary to the LTE variants for IoT networks, a long range (LoRa) technology developed by Semtech can also be adopted for drifter networking. This proprietary protocol can be used for drifter-drifter or drifter to RiverCore communication.

In scenarios where 3G/4G/LTE-IoT signals are not available or weak, the drifters will attempt to offload water data to a RiverCore when within the coverage area of a RiverCore. A WiFi modem has been included in the current drifter design to provide an infrastructure for ad-hoc networking. This can also be used to relay water data within a network of drifters to a fixed node or to a node with usable 3G/4G signal.

EWIN Project Benefits

This project has been able to generate benefits to partners as well as municipal regions in Mexico. These are but not limited to:

1. Economic benefits: The project has provided economic benefits to both Mexico and the UK. The industrial partners: Siteldi (a Colima based SME) and Dynamic Flow Technologies Limited (a UK based SME) will retain intellectual property resulting from this research. It is envisaged that a novel integrated flood forecasting sensor network will be developed from this project. This flood forecasting system would offer developing countries an opportunity to exploit information communication technology for managing the devastating effects of flooding. In addition, this project has provided research funds for four academics based in Mexico city and Colima. Furthermore, this project has provided financial resources through workshops and equipment purchase for the purpose of fostering research collaboration in a official development assistance (ODA) country. Within the UK group, three researchers have been fully funded through paid work and three academics have also been partially funded. As a result of this collaborative research, a new radio propagation research team has been created at the National Autonomous University of Mexico. This research team has benefited from the radio frequency measurement equipment purchased during this project.

2. Collaborative benefits: This project has fostered collaborative research between the UK and Mexico. Researchers and engineers from both countries have come together to study flooding and how information communication technology can be used to develop a flood forecasting system. As a result, the international reputation of the universities involved has improved and intellectual property rights resulting from this project will be beneficial to the industrial partners.

3. Municipal benefits: Given that flooding usually results into devastating impacts to agriculture, the research work carried out in this project will offer an avenue for environmental agencies in Colima to understand patterns in flooding events. While the system developed from this project has been evaluated in Mexico, the infrastructure can be reused in any developing country with similar information communication technology infrastructure.

Working with Stakeholders

During the course of this project, the research team in Mexico has liaised with different organisations and agencies. These include:

1. National Water Commission (Conagua) → Federal Authority
2. Water Commission → State Authority
3. Institute of the State Environment (Imades) → State Authority
4. State Agency for Civil Protection → State Authority
5. Municipality of Colima → Municipal Authority
6. Resilience Office of the Municipality of Colima → Municipal Authority
7. Institute of Planning of the City Hall of Colima → Municipal Authority
8. Municipal Civil Protection Directorate → Municipal Authority
9. General Directorate of Urban Development → Municipal Authority
10. H. Municipality of Villa de Álvarez → Municipal Authority
11. Municipal Civil Protection Directorate of Villa de Álvarez → Municipal Authority
12. General Directorate of Urban Development of Villa de Álvarez → Municipal Authority
13. American Tower Communication (ATC) → Mobile telecommunications infrastructure provider.

ATC has contributed to the EWIN project by providing location information and access to cellular towers close to river banks. This offers additional flexibility to the positioning of fixed nodes within the sensor network. It also provides an alternative for temporal installation of wireless transceivers for drifter connectivity. In addition, the municipal authority in Colima has also integrated this project into its multidisciplinary strategy for flood mitigation and control in the region.

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