Environmental monitoring is the most popular application of wireless sensor networks (WSNs). At present, WSNs have been used for a number of applications such as soil moisture monitoring, solar radiation mapping, aquatic monitoring, glacial control and climate change, and forest fire alarm. The ability to place autonomous and low cost nodes in large harsh environments without communication infrastructure enables accurate data collection directly observed from interested areas. In this paper, the use of WSNs for real-time monitoring of the hydrological conditions of rivers for flood forecasting and prompt warnings is investigated. This paper describes the design and deployment of a real-time flood monitoring system (RTFMS). The system performs flood forecasting based on readily available data to provide an indication of likely flood behaviour. RTFMS intends to predict flood in rivers using simple and fast calculations, to provide real-time results and save the lives of people who may be affected by the flood.

1. Introduction
Flooding is one of the major disasters occurring in various parts of the world. Although, we are able to forecast rainfall or to track cyclone path very precisely from the satellite images, the need to have real-time monitored data such as flow, precipitation level, or water level is essential in order to make a reasonable decision on the actions necessary to be performed to prevent flooding. The cost of damage caused by flooding correlates closely with the warning time given before a flood event, making flood monitoring and prediction critical to minimizing the cost of flood damage.

Although Mauritius has a surface area of only 1865 km², there is a high variation in rainfall over very short distances throughout the island owing to its topography. Annual mean rainfall varies from 1400 mm on the eastern coast to 4000 mm on the Central Plateau and 600 mm on the western coast (Mauritius Meteorological Services, 2013; Ministry of Energy and Public Utilities, 2011). While the number of rainy days has decreased, the frequency of heavy rainfall events accompanied by flash floods has increased in Mauritius (Ministry of Environment and Sustainable Development, 2011).

Wireless sensor networks (WSNs) is an emergent class of extremely dynamic environment on top of which a wide spectrum of applications, such as military systems, habitat monitoring, precision agriculture and building monitoring are built. A Wireless Sensor Network (WSN) consists of a potentially very large set of individual sensor nodes. Each of these nodes has very limited resources, both in terms of processing speed and memory. With the advent of small, battery-powered, wireless computing and sensing technology, it is now possible to monitor and observe the world at unprecedented levels of granularity. Networks of such devices typically consist of tens or hundreds of small, power constrained nodes deployed in remote locations which they are expected to monitor for months or years at a time. The miniaturization and the availability of numerous types of sensor nodes have allowed new deployments for increasingly complex applications. Recently, there has been
growing interest for using WSNs to perform real-time flood prediction and monitoring (Seal et al. 2012; Sunkpho and Ootamakorn 2011)

In this paper, the problem of floods in Mauritius is described and the related works on existing flood monitoring systems are discussed. Then the requirements for a real-time flood monitoring system that can realistically be used to monitoring flooding situations in Mauritius are derived and specified. Finally, the design of a Real-Time Flood Monitoring System (RTFMS) to monitor flood across a river is described and evaluated.

2. Flood monitoring and warning: The Mauritian Case Study

Flooding is a growing problem in Mauritius and affects a large number of people physically and economically. The problem was dramatically highlighted by the widespread floods of 26th March 2008, resulting in the death of four persons. After a severe drought during the period 2007-2008, the island had encountered an unprecedented downpour rain resulting in severe flood within hours on 26 March 2008. The weather bulletin issued by the Meteorological Services on Wednesday 26 March 2008 failed to issue a torrential rain and flood warning. The torrential rainfall resulted in flash floods in the northern and eastern part of Mauritius. Four persons died during this event, 22 vehicles were recovered from floods, while the Fire Services recorded more than 2,000 requests for assistance and intervention in about 50 areas (Cabinet Decisions, 2008; PNQ, 2008). The north of the island near La Nicolière reservoir and Mont Goût region were the most affected areas as shown in figure 1. These areas are still prone to floods during heavy rains and cyclones.

The flooding problem in Mauritius was also highlighted by the severe flash flood on March 30 2013 in which 11 persons died. Sudden torrential downpours caused flooding in Port Louis. According to local meteorologists, a total of 152 millimeters of rain fell in less than an hour, disrupting traffic and causing chaos in the city. Most victims drowned in rivers of water that rose swiftly in the pedestrian underpass leading to the waterfront and an underground car park. Major roads were blocked as surging floodwaters dragged away cars, forcing motorists to abandon them as shown in figure 2. Moreover, Rivers of mud and debris covered the Canal Dayot suburb, where hundreds of families have been left homeless.

Currently there is no automated system for monitoring of floods in Mauritius. The Cyclone and Other Natural Disasters Committee use the simple 100 mm rainfall in the last 12 hours criterion for issue of torrential rains warning and flood warnings are subject to a number of general parameter such as (Cabinet Decisions, 2009):

a. the nature of the preceding rainfall
b. the state of the rivers
c. the underground water level
d. the permeability of the soil
e. the evacuation rate of accumulating water
f. the prevailing weather conditions in the vicinity of Mauritius
The Cyclone and Other Natural Disasters Committee normally has to take stock of the above parameters before deciding on a flood warning. Clearly, the current flood warning system is very ineffective as timely and accurate decision are not being taken due to the absence of real-time data of the different established parameters. The current system has a primitive technique of flood detection requiring trained personnel. It involves mostly manual procedures and hence is expensive. Here, the reliability of the entire mechanism depends upon the skill and experience of the personnel employed and is subsequently limited by their speed and agility.

The Cyclone and Other Natural Disasters Committee needs access to a vital infrastructure system that is able to provide accurate, reliable, timely flood-related information and timely warnings to assist them respond to flood events. Flood monitoring using real-time sensors is one of the flood control measures. Losses due to flooding can be reduced by means of measures such as monitoring, forecasting, and evaluation. One nonstructural measure, the integrated use of wireless sensors and web-based decision support systems has been playing a very important role in monitoring, controlling, relieving, and assessing natural disasters, especially flood disaster (Zhang et al., 2002; Saphaisal, 2007).

3. Related Works

A warmer climate, with its increased climate variability, will increase the risk of both floods and droughts, whose management and mitigation are important to protect property, life, and natural environment. Real-time accurate monitoring of hydrologic variables is key for flood forecasting, as well as for optimizing related warning systems for damage mitigation.

Conventionally, researchers have directly collected hydrological data at the places of interest. This has now been commonly substituted by automatic sensor and datalogger systems, which provide high temporal data resolution, while reducing operational human resource requirements. Dataloggers permit local automatic and unattended data gathering, and reduce environmental perturbation. However, data retrieval from standard dataloggers and storage in processing and control/warning centers still has to be done either manually, which prevents its applicability in flood warning systems, or through wired connections, which leads to substantial investments and operational costs. To confront these problems, sensor network technology has been proposed in many monitoring applications (Ruiz-Garcia et al. 2009).

Castillo-Effer (Castillo-Effer et al. 2004) suggests an architecture for a flash-flood alert system. The primary purpose of the system was to aid the population of the Andean region of Venezuela, where large amounts of property damage and resident casualties caused by flash-floods were reported over the years. The system consists of a WSN for collecting information in the places where variables...
need to be measured such soil humidity, rainfall, and other meteorological sensors, such as wind speed, temperature, sun radiation and barometric pressure. A sink node, located close to the sensor network whose function is collecting data from the wireless sensor nodes. Periodically, or in case of abnormal conditions, the sink sends information via cellular network to a command center. At the command center, emergency preparedness authorities make decisions with the help of a computer system. The computer system collects data and augments a Geographical Information System, (GIS), with a layer of live data incoming from the distant WSN.

Ueyama et al. (2010) describe the implementation of a river monitoring system based on an event-based component model for wireless sensor networks called LooCI (Loosely-coupled Component Infrastructure. The system has been for river monitoring in creeks that flow through São Carlos (São Paulo). The sensor network application monitors flood, pollution and human tampering and warns potential stakeholders whenever they are at risk (e.g. of floods). The pollution monitoring system is used to inspect rivers and issues a warning whenever the condition of water reaches an unacceptable level. In addition, depth sensor monitors rivers and is used to predict potential flooding. Finally, three dimensional accelerometers detect any improper vibration caused by tampering with the deployed node.

Sunkpho and Ootamakorn (2011) present a real-time flood monitoring and warning system for a selected area of the southern part of Thailand. The two main objectives of the developed system is to serve 1) as information channel for flooding between the involved authorities and experts to enhance their responsibilities and collaboration and 2) as a web based information source for the public, responding to their need for information on water condition and flooding. The developed system is composed of three major components: sensor network, processing/transmission unit, and database/application server. The real-time data of water condition can be monitored remotely by utilizing wireless sensors network that utilizes the mobile General Packet Radio Service (GPRS) communication in order to transmit measured data to the application server. The application server is a web-based system that allows users to view real-time water condition as well as the forecasting of the water condition directly from the web via web browser or via WAP. The application server is also able to send warnings to the responsible authorities in case of emergency.

Seal et al. (2012) present a forecasting model designed using WSNs to predict flood in rivers using multiple variable robust linear regression technique. The proposed system architecture for flood forecasting consists of sensors which sense and collect the data relevant for calculations, some nodes referred to as computational nodes that have large processing powers and implement the proposed distributed prediction algorithm and a manned monitoring office which verifies the results with the available online information, implements a centralized version of the prediction algorithm as a redundancy mechanism, issues alerts and initiates evacuation procedures. The forecasting model demonstrates very precise results in forecasting critical parameters for flood when the data collected are accurate. The three components of the system are shown in figure 3 below.

4. Requirements for a Flood Monitoring System

Predictive environmental sensor networks require addressing several complicated design requirements. The network must cope with element exposure, node failures, limited power, and prolonged use. When the event damages the environment, such as the case with floods or cyclones, this further complicates the requirements. The system must withstand the event, which usually poses a hazard to network survival especially those nodes directly measuring the event. Additionally, the system must operate throughout long disaster-free periods, measure a variety of variables contributing to the disaster, thereby requiring heterogeneous sensor support, and communicate over the large geographical regions in which these events occur.

The Real-Time Flood Monitoring System (RTFMS)
is expected to be deployed it in a real-world environment. The planned deployment site is at the Rivière du Rempart river, which is located in the district of Pamplemousses. This site is prone to flooding for much of the year and thus offers good potential for evaluating the system under real-world conditions. Flooding at the site affects the nearby villages of Ville Bague, Petite Julie and Grande Rosalie, which thus additionally presents us with a motivation for evaluating warning systems for local stakeholders. The following main requirements are identified for the Real-Time Flood Monitoring System (RTFMS).

4.1 Collection of hydrological data
A flood monitoring system requires the collection of data a number of hydrological parameters. Collecting and analysing the set of data on a regular and real-time basis is tedious, time-consuming and would require lot of man-labour if these are done manually using traditional methods. RTFMS should collect the data through the use of appropriate sensors (depth sensors, rainfall sensors, flow sensors). Full coverage of hydrological parameters allows for the viewing of patterns of small-scale spatial variability. Seasonal patterns and regimes in hydrological parameters, as well as the transitions between these patterns can be viewed due to the high spatial and temporal resolution. Therefore, the system should collect data at the necessary resolution to allow this type of analysis to be undertaken. Three important hydrological data that should be considered in RTFMS are actual water level, rainfall, and speed of flow of water bodies in different regions. The system should allow for the sensor measurements to be taken on an event-driven or time-driven basis, i.e., they can be programmed to take measurements on a specific, pre-programmed schedule, when a specific environmental event occurs (e.g., rainfall), or at the remote request of a user. Collected data should be transmitted to the base station for processing.

4.2 Flood Prediction
RTFMS should be an early warning system and needs to predict the event, not simply detect the event since that would not provide enough time to evacuate. In the case of river flooding, water can travel down a large river like Grand River North West in only an hour, providing only enough time to alert the authorities, much less evacuate the community, so the system must predict the flood couple of hours in advance. Prediction entails a model of the physical system (although it could be a statistical model), an understanding of the relevant variables this model requires as input and the predicted output of the model. The grid-to-grid model (Bell et al. 2007; Moore et al., 2006) is a distributed rainfall-runoff model. The main input is precipitation and the main model output is basin flow. At a particular area in the catchment, the runoff production is determined
by the ability of the soil to absorb water. Surface runoff is the water flow that occurs when the soil is infiltrated to full capacity and excess water from rain. The RTFMS flood prediction model should take the appropriate hydrological parameters such as rainfall, water level and wave speed readings as input and should produce a forecast (e.g. 1 hr, 2 hr and 3 hr) for river and basin water level.

4.3 Remote Monitoring and Flood Warning

A monitoring software should be developed that will allow the Cyclone and Other Natural Disasters Committee staff to monitor the situation of the area of interest, for example to view readings of a particular node i.e. rainfall, water level or wave speed readings and corresponding flow discharge at that particular location. RTFMS should have an interface to remotely maintain the sensor network, providing data and predictions regarding the event of interest along with detailed information to monitor the system and display those nodes no longer functioning. A prediction alone of the likelihood of the event or key variable defining the event is not enough. To warn people, the system must transform the prediction of the event into an understanding of the effect of the event, a timeline of the progression of the event, and an understanding of the uncertainties involved. To quantify this in the case of flooding, knowing the river level does not help, but knowing which regions will flood due to that river level, how long those areas have before flooding, and how likely the flood will occur at that stage provides the information that can then enable a warning. RTFMS should also allow timely flood warnings to be distributed to local stakeholders. These flood warnings are based on the results of point prediction models executed by the base station and which may be disseminated to local stakeholders in a range of formats including on-site audio/visual warnings, a public Web site and SMS alerts.

5. Design of the Real-Time Flood Monitoring System (RTFMS)

In order to support the functionalities of the real-time flood monitoring system, RTFMS should implement the following three components:

a. Hardware platform: The hardware platform may consist of two kinds of motes namely MicaZ (Crossbow, 2011) and SunSPOT (SunSPOT, 2011). The motes should be equipped with a depth, flow and rainfall sensors.

b. Gateway: The gateway node would act as a bridge between the sensor network and the access network. It allows exchange of data between the motes and the applications implemented on the access network.

c. Central Monitoring Office: The central monitoring office hosts the application server and database which should be implemented as web-based applications to allow users to view real-time water-related data as well as historical data.

5.1 RTFMS Deployment Area

The Real-Time Flood Monitoring System (RTFMS) is a river flooding monitoring system with the main deployment target being the Rivière du Rempart. This region was the most affected during the major flood of March 2008. The Rivière du Rempart is a river in northeast Mauritius. It is the outflow of La Nicolière, a lake in the central north of Mauritius, and flows northeast to reach the sea north of Poste de Flacq. Figure 4 shows the catchment area of La Nicolière Reservoir.

Figure 4: Catchment Area of La Nicolière Reservoir

5.2 Hardware Components

Twomototechnologiesarechosenforimplementation in the RTFMS. First, the MicaZ mote (Crossbow, 2013) running the TinyOS platform and second, Sun Microsystems’s SunSPOT mote (SunSPOT, 2013) implemented on Java programming language and operates on top of Squawk Virtual Machine. Each of these motes needs to be integrated with a depth, flow and rainfall sensors. Moreover, the motes need to be customized to make them sufficiently robust for outdoor monitoring. Description of each mote technology to be used in RTFMS is given below.

![Figure 5: The MicaZ 2.4Ghz Mote](image5)

![Figure 6: SunSPOT Java Development Kit](image6)

![Figure 7: RTFMS deployment site](image7)
5.2.1 MicaZ 2.4Ghz Mote
The MicaZ 2.4Ghz mote from Crossbow Technology Inc. (Crossbow, 2013) shown in figure 5 has 128 KB of flash memory, IEEE 802.15.4/ZigBee compliant RF wireless radio transceiver (250 kbps transfer rate, 100 meters maximum range), and is powered by two AA batteries. Pluggable sensor boards with temperature, light, magnetic and other sensors are available. Crossbow offers a variety of sensor and data acquisition boards for the MICAz Mote. All of these boards connect to the MICAz via the standard 51-pin expansion connector. The MDA300 data acquisition board is used in RTFMS. The 51-pin expansion connector supports Analog Inputs, Digital I/O, I2C, SPI and UART interfaces. These interfaces make it easy to connect to a wide variety of external peripherals. The MICAz IEEE 802.15.4 radio offers both high speed (250 kbps) and hardware security (AES-128). The MicaZ motes run the TinyOS operating system, an open source, event driven and modular OS designed to be used with networked sensors. TinyOS handles task scheduling, radio communication with error detection, clocks and timers, ADC, I/O and EEPROM abstractions, and power management. Application developers can select a subset of the modules implementing these functionalities, extend or override them if necessary, and statically compile them into the final executable.

5.2.2 SunSPOT Sensor Technology
SunSPOTs (SunSPOT, 2013) are embedded hardware modules that are equipped with a 180 Mhz CPU, 512 KB RAM, 4MB flash memory, three on-board sensors (temperature, light and three-axis accelerometer), hardware interfaces for the integration of arbitrary external sensors, and the IEEE 802.15.4 wireless transmission technology, which is enabled for mesh networking. SunSPOT devices run a Java Micro Edition Virtual Machine directly on the processor without an operating system. SunSPOTs are entirely programmable in the Java programming language and thus help to abstract from the underlying hardware. No direct interaction by machine code with the hardware is necessary, which significantly eases the development of sensor-based applications. Figure 6 shows the SunSPOT Java Development Kit. Six analog-to-digital converter inputs and five general purpose I/O pins can be used to add custom sensors and devices. The internal battery is a 3.7V 720maH rechargeable lithium-ion prismatic cell. The battery has internal protection circuit to guard against over discharge, under voltage and overcharge conditions.

After integrating the MicaZ and SunSPOT motes with batteries and the appropriate sensors, the entire package should be mounted in a weather-proof case and deployed at specific locations of the Rivière du Rempart region.

5.2.3 Sensors
The specific sensors necessary for the system of river flooding monitoring is now considered: depth, rainfall, and flow sensors. Other measurements could aid the prediction of river flooding; however, only these three sensor types are chosen because of the ease of finding them, connecting to them, and installing them. Additionally, these sensors tend to be inexpensive.

Water depth is monitored using a hydrostatic level sensor. A hydrostatic level sensor will be used to measure the pressure created by a liquid. Using this sensor, software components provide warnings when the water level approaches that of the river-bank. The rainfall sensor in RTFMS will perform measurement using reed magnetic switches, which cause an interrupt after every 1 mm of rainfall. A submersible area velocity sensor will be used to measure average velocity directly, without the need for time-consuming and costly flow profiling. The sensor will need to be sealed to withstand submergence and prolonged surcharge conditions.

5.3 RTFMS System Deployment
Fourteen MicaZ and eight SunSPOT nodes will be deployed to perform flood monitoring on 2 km stretch of the Rivière du Rempart. All of these nodes will be equipped with pressure-based depth sensors and a subset equipped with flow and rainfall...
sensors. The deployment site is shown in figure 7. The SunSPOTs nodes were used to monitor the reservoir, while the MicaZ nodes were used for the river. The 2 km stretch of the river will be covered by the twenty-two motes forming three clusters as shown in figure 7.

The gateway node receives all the data from the deployed sensors, and acts as a data-logger and transmits sensor readings back to the Central Monitoring Office (CMO). Each mote sensor transmits data to the gateway in a multi-hop fashion at an interval of fifteen minutes, which is the maximum sampling frequency.

5.4 Flood Prediction Model

RTFMS uses the Grid-to-Grid model (Bell et al. 2007; Moore et al., 2006) to determine the rainfall-runoff flow and predict flood. The main input is precipitation and the main model output is basin flow. Flow routing along land and river flow paths is used to propagate grid-square estimates of runoff laterally to estimate flow at points along the river.

5.5 Application Server and Database

The application server and database will be hosted at the Central Monitoring Office (CMO). The 22 motes of the sensor network, each recording data every 15 minutes, will communicate to the gateway node. This will allow for data to be transmitted from all clusters to the gateway node at the catchment area. Data will then be communicated to the CMO through wireless GPRS tunnels. Indeed, the network may utilize the long-range mobile GSM communication to provide data communication continuity.

The database and application server will be implemented as a web-based application to allow users to view real-time water-related data as well as historical data. The application server will also be able to send warnings to the responsible authorities in case of emergency. To store all received information, the monitoring system will use an object-relational database management system (ORDBMS), for example PostgreSQL. PostgreSQL is a free solution that supports almost all SQL constructs, transactions, and user-defined types.

The application server will host the real-time monitoring/reporting software and the flood prediction algorithm. The monitoring software will consist of four modules: real-time data reporting module, prediction module, statistical and historical information module, and warning module. The application server will analyse and process the water level, rainfall and flow which serve to directly detect flood situations through the flood prediction algorithm. Based on the results of the prediction model the warning module will disseminate flood warnings to local stakeholders in a range of formats including a public Web site and SMS alerts. The communications between the RTFMS system components are illustrated in figure 8.

The monitoring system will allow remote administration of the sensor networks by the web interface. The objective goes toward zero human presence for maintenance and administration during the monitoring period. For this reason, the application server will provide a web interface that enables the access to the sensor network directly.
from the Internet using a standard web browser. Using the web interface, end-users will be able to perform administration tasks, such as configuration changes, software updates, and health-status control. For example the frequency for sensor readings and transmissions may be set remotely (e.g. recording and transmission of data every 5 minutes).

5.6 Operation modes of RTFMS

Different operation modes are defined for the RTFMS. The system will allow for the sensor measurements to be taken on an event-driven or time-driven basis, i.e., they can be programmed to take measurements on a specific, pre-programmed schedule, when a specific environmental event occurs, or at the remote request of a user.

The RTFMS flood monitoring system can be configured to work in the following operation modes:

(a) periodic monitoring – where readings from sensors are sent to the central monitoring office at a specified time interval (e.g. every 15 minutes). The time interval may be remotely set from central monitoring office.

(b) query-based – where end-users at the central monitoring office may request readings from a particular region (cluster) of the monitoring area. Each cluster region is identified by a cluster ID.

(c) event-based – where the end-users may register interest on the occurrence of a particular event (e.g. water level greater than a threshold or rainfall greater than a threshold) through a subscription message.

6. Conclusion and future works

Floods are responsible for the loss of precious lives and destruction of large amounts of property. Mauritius has experience severe flood situations recently. A lot of effort is required to be put in developing systems which help to minimize the damage through early disaster predictions.

A complete real-time flood monitoring system called RTFMS has been proposed in this paper. RTFMS uses wireless sensor network to monitor water conditions: water level, flow; and rainfall, in the region of the Rivière du Rempart which is prone to flood. The proposed monitoring system presents useful characteristics as large network capacity, sensor hardware compatibility, long-range communication, and minor impact on the natural environment.

Future work involves real hardware implementation of the RTFMS system and performing field tests to observe the communication process between the nodes and the real-time implementation of the distributed prediction algorithm in situ. Moreover, the prediction algorithm should be improved further, we can also improve upon accurate time prediction by manipulating the prediction algorithm to suit specific rivers.

References


