PL-UDMS: A Wireless Sensor Network System for Monitoring of Urban Drainage in Mauritius

Bujun Heerish[1,*], Khedo Kavi[1], Proag Virendra[2]

[1]Computer Science & Engineering, University of Mauritius, Reduit, Mauritius
[2]Civil Engineering, University of Mauritius, Reduit, Mauritius

Abstract   Mauritius has recently been experiencing drastic climatic changes. During high rainfall, the drainage system in the urban regions is not able to evacuate the incoming water. Wireless sensor network comprising of numerous interconnected wireless sensor nodes captures real-time data from the environment and transmit these data to a base station for analysis and actions. Using wireless sensor nodes, the level of water in the drains and difference in water-flow between two points in the drainage system can be captured and monitored. Events of urban drainage overflow and drainage obstruction can thus be predicted. In this paper a cluster-based wireless sensor network system for monitoring urban drainage is proposed. Real-time data collected from wireless sensor network are used by a prediction model to detect overflow and give alarms before occurrence of chaotic situations. The system also consists of a monitoring application allowing the visualization of the conditions of the drainage system. Results for three rainfall episodes are provided and discussed in this paper.

Keywords   Wireless sensor network, Cluster based, Real-time data, Water level monitoring, Obstruction detection

1. Introduction

Wireless sensors have the capacity to measure, compute and communicate environmental data to other systems where they can be interpreted into meaningful information [1]. Wireless sensor network consists of a series of sensor nodes. They collect data and send the latter to a base station where the gathered data are analysed, processed and stored. Nowadays, wireless sensors have on board sensing, processing, communication and storage capabilities which help them to collect, analyse, correlate and fuse their own gathered data [2]. Figure 1 illustrates how wireless sensor nodes are connected to base stations and how data are transmitted over the internet.

Urban drainage systems have been helping mankind to construct highly modern cities since past 150 years. There have been a lot of progresses in terms of determining the location and forecasting the amount of precipitation in the different regions in Mauritius. But along with our highly advanced methods of forecasting, the climate has constantly been changing. Inaccurate forecasting of precipitation has led to inefficient urban drainage constructions and ineffective urban drainage systems [3]. Drainage designed in past years in Mauritius no more serves the purpose of

evacuating all the precipitation water in urban regions. Drains usually get clogged due to waste obstructions and results in blockage of the water channel [4]. Hence, drainage system needs to be constantly monitored and maintained to avoid overflow.
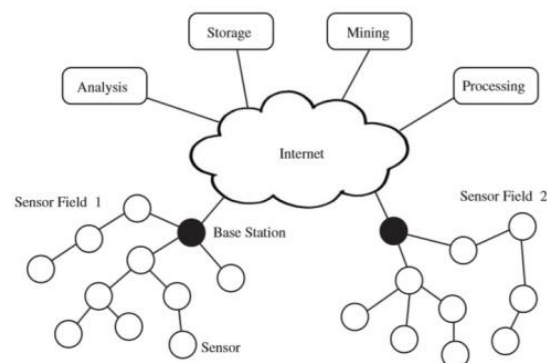

Figure 1.   Wireless Sensor Networks architecture

The purpose of this paper is to present the research challenges and implementation of a wireless sensor network for the monitoring of urban drainage system in Port-Louis, the capital city of Mauritius. Section 1 (Introduction) gives an overview of wireless sensor network and drainage systems in urban regions. Section 2 (literature review) highlights the advancement in wireless sensors and application of wireless sensor network in existing systems such as drains and rivers. The drainage problems faced in urban regions in Mauritius are discussed in section 3

* Corresponding author:
heerish@hotmail.com (Bujun Heerish)

(problem analysis). Section 4 (design of WSN for urban drainage) focuses on the design of a wireless sensor network for monitoring of urban drainages for the city of Port-Louis. It also underlines the components interaction and information flow in the system. Results and discussions, (section 5), critically analyses the implementation of such a system in Mauritius, along with its drawbacks, benefits and challenges. Results obtained from the wireless sensor network for monitoring of urban drainage are presented in this section. Finally section 6 concludes the overall analysis of the system together with future works that can be carried out.

2. Literature Review

Wireless sensor networks are widely used to capture data from our external environments. These data help to monitor and predict environmental changes and take precautionary measure in case of forthcoming disasters like floods, tsunamis and earthquakes. The miniature size of wireless sensors enables to observe variations in pressure, light, vibration, inclination and sound at practically inaccessible places.

With the advancement in microchips and battery storage capacities, wireless sensor nodes have the capability to communicate, process, and store a relatively large amount of information. Data gathered by nearby sensors within a cluster are sent to a cluster-head for aggregation. This activity decreases high volume of transmission over the network and also decreases the energy consumption of the sensor nodes. Wireless sensor nodes can communicate via local area networks or even through the internet. Several systems use the same technique for data monitoring of the physical environment. In this section, a literature of drainage water flow models and existing wireless sensor networks for drainage and flood monitoring is carried out.

2.1. Drainage Waterflow Models

There are numerous waterflow models that are used for calculating the peak discharge. By determining the peak water discharge in a region, the drainage size and design will be made to match the need. The section below mainly discusses about the Rational Method and the Saint-Venant method, two popular waterflow models that are used in Mauritius.

2.1.1. The Rational Method

The Rational method is used to calculate the total flow of water that can be collected in a catchment. The calculation for the average rainfall intensity, used in the Rational method, is determined based on historical data analysis of the rainfall intensity during the past years. The formula of the Rational method, for calculating the peak discharge is as follows:

$$Q = 0.278ciA$$

Figure 2.   Formula for calculating the peak discharge [5]

Where:

- Q = Peak discharge into drainage (m^3/s)
- c = Runoff coefficient. Varies depending on the material type (dimensionless)
- i = Intensity of rainfall. Varies depending on the environment (mm/hr)
- A = Catchment area. The area of water that flows into the drainage (km^2)

The Rational method is applied based on the following assumptions [7]:

- There is uniform area distribution of rainfall across the whole catchment.
- The rainfall intensity is constant for at least a duration equal to the time of concentration, tc.
- The peak flow occurs when the rainfall intensity lasts at least as long as tc.
- C, the runoff coefficient, remains constant throughout the storm duration.
- The return period of the peak discharge, Tr, is the same as that of the rainfall intensity.

Parameters such as the material type and the size of the drainage provide enough flexibility such that the Rational method can be used in various situations. The intensity of the rainfall can be measured or even calculated using the amount of rainfall per hour. But in numerous cases the average intensity for rainfall is taken based on the historical data of 50 years. While calculating the catchment area, the land slope is considered as negligible [5].

2.1.2. The Saint Venant Equation

The Saint-Venant equation is used to model the flow of water in an open canal in sewer pipes. The equation is based on physical principles of mass conservation of energy [6]. For calculation, the equation is simplified by decomposing the sewer network into several virtual and real tanks. The formula is as shown below.

$$u_{n1}(k+1) = u_{n1}(k) + \Delta t\varphi_{n1}s_{n1}P_{n1}(k) + \Delta t\left(\sum_j q_{in}^{n1j}(k) - \sum_h q_{out}^{n1h}(k)\right)$$

Figure 3.   Saint-Venant equation [6]

Where

- n = Virtual tanks
- ∂_{n1} = Ground absorption coefficient of the $n^{1\text{-th}}$ catchment
- S_{n1} = Surface area
- $P(k)$ = Rain intensity at each sample with a sampling time Δt
- $q_{in/out}$ = The flow through control gates

Control gates are used as control devices to either divert the flow of the sewage (diversion gates) or stop the flow of the sewer (detention gates). In Saint-Venant equation, nodes are considered to be points in the network where the sewage

can be propagated or merged [6]. The rainfall intensity differs for each virtual tank calculation. Furthermore, the ground absorption varies depending on the type of soil.

2.2. Wireless Sensor Network Systems for Urban Drainage and Flood Monitoring

There are numerous systems that have been designed to monitor the external environment using wireless sensor network. These systems are mainly used to monitor and detect overflow in urban drainages, pipelines and rivers. The identified systems are discussed in the sub-sections below.

2.2.1. Design and Optimisation of Monitoring Networks in Urban Drainage

Henckens and Clemens [7] proposed a drainage monitoring system in the Beekbergen catchment in Netherlands. The main aim is to forecast unexpected flood. These situations are not foreseen due to the inefficient forecasting giving inaccurate results in the real time situations [7]. The solution is to calibrate a hydrodynamic model by gathering a high volume of real time data for the Beekbergen catchment (combined sewer system). The sewer system of Beekbergen is shown in Figure 4 below.
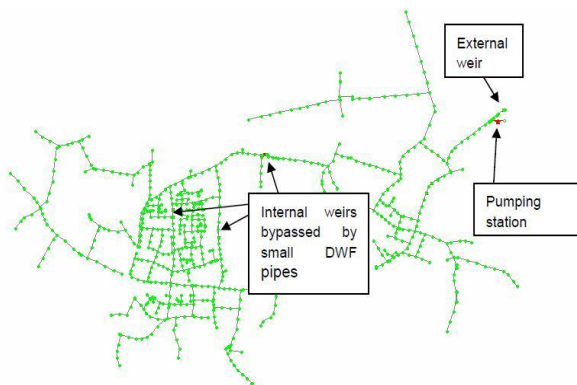

Figure 4. Beekergen sewer system [7]

Some criteria taken into consideration for the design of the Beekbergen sewer system monitoring network are:

- How many locations should be monitored?
- Which locations are most suitable for obtaining appropriate information?
- What is the accuracy and measuring frequency required?

The above conditions help to obtain most relevant information with a limited number of nodes placed at appropriate locations. The Jacobian matrix and the decorrelation method were used to analyse the results. The formula for decorrelation method is shown in Figure 5. The decorrelation method is used to find the relationship between the variables and to also validate the results obtain through elimination of wrong data.

Combination of relevant information gathered results into an optimal network monitoring which provides sufficient information to calibrate the model [7]. The data results shows that network optimization has numerous advantages such as being fast, cheap and giving relatively good results as compared to conventional measurement for network designs.

$$\frac{\left(\frac{1}{abs(C_{11})} + \frac{1}{abs(C_{12})} + \frac{1}{abs(C_{13})}\right)}{\left(\frac{1}{abs(C_{11})} + \frac{1}{abs(C_{12})} + \frac{1}{abs(C_{13})} + \frac{1}{abs(C_{21})} + \frac{1}{abs(C_{22})} + \frac{1}{abs(C_{23})} + \frac{1}{abs(C_{31})} + \frac{1}{abs(C_{32})} + \frac{1}{abs(C_{33})}\right)} = W_1$$

in which:
C_{12} = Correlation factor (0-1) between location 1 and 2
W_1 = total weight factor for location 1

Figure 5. Decorrelation method [7]

2.2.2. A Framework Web-GIS for Urban Drainage Monitoring System

Nowadays internet and Web-GIS (Geographical Information System) technology have been widely spread. The aim of the Web-GIS system proposed by Yang et al. [8] is to offer an infrastructure for an urban drainage network integrated system based on Web-GIS and GPRS (General Packet Radio Service) technology. J2EE-EJB technology was used to construct an enterprise level system that is platform independent, offers network support security and provides a runtime environment and remote transactions [8]. The system uses a three layered architecture to provide numerous functionalities. They are namely dynamic format of hydraulic model, urban drainage network optimization design and planning, visual information management, dynamic state analysis and real time monitoring of an urban drainage system. Figure 6 below shows the system architecture design of the three layered architecture.
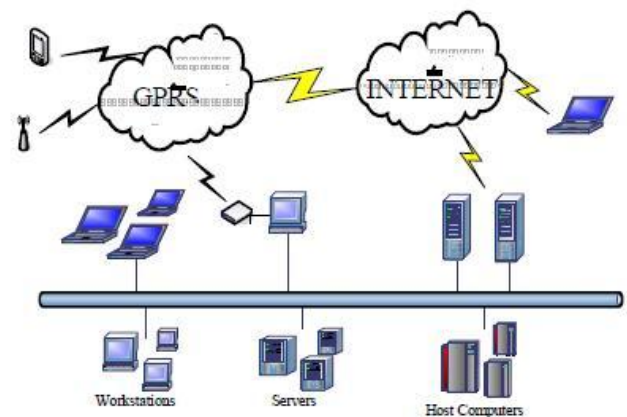

Figure 6. System Architecture Design for a three layer system architecture [8]

During the analysis phase, parameters such as geometry layer of the pipelines and topology layer of the drainage network were analysed. The drainage network structure is a factor which critically affects the waterflow in pipelines. Hence a study was carried out on the different types of nodes available in the urban drainage system [8]. Figure 7 below shows the type of nodes and the formula for the calculation of the depth at any point of the pipeline segment. Since the depths of the pipes at the ends are known, the depth at any point can be obtained from the formula below.
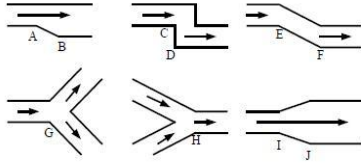
Given (x_1, y_1, d_1) and (x_2, y_2, d_2), depth of point $P(x, y, d)$ is $d = \dfrac{(Bd_2 + d_1)}{1 + B}$ where

$B = \sqrt{\dfrac{(x - x_1)^2 + (y - y_1)^2}{(x - x_2)^2 + (y - y_2)^2}}$

Figure 7. Type of node and formula for depth of pipeline segment [8]

The Web-GIS structure gives us a reliable system for the drainage network management with real time data provided via GPRS [8]. An environmentally adaptive development of hydraulic model was made and the information is displayed on a user-friendly interface where the data can be analysed.

2.2.3. Using Wireless Sensor Networks in the Sensor Web for Flood Monitoring in Brazil

Flood causes significant damage to people and infrastructure. The city of S ão Paulo, situated in Brazil has lately been visited by numerous floods that caused loss of lives, infrastructural damages and propagated waterborne diseases. Degrossi et al., [9], proposed a geospatial software platform that helps to predict rise of water at any point in time. Interoperability was a functionality that they wanted to implement in the system. Hence they adopted the Sensor Web Enablement standard [10]. The system was built using open source code distributed under the GNU license (General public license), making it easily adaptable. PostgreSQL data management system and PostGIS geographical database were used for the data server.

The aggregated data already present at the database are accessed via web service [9]. Some characteristics of the system built are robustness, interoperability and scalability. For the monitoring of flood in S ão Paulo, an application is built using the GeoExt API (Application Program Interface). The database already stores information retrieved from the wireless sensor network such as water gauge level, level of pollution and turbidity, and other related information from the sensors. It also contains data about the limitations of watersheds and the source and trajectory of the river. Once the data is recorded, it is accessed from the web service and populated on the API. A screenshot of the prototype interface is shown in Figure 8.

Figure 8. Prototyping interface of the system [9]

The system provides a real-time service through wireless sensor networks and geospatial service such as to monitor the water level in rivers across S ão Paulo. The system queries the aggregated data from the database and results are displayed on a map. Through this application, any overflow in the river can be easily detected.

2.2.4. SWATS: Wireless Sensor Networks for Streamflood and Waterflood Pipeline Monitoring

The Supervisory Control And Data Acquisition (SCADA) system was previously being used for pipeline monitoring. Concerns of not satisfying the expected criteria, namely acceptable expenses, flexibility, interoperability and fast data result gave rise of finding another means for the monitoring of the oil fields by the United States. Wireless sensor network was considered to be a possible solution in regions of high temperatures and where dangerous chemicals are usually present. The SWATS system [11] was designed based on wireless sensor networks resulting in a low cost solution, giving results in short delay, and providing coverage with fine granularity. Furthermore with the new SWATS system, leakages, blockages, outside damages, and generator and splitigator malfunctioning can be detected by using data correlations.

The SWATS system was deployed using the IEEE 802.11 mesh network standard with a long range and a high speed communication between the nodes (forming clusters) and the control room [11]. The proposed wireless network architecture is shown in Figure 9.
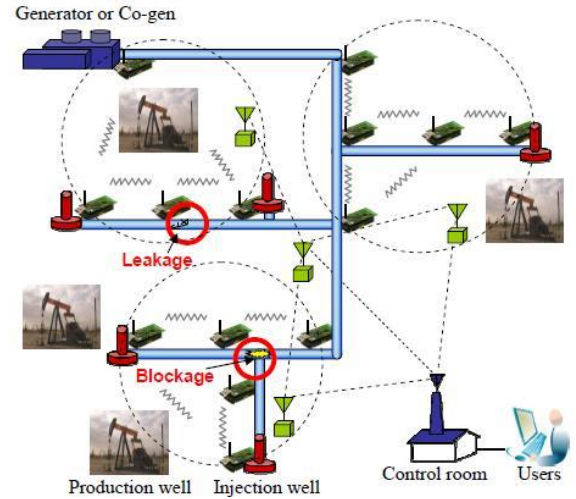

Figure 9. Proposed SWATS architecture of steam distribution system and monitoring using WSN [11]

Some of the challenges faced for proper monitoring of the oil fields are provision of reliability and accuracy with low cost sensors, false alarm detection, consideration on the topology of the pipelines and transients in steam and waterflood. Results gathered from SWATS system shows that it outdoes the SCADA system in terms of flexibility, cost and data rate. Details about the specifications of both systems are shown in table 1 below [11].

Table 1. Proposed SWATS architecture of steam distribution system and monitoring using WSN [11]

System	SCADA	WSN
Architecture	Centralized	Decentralized
Storage and Control	Central site	Local sensor node
Flexibility	Inflexible	Versatile
Cost	Expensive	Inexpensive
Node Density	Low	High
Data Rate	Low	High
Network Protocol	Proprietary	Non- proprietary

3. Problem Analysis

Mauritius is an island with a surface area of 1860 km^2, situated in the Indian Ocean [12]. Mauritius is a developing country which has a well diversified economy. Port Louis, the capital of the island, is the pivot for all economic activities. With the climatic changes on the island, Port Louis has been experiencing regular high rate of rainfalls which have resulted in frequent flood situations.

3.1. Flash Flood 2013

On 30th of March 2013, Port Louis experienced a major flood where there were massive infrastructural damages and loss of human lives [13]. The drainage system of Port Louis was not able to evacuate the incoming water which was due to a high rate of rainfall in that region. A total of 140.8 mm of rainfall was recorded within a duration of 4 hours. The increasing water level in the drains could not be observed due to lack of monitoring of the drainage system. In such situations, an early warning could have helped to take timely decisions to evacuate the inhabitants. Figure 10 shows the situation of Port Louis after the flash flood.

Figure 10. Flash flood of 30th March 2013

In Mauritius, the Rational method is used to calculate the peak discharge of the drainage system. Based on the results obtained from the Rational method, the design and size of the drainage system is determined. Climatic change has altered the precipitation rate in Mauritius. The island is being visited by more intense rainfall within less amount of time, hence causing the water level in the drains to rise drastically [13]. By means of average rainfall intensity and calculation based on historical data, it is 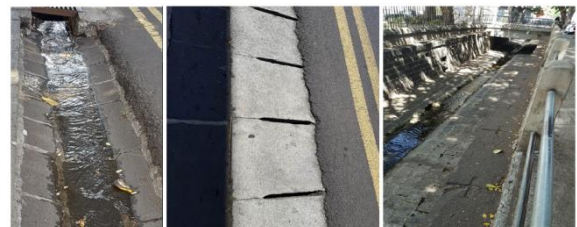no more feasible to forecast rainfall rate and location. Inadequate drains' sizes are the results of rainfall intensities based on short return periods. In numerous situations, open drains carry solid waste like plastic, branches and leaves blocking the water passage. In other situations, solid wastes are dumped in the drainage system thus blocking the water from evacuation. The Rational method makes several assumptions, which might make the calculations non-realistic and non-reliable. Some shortcomings of the Rational method are:

- Cannot give the real time status of the level of water inside the drainage.
- Cannot detect if there is any obstruction inside the drainage.
- Does not consider that the peak discharge depends on the inclination of the slope.

Hence, there is a need to find a more dynamic and real-time solution that takes into consideration parameters like change in rainfall intensity, obstruction detection in drainage and can give real time status of the water level in the drains. The use of wireless sensor network with sensor nodes placed at strategic locations in the drainage system of Port-Louis for the real-time monitoring of the conditions inside the drainage is considered in this paper.

3.2. Drainage System in Mauritius

Drainage systems are used to evacuate excess water from precipitation which can cause flood and damage to buildings and other infrastructure in the region. The constructions of drains in Mauritius started long ago, during the early 1900s, but several drains (e.g. Le Pouce stream) dated from the French period in the 18th century [14]. The only few drainage and paved gutters at that time were not regularly maintained. Drainage systems in Mauritius are mainly in the form of pavement drainage and open outlets. Figure 11 gives an overview of the drainage system in Mauritius.

Figure 11. Drainage system in Mauritius

Pavement drainages are constructed along the side of roads for evacuation of excess water. Three types of pavement drains mainly used in Mauritius are grate inlets, curb-opening inlets and combination inlets. Grate inlets are useful in extracting excess water to avoid flooding of the roads [15]. One main disadvantage is that grate inlets easily get clogged by floating trash and debris. Curb-opening inlets are similarly built on side of roads but these drains are more effective when the landscape has flatter slopes. But curb-opening inlets also have the possibility to be clogged by solid wastes and debris. Combination inlet is a fusion of

grate inlet and curb-opening inlet. When the curb opening precedes the grate, it acts as a trash interceptor during the initial phases of a heavy rainfall thus avoiding early obstruction. Figure 12 shows the designs of grate inlet, curb-opening inlet and combination inlet.
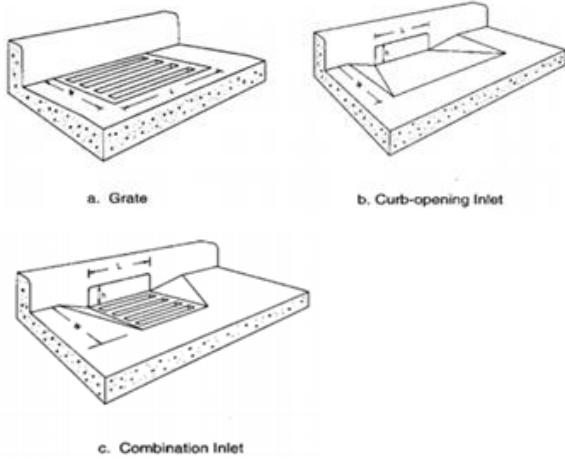

Figure 12.   Design of grate inlet, curb-opening inlet and combination inlet [15]

4. Proposed WSN System for Urban Drainage Monitoring

This section describes the design architecture of the proposed urban drainage monitoring system using wireless sensor network for the city of Port-Louis. Detailed implementation of the interaction between the sensors, the database, the front end system, and routing protocol used are discussed below.

4.1. Monitoring Area

Port-Louis, the capital city of Mauritius, is found in the north-west part of the Mauritius Island and has an area of 42.7 km^2 [16]. Port-Louis has an estimated population of 127,855 and consists of a harbour, a huge market, a high number of administrative and commercial buildings, making it the centre of economy with a heavy and congested traffic in its daily routine. The west side of Port-Louis is surrounded by the sea while the Port-Louis mountain range is on the east side, which protects the city from strong winds. The Port-Louis mountain range consists of a series of mountains with Le Pouce being the highest elevation of 812 m. The Figure below shows the region of Port-Louis highlighted in green and the topography of the capital.
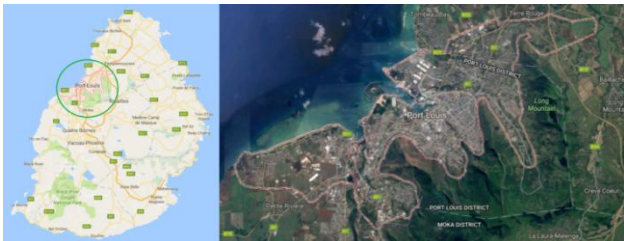

Figure 13.   Region of Port-Louis

Port-Louis is usually frequented by high precipitation, especially during summer seasons with an average rainfall of approximately 1,287 mm per annum [17]. Most of the drains of Port-Louis are old and no proper assessment of their efficiency has been carried out. The drainage system consists of smaller carriers which output to a main carrier for evacuation of waste water and excess water from precipitation. The main carrier has an approximate width of 4 m and depth of 1.5 m. Figure 14 shows part of the drainage system of Port-Louis.
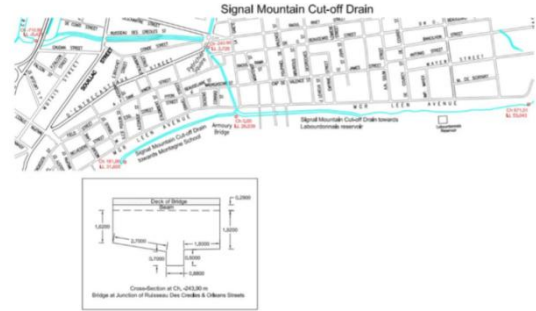

Figure 14.   Part of the drainage system of Port-Louis

4.2. High Level Architecture of the Urban Drainage Monitoring System

With the instant climate change occurring at specific locations, a real time system will enable the monitoring of urban drainage. Real time information such as water level and difference in water-flow inside the drains will be captured and sent within milliseconds to the base station. The gathered data will then be analysed for determining overflow situations or obstruction in the drains.

Hence there is a need of an urban drainage monitoring system which consists of numerous sensor nodes that are dissipated in the urban drainage of Port-Louis. The sensor nodes are placed at strategic locations such that the detailed status of the urban drainage can be observed. Data captured by sensor nodes are sent to a base station. From there, the data is combined and sent to a server which is connected to the monitoring system. Computation of the gathered data is sent to the front end where the results are displayed. Figure 15 shows the component diagram of the proposed urban drainage monitoring system.
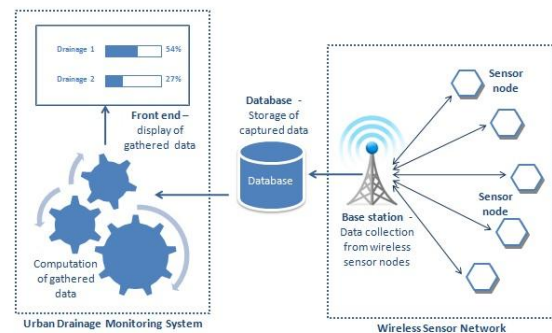

Figure 15.   Component diagram for urban drainage monitoring system Region of Port-Louis

In order to measure water level in the drainage system water level sensors are used. Water level sensors are able to measure the distance between the drainage's bottom surface and the water surface even if the latter is not steady. Water flow meters are used to measure the flow of water in the drain. In situations where waste materials in the drains are most likely to affect the sensor, the latter will be placed in a metal crate. Hence, waste materials from drains have less probability to block the sensor or affect its readings.

The proposed drainage monitoring system uses the Arduino boards to monitor the drains by capturing the sensor's information. Arduino is an open-source platform is compatible which 'easy to use' hardware and software. It is a single-board microcontroller which has a set of digital and analogue input/output pins. The board makes use of serial communication interface for easy swapping of information between the board and any external device like personal computers or laptops.

4.3. Topology Selection of the Urban Drainage System

Drainage system in urban regions, such as in the city of Port-Louis, consists of multiple sections that are connected together. The area to be monitored is relatively large and the wireless sensor network lifespan is an important factor to consider in the proposed system. There are numerous topologies such as chain based topology, tree based topology and hybrid topology that can be implemented. The cluster topology is selected because of the following advantages:

- Cluster based topology are scalable.
- Even after loss of nodes, the network of the cluster topology can be reorganized.
- Cluster based topology caters for load balancing.
- Data aggregation helps to decrease the communication load between the sensor nodes.
- Energy is conserved by efficient utilization of resources, hence also increasing the lifespan of the wireless sensor network.
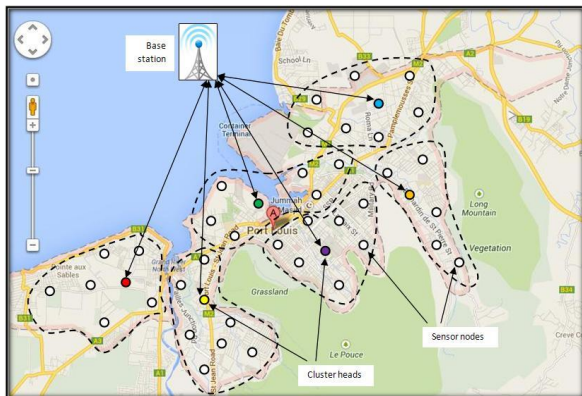- Nodes can be added/ replaced and cluster can be reformed without switching off the whole system.

Figure 16. Sensor nodes transferring data to server via base station

Figure 16 shows how the sensor nodes will be transferring data to the server via the base station. The coloured circles represent the cluster head sensor node and the empty circles represent the normal nodes.

4.4. Routing Protocols for the Urban Drainage Monitoring System

There are numerous routing protocols that are compatible with the cluster based topology; namely single/multi hop protocols, LEACH (Low Energy Adaptive Cluster Hierarchy) protocol, HEED (Hybrid Energy Efficient Distributed) protocol and VGA (Virtual Grid Architecture) protocol. The LEACH protocol has been selected as it best fits the requirements of the proposed system. The latter has load balancing capabilities and yields high energy saving percentage thus increasing the lifespan of the wireless sensor network. To minimize energy consumption, it ensures that all nodes die, i.e. run out of energy, about the same time by extending the network lifetime and leaving very little energy left in the nodes when the network dies. It can also be configured so that nodes die at about the same time by rotating the role of the cluster head and selecting the cluster head based on residual energy.

LEACH is broken into rounds with each round consisting of two phases: the setup phase and the steady state phase. The setup phase is when the nodes organise themselves into clusters [18]. A node decides to be a cluster head for that round independent of all other nodes in the network. The node will select a random number and if that number is less than the threshold value then the node will become a cluster head. The threshold value is based on the suggested percentage of cluster heads for that round (determined a priori), the number of times the node has been a cluster head. The cluster head will broadcast an advertisement message indicating it is a cluster head. A non cluster head node will join the cluster from which it received the strongest advertised signal from the cluster head. The non-cluster head node will send a join request to the cluster head and will then join that cluster. The steady phase is the normal data collection and routing. Clusters members send the data to its cluster head. The cluster head will fuse all the data received from its member nodes and then transmit the message to the base station.

A random selection is made for the cluster head at the start of a round. The algorithm selects from the pool of nodes the one that have energy level greater than average [19]. Each sensor node i generates a random number in the range $0 <$ random < 1. The random number generated is compared to the predefined threshold T(i). If random $<$ T(i), then the node becomes the cluster head, else it remains a cluster member. For the next round for data transmission, a different node is selected as the cluster head on a rotation basis [18]. The cluster head aggregates, compress and transmits the data to the base station. Due to the rotation in cluster head selection, the energy consumption is more or less similar for each node. When not in use, the non-cluster head nodes are switched to sleep mode. TDMA (Time Division Multiple Access) is used for scheduling in LEACH protocol, which can result to long

delays when the sensor network is relatively large. The algorithm used for cluster head selection in LEACH is as follows:

$$T(i) = \begin{cases} \dfrac{p}{1 - p(r \bmod(1/p))} & if \ i \in C \\ 0 & otherwise \end{cases}$$

Figure 17.   LEACH algorithm for cluster head selection [19]

where:

- p = desired percentage of cluster head.
- r = current round.
- C = the set of nodes that have not been cluster heads in the last 1/p round.

Given that the energy consumption varies depending on the distance of the cluster head from the base station, the residual energy of all the nodes in a cluster for a given time t can thus be different. LEACH algorithm can be further enhanced to cater for this by taking into consideration the energy present in each node before the selection of the cluster head. It then increases the probability of selecting the node having the highest energy as the cluster head. It is known as the L-LEACH algorithm (an enhanced version of normal LEACH) and the formula is shown in Figure 18.

$$T(n) = \frac{p}{1 - p * (r \bmod \dfrac{1}{p})} * \frac{E_{cur}}{E_0}$$

Figure 18.   L-LEACH algorithm for cluster head selection [19]

Based on the area, design, number of junctions, inclination and height of the urban drainage system, it has been figured out that placement of 8 wireless sensors placed at strategic locations along the drains will be enough to monitor for overflow. The phases for LEACH algorithm are as follows:

1. The first phase is called the set-up phase, where a random number is generated between the 0 and 1. The generated number is also compared to a threshold value which corresponds to the remaining energy. The formula for calculating the threshold value is shown above in Figure 18. In this particular situation, the value of n = 8 (the total number of nodes). E_0 is the initial energy for each node and E_{cur} is the current energy level in each node at that current point in time. p is the percentage of cluster head and r is the current round number for cluster head selection.

2. During the steady phase, each node within the cluster gathers and transfers (in single hop) their data to the cluster head. To avoid packet collision during transfer, the TDMA (Time Division Multiple Access) technique is used, which gives each node a specific time slot for data transfer. The cluster head, aggregates the data hence helping to reduce the packet size. The smaller the packet, the minimum will be the energy required to transfer the packet from the cluster head to

the base station. It has been noted that steady phase takes more time compared to the set-up phase due to the time consuming activities mentioned above in phase 2. After this last step, the cycle starts again with the set-up phase.

LEACH is a flexible and self-adaptive algorithm. It is robust to node failures since most node failures will not affect the overall network operation. Communication within clusters is done by using Code Division Multiple Access (CDMA) and different codes preventing interference between clusters.

4.5. Database Architecture of the Urban Drainage Monitoring System

A relational database is used for the storage of the gathered data. A table "DRAINAGE DIMENSIONS" stores the details of the drainage system, namely the width and height of the drainage at each section where the sensors are placed. It consists of 3 fields; RefPoint, Width and Height. The specific locations where the sensor nodes are placed are known as reference points (RefPoint). The table "WATER LEVEL AND WATERFLOW" stores the data captured by the sensor nodes such that the height of water in the drainage and water-flow at regular time intervals t at each reference point is known. This table also consists of 3 fields namely RefPoint, WaterLevel and WaterFlow. Overflow of drainage occurs mostly along the water carrier resulting in the overflow of a whole section. The third table "DRAINAGE REGION" categorizes all reference points in a specific region that are functionally linked such that during overflow, the whole section can be monitored. The table "DRAINAGE REGION" contains 2 fields namely Section and RefPoint. Given that a relational database is used, stored procedures are used for quick retrieval of data. Indexing and normalization are applied on the tables which improve the response time for querying the database and eliminate data redundancy. The database architecture is as shown below.
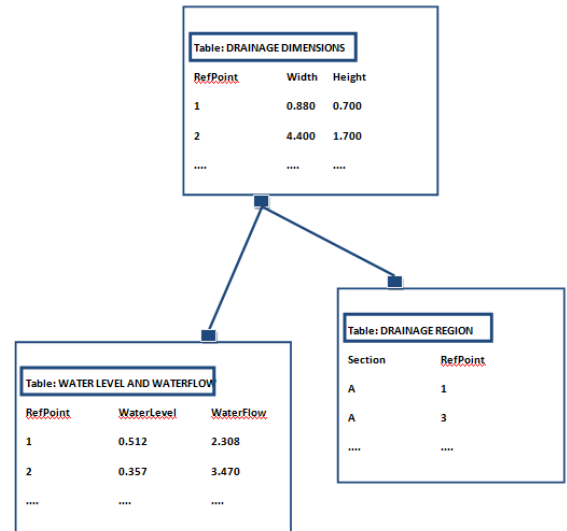

Figure 19.   Database architecture

4.6. Determination of Drainage Overflow

Reference points are strategic locations where there is highest probability of overflow. Once the reference points are identified, the width and height of the drain at that specific location are recorded. Water level sensors are placed inside the drains and based on the rate of increase in the water level, overflow of the drains can be predicted. Moreover, sonar sensors are also placed outside the drains to detect water overflow. Water flow sensors are used to record the speed at which water is flowing at each reference point. The water-flow at each reference point can be calculated using the Manning's equation [20]. The measure flow rate is compared to the calculated flow rate for the detection of obstruction in the drainage system. Moreover, the difference in water level at the reference point is calculated in order to determine the presence of an obstruction in a specific section of the drainage system. The formula for Manning's equation is as follows:

$$V = \frac{k}{n} R^{2/3} S^{1/2}$$

Figure 20. Manning's equation [20]

Where:

- $V =$ mean velocity (m/s).
- $k =$ 1.00 (constant).
- $n =$ Manning's roughness value.
- $R =$ Hydraulic radius (m) = [wetted area, A/ wetted perimeter, P].
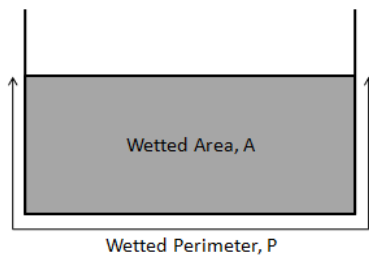- $S =$ Friction slope (m/m).

Figure 21. Calculation of the hydraulic radius, R

The Manning's equation is implemented in the system to verify the recorded water-flow in the drain. If the recorded waterflow is near to the calculated value, the sensors are less prone to be sensing erroneous data. The Manning's roughness coefficient is determined and the friction slope and hydraulic radius is measured.

4.7. Implementation of the Drainage Monitoring System

A monitoring application, namely PL-UDMS (Port-Louis Urban Drainage Monitoring System), is implemented in order to visualize the status of the drainage system in real-time. PL-UDMS displays the time period in hr, the rainfall intensity in mm and the water runoff in m^3/s. The urban drainage monitoring application consists of a Main Menu tab, a Detailed Report tab and a Graphical Representation tab.

Along with the display of real-time status of the drainage system of Port-Louis, the PL-UDMS application also allows the simulation of the drainage system for varying number of sensor nodes and varying rainfall intensity. The drainage overflow in the simulation is calculated using the formulae below.

If peak discharge > capacity of drainage, then the drainage overflows.

Formula for calculating the peak discharge:

$$Peak\,discharge\,into\,drainage, Q = 0.278ciA$$

Figure 22. Formula for peak discharge [5]

Where:

- Peak discharge into drainage, Q (m^3/s).
- Runoff coefficient, c = varies depending on the material type (dimensionless).
- Intensity of rainfall, i = varies depending on the environment (mm/hr).
- Catchment area, A = the area of water that flows into the drainage (km^2).

Formula for calculating the capacity of the drainage:

$$Capacity\,of\,drainage, Q = \frac{A}{n} S^{\frac{1}{2}} R^{\frac{2}{3}}$$

Figure 23. Formula for calculating the drainage capacity [21]

Where:

- Flow in channel, Q (m^3/s).
- Coefficient of friction, n = Manning's coefficient of roughness.
- Slope of channel, S.
- Wetted area, A (m^2).
- Hydraulic radius, R = A / P.
- Cross sectional area, A = b * y.
- Wetted perimeter, P = b + 2y.
- y = Depth of water.
- b = Width of drainage

The Main Menu tab consists of a map of the region under monitor. Based on the data fed from the database, PL-UDMS indicates whether overflow occurs. The map has been divided into sections based on the size of the drain. The arrows show the direction in which the water is flowing. The yellow circles indicate the strategic locations where the sensor nodes have been placed. In cases of overflow, red circles will appear at sensor nodes location. The time for the precipitation duration, the rainfall intensity and the number of nodes for monitoring can be entered in the simulation application. The 'run' option will trigger a calculation in the background of the system to determine overflow. The output result varies depending on the input data.

The Detailed Report tab gives the detailed status, in percentage, of the drainage section where the sensor nodes have been dissipated. It also displays the drainage capacity

and water runoff at each monitored location. The size including width, height and area for the different drainage section is available at the bottom of the Detailed Report tab. The approximate distance and approximate inclination between nodes are also displayed on the right.
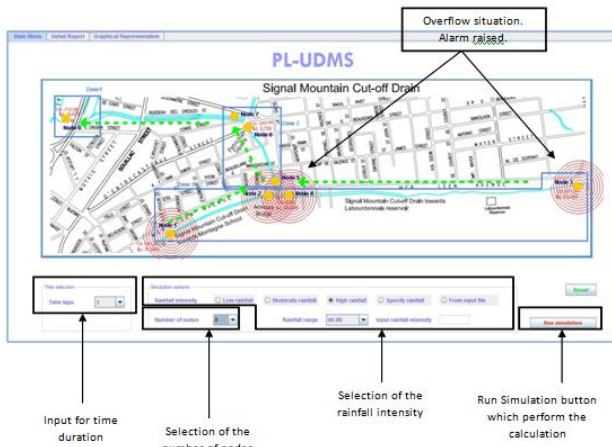

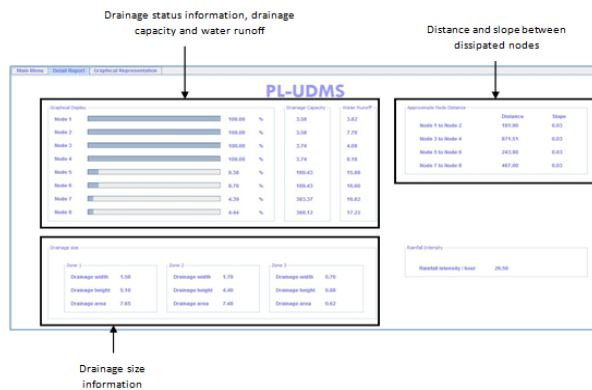**Figure 24.**   Main Menu tab of PL-UDMS

Figure 25.   Detailed Report tab of PL-UDMS

The Graphical Representation tab consists of a graph of inflow rate per unit time for each node. The inflow rate is displayed in mm/hr and time duration displayed in hr. This graph is dynamically populated based on input such as the rainfall intensity, the time duration and the number of nodes dissipated. Each node in a specific region is represented by a different colour in the Graphical Representation tab.
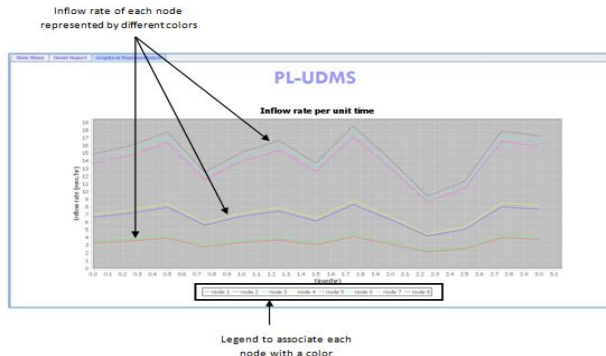

Figure 26.   Graphical Representation tab of PL-UDMS

4.8. Workflow Diagram of the Urban Monitoring System

Figure 27 illustrates the workflow diagram in the proposed drainage monitoring system. The water level and water flow is captured by each sensor node and transmitted to a server via a base station. The server stores all important data such as water level, water flow rate, drainage width, drainage height, distance between nodes and inclination of slope. These data will be fetched by the urban drainage monitoring application whenever the need for computation or for display of the real-time information on the screen. Meteorological data can also be added to the system to obtain realistic values of the precipitation rate in Port-Louis. The gathered data related to water level and water-flow in the drainage system is then analysed and an alarm is raised in case of drainage overflow or drainage obstruction detected.
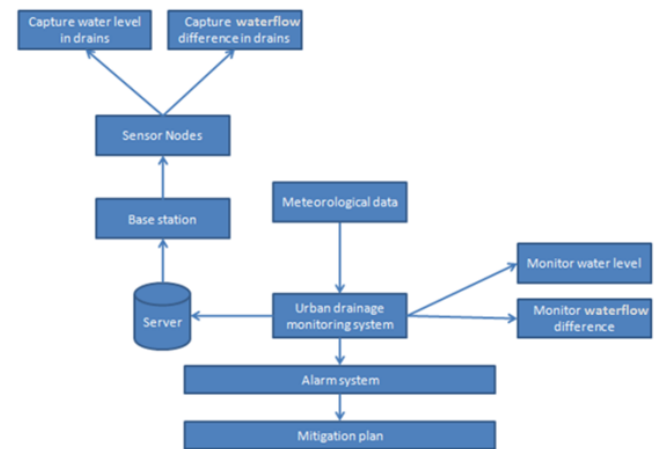

Figure 27.   Workflow diagram of the urban drainage monitoring system

5. Results and Discussion

The results of the drainage monitoring system, PL-UDMS, were observed for three rainfall episodes of 15 mm, 20 mm and 50 mm in the eight regions of Port-Louis. The result obtained for first rainfall episode shows that with water runoff of 4.35 m³/s and 4.62 m³/s in regions 2 and 4 overflow respectively with an amount of rainfall of 15 mm for a time period 1 hr.

Rainfall intensity of 15 mm for 1 hr.

Table 2.   Result with rainfall intensity of 15 mm/hr

Region Number	Water Runoff (m³/s)	Drainage capacity (m³)
1	2.16	3.58
2	4.35	3.58
3	2.30	3.74
4	4.62	3.74
5	8.97	12.43
6	9.37	13.43
7	9.50	15.37
8	9.73	15.12

The result obtained for the second rainfall episode shows that with a rainfall intensity of 20.00 mm for a time period of 1 hr, overflow occurs at regions 2 and 4 again. The water runoff is 5.80 m^3/s and 6.16 m^3/s, which is greater than the drainage capacity of 3.58 m^3 and 3.74 m^3 for region 2 and 4 respectively. It can be concluded that regions 2 and 4 are vulnerable and are prone to overflow.

Rainfall intensity of 20.00 mm for 1 hour.

Table 3. Results with rainfall intensity of 20.00 mm/hr

Region Number	Water Runoff (m^3/s)	Drainage capacity (m^3)
1	2.88	3.58
2	5.80	3.58
3	3.07	3.74
4	6.16	3.74
5	9.24	12.43
6	10.84	13.43
7	11.29	15.37
8	12.56	15.12

Rainfall intensity of 50 mm for 2 hours.

Table 4. Results with rainfall intensity of 25 mm/hr

Region Number	Water Runoff (m^3/s)	Drainage capacity (m^3)
1	4.54	3.58
2	7.67	3.58
3	5.58	3.74
4	8.22	3.74
5	11.43	12.43
6	12.15	13.43
7	13.76	15.37
8	14.21	15.12

With a rainfall intensity of 50 mm for a time period of 2 hrs, overflow occurs in the first 4 regions where the drainage capacity is relatively small. Regions 5 to 8 where the drainage capacity is above 10 m^3 is able to contain the water-flow.

The water runoff for the various intensities above; namely 15 mm/hr, 20 mm/hr and 50 mm for 2 hours for the 8 regions in Port Louis are shown in the Figure 28.

The results obtained for the three rainfall episodes demonstrates that the wireless sensor network urban drainage monitoring system is able to monitor and gives real-time information on the status of the drainage system in eight different regions of Port-Louis. The urban drainage monitoring system uses efficient algorithms for monitoring of the drains based on real-time data. The capture of water level and water-flow through wireless sensors is a simple and reliable solution for urban drainage monitoring. Data are recorded and transmitted to the monitoring system within seconds. When the wireless sensor nodes are placed at strategic positions such as drainage junctions a large drainage area may be covered with a minimum number of nodes thus reducing the overall cost of the monitoring system. The type of sensors and number of sensors are highly dependable on the design and size of the drains under monitoring. This paper describes a mechanism to determine events of drainage overflow and obstructions through simple method of monitoring the water level and water-flow in the drains. By analysing the data available from the monitoring application, the status of the drains can be monitored on a 24/7 basis with high granularity and without requiring physical displacement to the drains. As soon as there is a case of overflow, alarms are raised before occurrence of chaotic situations. Using the wireless sensor monitoring system, human lives can be saved by predicting floods and evacuating the inhabitants from the danger zone within the required time.
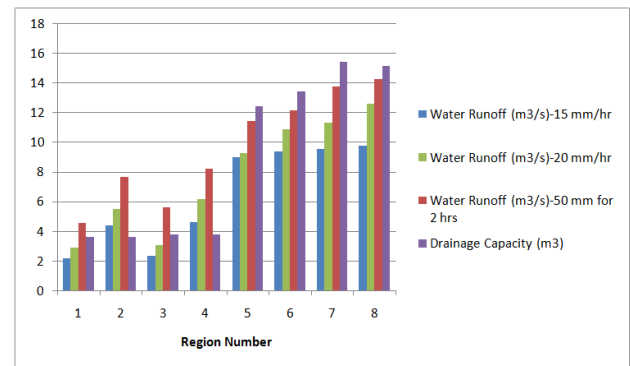

Figure 28. Water Runoff for rainfall intensities of 15mm/hr, 20mm/hr, 50mm and Drainage Capacity for 8 regions in Port-Louis

The most challenging part is in finding the strategic location for placing the sensor nodes, taking into consideration that the formation is the most efficient and effective for the wireless sensor network. Further analysis is also required on the number of nodes required for ideal formation of cluster and proper transfer of data within the network. It also includes re-formation and re-organization of the wireless sensor network upon death of sensor nodes due to battery depletion or physical damage. Combining the real-time data of water level and historical data of rainfall rate, appropriate algorithms may be developed in order to predict situation of overflow with a high degree of precision.

6. Conclusions

Past situations of high rainfall at specific locations in Mauritius have led to overflow of urban regions' drainage system, major infrastructural damages and loss of human lives. Wireless sensors becoming more powerful, reliable and affordable gives the possibility to monitor our environment to avoid catastrophic situations. Hence the proposed system is designed to detect real time cases of overflow and obstruction in urban drainage by placing sensor nodes at strategic locations inside the drains to monitor water level and water-flow. The proposed monitoring system

allows early detection of obstruction in the drains and local authorities can deploy the concerned team to go and clear the water-flow passage before overflow occurs. Moreover, in case of water level rising to the drainage level and a prediction of continuous high rainfall, an alarm can be raised to evacuate the inhabitants. The paper discusses about the architecture, cluster formation, routing algorithm and topology required for the implementation and deployment of a wireless sensor urban drainage monitoring system.

The urban drainage monitoring system (PL-UDMS) can be used to validate the designs of proposed urban drainage systems. The design with related measurements can be fed into the system to output the runoff in the drainage, thus making the application flexible. Rainfall intensity and time period can be varied to assess drainage systems and determine overflow. The real time drainage monitoring system deployed in Port-Louis can be extended to monitor other highly vulnerable cities in Mauritius such as Ebene and Curepipe where there are frequent occurrences of high precipitation.

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