Application of GIS to Detect Vulnerability of Water Distribution System

H. A. N. S. Kadurugamuwa, G. W. A. S. Dilthara, and H. K. Nandalal

Abstract The water distribution industry is facing challenges of water leakages in drinking water distribution networks. Mainly high pressure and the deterioration of ageing pipes and fittings cause the increase of the leak, and the consuming water and the number of bursts in the network. This study based on hydraulic and geospatial information system model has been suggested to estimate the probability of leaking for each pipe segment in the selected water distribution network. In this model, the likelihood of leaking is illustrated using pressure, age, length, diameter and slope of the pipe. The system is implemented with GIS tools, WaterGEMS, Google Earth Pro and Minitab software. Google Earth Pro is used to design the pipe network. The hydraulic model creates with WaterGEMS is integrated with ArcGIS. Minitab is used in elaborating the linear regression model, which is proposed to gain the leakage probability. The formed methodology is applied in identifying vulnerability ranges that have been identified for the pipe segments in the water distribution network. For the adducting results, a Geographic Information System (GIS) is used. Using the capabilities of this GIS model, the colour coded map represents the vulnerability ranges of the areas. The gained results can be used in detecting the most leakage areas and control pipeline leakage in the water distribution network. This methodology is developed to provide maximum protection against water leaks in the selected region.

Keywords Geographic information system (GIS) · WaterGEMS · Google earth pro · Minitab

1 Introduction

Water not only gives us life; it is the origin of life. The development and survival of life and civilization are centred around water. Man's need for water consumption has increased with his standard of living. Therefore, when considering settlements,

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the existing water distribution system is a crucial requirement in the modern world. Due to water and revenue losses, the water industry worldwide is facing demanding consequences. So, it has become a requirement to improve the efficiency of water distribution systems by reducing these losses [1].

According to the World Bank study, water distribution systems is lost about 48 billion m^3 of water. It has cost water utilities nearly US\$14 billion per year around the world (Liemberger, R. and Marin, P et al. 2006). In Sri Lanka, where the National Water Supply and Drainage Board maintains most of the urban schemes, Non-Revenue Water (NRW), being 33% on average, is reasonable amongst South Asian countries. Major expenditures on municipalities and state governments have been imposed, especially in urban environments, due to the repair and replacement of ageing water pipes. So, there is a gradual increase in the necessity to more actively occupy in the monitoring and managing such water distribution networks. According to Puust et al [2], as presented by companies that maintain water distribution networks, it is an economic issue and an environmental, sustainability, and possibly a health and safety issue. Colombo and Karney [3] reported that due to low-pressure conditions, water leakage may affect water quality due to contamination into water distribution networks.

This study focused on developing a system for detecting and controlling pipeline leakage in drinking water distribution. At first, an integrated GIS and hydraulic model is produced. This model can be able to combine spatial data with hydraulic and quality parameters of the network. A multilinear regression model is then developed, consisting of different criteria such as the probability of leakages, pressure, length, diameter, age of pipe, and elevation to be used in a pipe rehabilitation and replacement programme by decision-makers. The model is applied in the subsection of the Kandy Municipal Council water distribution network. Finally, the study aims at the graphical representation of the risk in a visual GIS-based interface that assists users to evaluate the degree of risk. Vulnerability ranges are colour coded and continually updated as the system processes time-related data.

2   Literature Review

If water escapes from the pipe network by means other than through a controlled action that can be interpreted as a general definition for leakage [2]. For the operation of water distribution, many parameters will be affected. Many pipes' bursts and accidents are occurring in a water network due to the influence of these parameters.

Intending to develop or improve predictive planning models, researchers have considered many factors that affect the deterioration of water pipes. As Wang et al. [4] emphasized, the factors contributing to pipe deterioration can be classified as dynamic or static. The factors that do not change over time are interpreted as static factors. Pipe diameter or pipe material can be considered as static factors. In contrast, pipe age, water pressure, temperature, water contents of the surrounding soil, and previous pipe breaks are examples of time-dependent factors called dynamic factors. Due to the

interaction of static and dynamic factors, internal and external deterioration of pipes occurs [5]. System pressure is the primary factor affecting the leakage. If the pressure is high, the leak flow is more prominent. According to Zyoud [6], controlling pressure is not a solution because it increases the side effects such as leakage, busting and, to some extent to water hammering [2], Walski and Pelliccia [7], Kettler and Goutler [8], and O'Day [9] also have presented factors affecting the leakage. Studies conducted previously also identified several environmental factors that affect the deterioration of water mains, such as soil conditions, frost and traffic loading, and quality of external underground water [10]. Other factors, such as rehabilitation methods, water quality, and break history, were critical for water pipes deterioration [11]. Incorporating these parameters, most studies in the literature present a relationship between failure rates and time of failure and some of them propose a methodology to optimize the replacement time of pipes.

Evaluating leakage probability is an efficient way to detect, rehabilitate, and maintain the pipeline system [12], has introduced a physica l probabilistic failure model for PVC-U pipes. This model uses fracture mechanics to forecast slow crack growth from inherent defects in the pipe wall. From the Monte Carlo Stimulation, the failure rate versus age curves was derived. Assumption deliberated was that all pipe segments along a pipeline have the same probability of failure. The expected failure rate (predicted failures per unit pipe length/time period) can be predictable through this model.

$$E[N(t)] = nh(t) \tag{1}$$

$E[N(t)]$	the expected number of failures
n	the number of segments in the pipeline
$H(t)$	a measure of the probability of imminent failure at time t
t	the pipeline at time.

Shamir and Howard [13] introduced a method for determining the optimal time to replace a pipe. To carry out the study, they studied break data. These data had been used to estimate how the number of breaks in the existing pipe is going to change over time. In this analysis, the number of breaks that would happen in a replacement length of pipe has to be assessed. Here, pipe break data were plotted against time, and regression was used to develop an equation that gives the number of breaks (per year per 1000 ft) as a function of time. After further analysing, [13] had extended this exponential regression equation further. They have incorporated additional parameters. Their study was based on observations made by the US Army Corps of Engineers in Binghamton, NY. Clark et al. [14] improved Shamir and Howard [13] model further to transform it into a two-phase model. They used the Eq. 2.

$$NY = x_1 + x_2 D + x_3 P + x_4 I + x_5 RES + x6LH + x7T \tag{2}$$

$NY = $ the number of years from installation to the first repair.

$x_i = $ regression parameters.

$D = $ diameter of the pipe.

$P = $ absolute pressure within a pipe;

$I = $ percentage of pipe underlain by industrial development.

$RES = $ percentage of pipe underlain by residential development.

$LH = $ length of pipe in highly corrosive soil;

$T = $ pipe type (1 = metallic, 0 = reinforced concrete).

They observed a pause between the year of installation of the pipe and the first break. So suggested the above model forecast the time elapsed to the first break.

Tabesh et al. [15], presented two types of linear and nonlinear regression for analysis of break rates to show the importance of renovation scheme. For linear regression, the Eq. 3 is used.

$$y = \beta 0 + \beta 1 x \tag{3}$$

and nonlinear regression is determined as:

$$y = cd\, x \tag{4}$$

$c = 10\beta 0$ and $d = 10\beta 1$.

Tabesh et al. [15] all the burst records were assembled and examined. Analysing the assembled data, areas with the highest burst records were marked and highlighted on the map using the GIS model records. Also, this GIS model can recognize the position of the valves required to be isolated for rupture repair. According to a decision aid GIS-based risk assessment, [16] studied the risk of vulnerability and pipe failure in distribution networks in Miami, Florida. In their research, [11] used a strategy model to find the number of annual failures in the water networks of three cities. Rasooli et al. [17], Patel and Katiyar [18], Vairavamoorthy et al. [19] interpreted GIS as a powerful tool to analyse pipe networks and introduced it as the best application to manage, manipulate and maintain geospatial data and to develop and sustain asset management for today's water utilities worldwide. Rasooli and Kang [17] reported that GIS is comprehensive and multifunctional computer-based software being used in water transmission and distribution systems in a modern and systematic water supply. To manage water systems, researchers have used a combined GIS and hydraulic model. According to Rossman et al. [20], the employment of the EPANET software is capable because of its availability, popularity, and capability to be linked with GIS models. Rasooli and Kang [17] presented a method to design and balance Water Distribution networks based on loops hydraulically as well as using GIS methodology with the contribution of EPANET. In this research, they
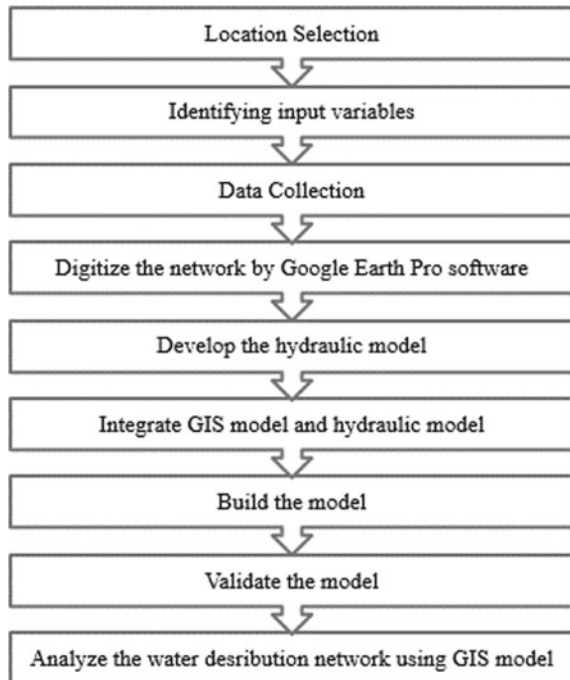
have analysed water flows in each pipe. They performed the iterations process on loops to make the algebraic summation of head loss around any closed loop zero, in case the outline of pipe flows must be equal to the flow amount entering or leaving the system through each node. Stimulation was done by using EPANET and GIS for the water distribution network. They have examined and replicated hydraulics parameters for the targeted area in Kabul city.

Researchers were used different parameters according to their methodology to find leakages in water distribution systems. Then they have developed various models to find the degree of risk of failure. According to them, the spatial analyses in ArcMap allowed visualization of the vulnerable areas, identification of the regions with different levels of vulnerabilities, and quantification of the potential impacts.

3   Methodology

The methodology was developed to detect and control pipeline leakage in drinking water distribution using the hydraulic and geospatial information systems model. The proposed hydraulic and geospatial information system model approach narrows down leaks to specific pipe segments of the water distribution system. The summary of the methodology is shown in Fig. 1.

Fig. 1 Summary of the methodology

Location Selection

Identifying input variables

Data Collection

Digitize the network by Google Earth Pro software

Develop the hydraulic model

Integrate GIS model and hydraulic model

Build the model

Validate the model

Analyze the water desribution network using GIS model

3.1 Location Selection

The water resource of Kandy Municipal Council water distribution network is Dunumadalawa reservoir and Roseneath reservoir. The intake of the Roseneath reservoir is selected as the subjective area of the study. Roseneath reservoir supplies water to the regions including Thottipallama (Ginihiriya), Rajapihilla, Kamhillwatta, Dalukgolla, Keerthi Sri Jajasingha Mawatha. The daily intake of the Roseneath reservoir is 370 m^3. The water distribution network that is used as a case study in the project is an isolated medium size network which supplies water to Rajapihilla and Kamhillwatta. The location of the study area is shown in Fig. 2. The number of houses, temples, and hotels in these areas are shown in Table 1.
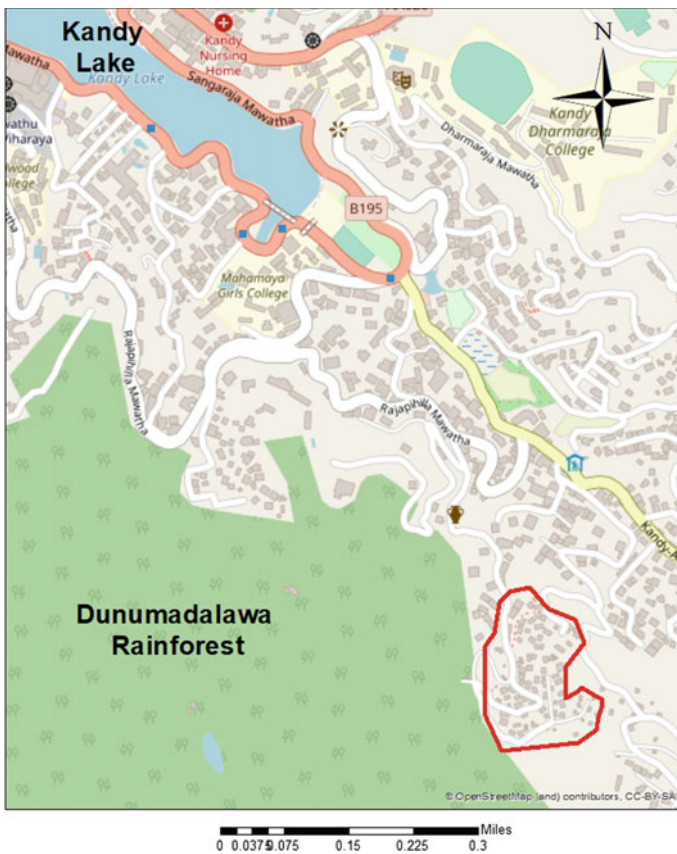

Fig. 2 Study area

Table 1 Service area and number of houses/hotels/temples

Service area	Number of houses/hotels/temples
Kamhillwatta	48
Rajapihilla	11

3.2 Input Data

There are many factors and incidents which are adversely affecting the vulnerability of a pipe network. This research mainly focuses on pipe length, pipe diameter, pressure, age of the pipe, and slope of the pipe.

3.3 Methodology

Kandy Municipal Council has not modelled the selected water distribution network in any electronic format. As the preliminary step, the GPS coordinates of the nodes of the pipe network was measured from the CT Droid mobile application during the site visit. CT Droid Sri Lanka 3.0.0 application is designed for Sri Lanka to perform coordinate transformation to project Geographic coordinates to Cartesian coordinates that suit Sri Lanka. It supports both KANDAWALA EPSG:4244 and SLD99 EPSG:5233 datums. Collected GPS coordinates were exported to Google Earth Pro. Considering these coordinates, the pipe network was drawn as in Fig. 3.

The drawn water distribution network was imported to WaterGEMS as a base map. In the WaterGEMS, the pipe network was hydraulically modelled. The relevant
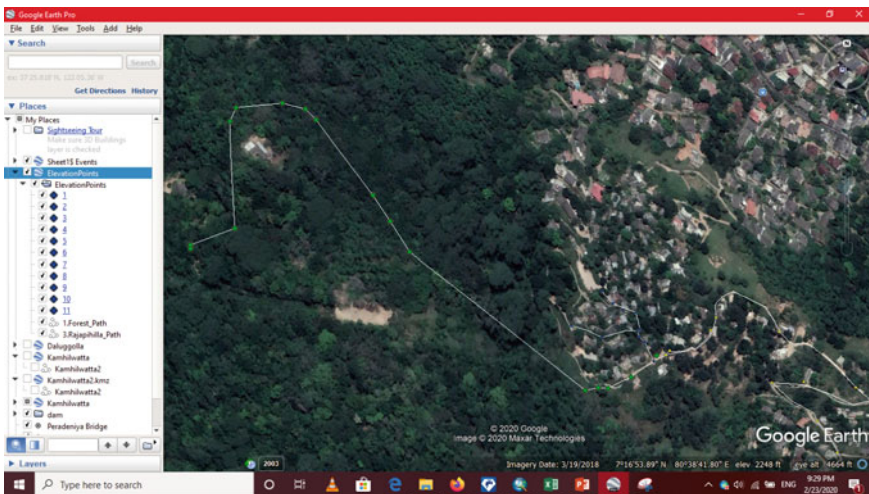

Fig. 3 Representation of pipe network using Google Earth Pro
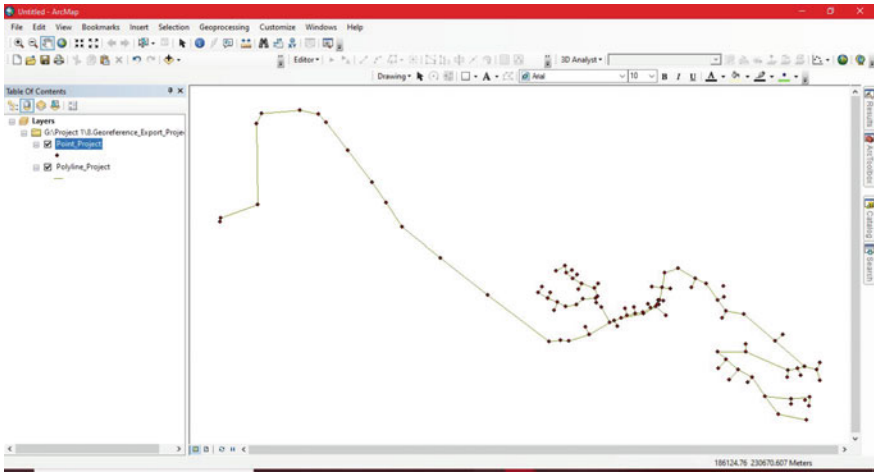
Fig. 4 Pipe network in GIS interface

properties such as diameter, material, demand and Hazen-Williams coefficient for the pipe network were intercalated to the hydraulic model.

This hydraulic model was integrated with ArcGIS. Then, the pipe network was modelled using the Geospatial Information System (GIS) in the ArcGIS 10.6 version. The water network was georeferenced using the "add control points" tool. The coordinate system was defined to WGS1984 using the "Define Projection" tool. Afterwards, the network was projected from WGS1984 to Kandawala Sri Lanka grid using the "project" tool in the "Projection and Transformation" tool, as shown in Fig. 4.

Then the Digital Elevation Model (DEM) was created as shown in Fig. 5.

Required data such as average slope, nodal elevation and length of the pipe was obtained using the attribute table. In the hydraulic model, the obtained above data was inserted. Then the model was computed to get the pressure distribution. In the next step, using the relevant data obtained, the equation was executed. For this, MiniTAB Software was used. Afterwards, the validation part was carried out.

In this research, it is mainly focused on the probability of leakages in pipe segments of selected area and effect of external factors to the vulnerability of pipes and it is considered that the topography of a certain area would make a huge influence in this case. Depending on the factors that we considered, the probability of leakage being the pipe network vulnerable varies. The probability of Leakage (N) would be developed on those factors.

$$N = \beta + \beta_1 l + \beta_2 d + \beta_3 p + \beta_4 a + \beta_5 s \tag{5}$$
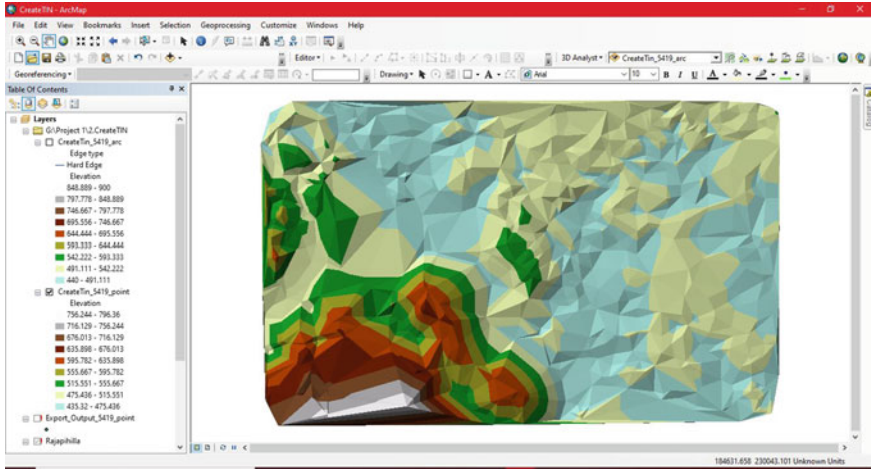
N = Probability of leaking

l = Length of the pipe

Fig. 5 Digital Elevation Model (DEM)

d = Diameter of the pipe

p = Pressure

a = Age of the pipe

s = Slope of the pipe.

4 Results and Discussion

Leakage records collected from the Kandy Municipal Council was used to calibrate and validate these models. In the calibration process, the highest number of leakages on a segment of a pipe per year is considered as the probability of a hundred per cent. Then the leakage probability of the other segments of pipes is compared concerning that value. By using the Minitab software, the equation was obtained as follows.

$$N = 0.877 - 0.576d + 0.000008p + 0.1525l + 0.01468s \qquad (6)$$

Linear regression is a linear approach to modelling the relationship between a scalar response and one more variable. In this modelling length of the pipe, the diameter of the pipe, pressure and the slope of the pipe are variables.
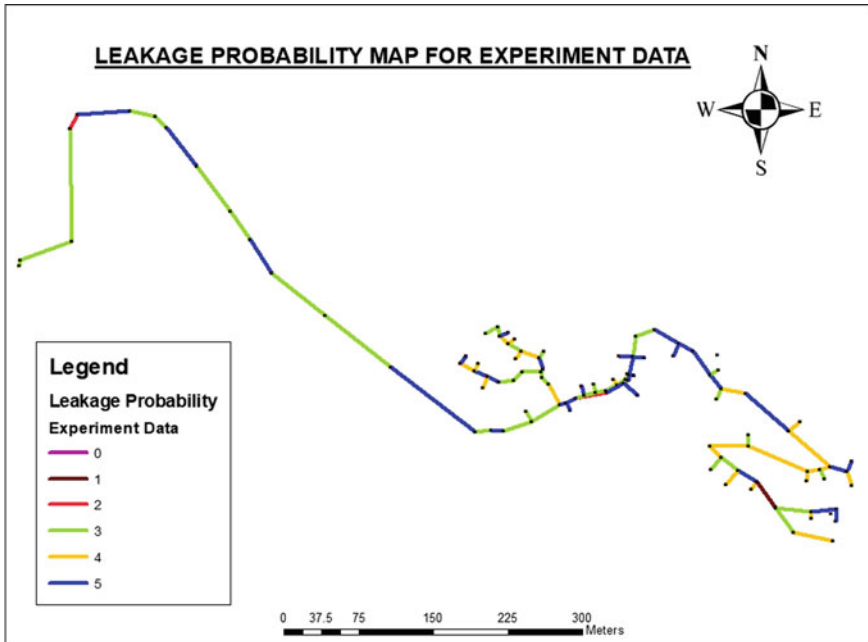
Fig. 6 Leakage probability map for experiment data

4.1 Risk Map for Leakage Probability

All the pipes with burst records can be easily identified, marked and emphasized on the map using the GIS model. For the replacement programme, this map is the key tool to identify the vulnerable area with the highest burst records for the replacement programme. The risk map generated for the KMC case study area is shown in Fig. 6. This figure elaborates that most of the water pipes have a medium or low risk. However, a small number of pipes have a high risk of leakage probability. Then the results obtained for the regression model has been validated with actual field data. The R-squared value for this model is 0.68. It is a little bit low. But it shows a positive correlation between actual data and results obtained for the regression model. For further clarification, leakage probability map for actual data (Fig. 7) and experimental data depicted by GIS-based tools. Then the validation was carried out in a more precise manner.

5 Conclusion

Leakage vulnerability levels are shown in the selected area, considering the risk map for leakage probability. The map for leakage detection is an easy and effective
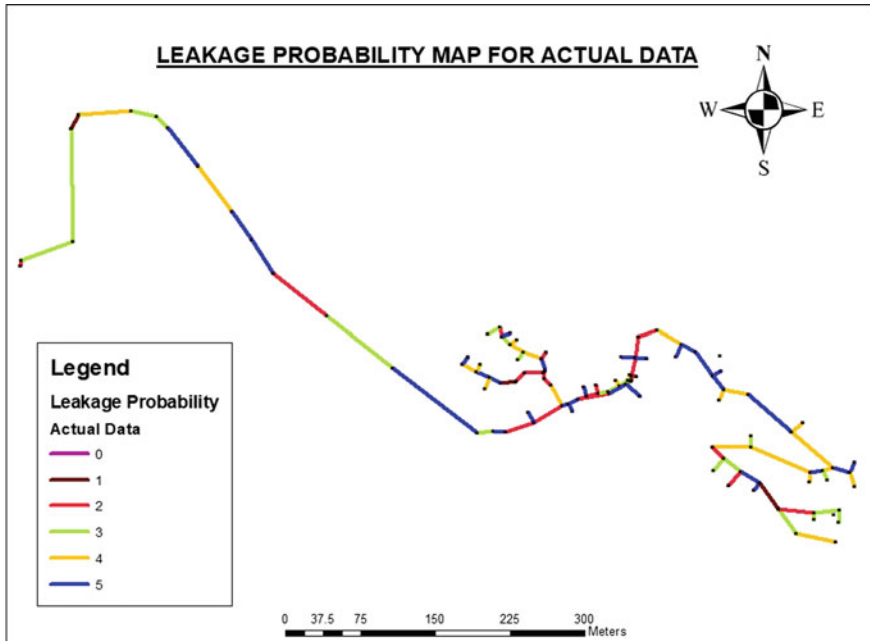
Fig. 7 Leakage probability map for actual data

method to detect and control pipeline leakages. Under this research, the importance of measuring the probability of pipe leakage is highlighted and represents a methodology to analyse and evaluate the vulnerability numerically. From the results of this methodology, it can be identified the places where the worst consequences for the functioning of the water distribution network may occur. It has also been focused on tools for planners and engineers in designing the critical location of the pipe network.

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