PEOPLE-CENTRED APPROACHES TO WATER AND ENVIRONMENTAL SANITATION

Development of GIS based contamination risk assessment in water distribution systems

S. Mohan and K. Danimon, India and K. Vairavamoorthy, UK

The study aims at developing a GIS based contamination Risk Assessment procedure in water distribution systems. Water distribution network analysis model EPANET 2.0 was integrated with ArcGIS 8.3 for the water quality analysis retrieving data from the GIS database. Water supply system of Zone VIII of Guntur, India was selected for the case study. The results of water quality simulation were displayed in the GIS interface and the areas affected were mapped with the spatial analyst tool of GIS. Data on number of household connections and standpipes affected by a particular event of contamination was also retrieved from the GIS database. The events resulting in high risk were identified from the GIS maps. This information helps in the decision making process of prioritizing the maintenance activities particularly, in case of limited fund availability. Since the resource availability for maintenance activities are limited in developing countries, prioritizing the activities using GIS helps to achieve maximum risk reduction.paper

Introduction

Safe drinking water is essential to sustain life, and a reliable and adequate supply to the general public is to be ensured by the service providers. Water supply systems have close association with the health of the people, in urban societies, as it is the major source of water for them. Water in a water distribution system may get contaminated either at the source or during the transit through pipelines. Most of the water supply networks have water treatment plants for purifying water before it is supplied. However, there are only few or no check on the water quality, if water is contaminated whilst in transit. Quality deterioration at the source can be averted to a great extent by appropriate and ample treatment processes. Intermittent water supply systems are highly prone to contamination during transit. Since the pipes in such systems are often under zero or negative pressure, there are always chances of contaminant intrusion. Many designs of water distribution networks and analysis of water quality is done considering it as a continuous supply scheme, despite the fact that water supply is not continuous but is intermittent in most developing countries (WHO Study Group 1987, Kalbermatten 1989 and Akinpelu 2001).

Water Quality deterioration during transit can occur due to many reasons; the major one being the contamination due to seepage from drainage networks and foul water bodies. A low pressure inside the water supply pipeline favours the entry of sewage into the pipeline. Thus the leakages in the drinking water pipeline that are in close proximity to sewer lines, foul water bodies and garbage disposal areas pose a serious risk of contamination of the drinking water and hence pose a risk to the health of the people.

In developing countries, the available funds for maintenance or renovation works are very much limited. Thus it becomes essential, to have a trade-off between the works to be undertaken. The maintenance task(s), that are likely to positively affect the health of the maximum number of the general public should be identified and be given top priority. This decision-making is crucial in protecting the health of the public and management of available funds. Such decision support systems require handling large amount of data, for which Geographical Information Systems (GIS) are the best tool. GIS technology is applied in a variety of problems in water distribution networks. It gives a visual model of the field conditions and hence can be used with ease, even by professionals with very little experience.

Schindler and Garrard (1999) observed that GIS technology is used primarily to acquire and maintain an inventory of the distribution system assets. They described how GIS can be configured to reflect the overall pressure regime and allowing the system to operate in a predictive mode.

The main objective of the study reported here is to develop an integrated model by combining water supply network analysis model (EPANET 2.0) and ArcGIS Desktop 8.3 (GIS package) to meet the following tasks:

1. To determine the locations prone to contamination and the propagation of contaminant in a water supply network,
2. To apply the integrated model to a real world water supply system, and
3. To evolve strategies for management of water supply, and mapping of risk areas using GIS.

Integration of water supply network analysis models and GIS is a feasible, affordable and efficient tool in water distribution system management. The applicability of the developed models has been demonstrated with a case study of the Guntur water supply system, India.

Study Area

The site chosen for study is B. R. stadium zone in Guntur City, Andhra Pradesh, India. Guntur is divided into 10 zones for administrative purpose and the B. R. Stadium area constitutes zone VIII. The data available for Zone VIII include maps on road network, water distribution networks, sewer networks, foul water bodies, stand pipe locations and house connections to a pipe.

Guntur Municipal Corporation, the administrative body for Guntur City, is responsible for drinking water distribution in the city. Water is supplied through pipe networks for 1 hour per day and thus can be categorized as an 'intermittent water supply system'. Zone VIII is selected for the study due to frequent occurrence of contamination in its water supply network. Leakages in the water supply pipe-network are a common phenomena in this area. Frequent leakages from sewer networks have also been observed in this zone. The fact that it takes 3-4 days to rectify a leakage aggravates the problems. As the field survey revealed, 7-8 new pipe leakages occur each day. Also there are frequent leakages and overflows from sewer pipes and drains due to blockages. There are water supply pipelines passing through open drains. Contamination of water, by mixing of sewage with drinking water supplied has been reported at many locations in Zone VIII. These features reveal the high level of risk involved in the water supply system of that zone.

Zone VIII has a population of about 60,000 and the area of this zone is 4 km2. A vast majority of the population in zone VIII depends on the public water supply system through house connections or standpipes. There are two overhead water tanks to cater the domestic water demands of Zone VIII. The source of water is Krishna River which is treated in a 10 MGD capacity water treatment plant. The main supply lines from B R Stadium area tanks are 600mm diameter RCC pipes. Distributaries are mainly AC pipes and there are few CI and GI pipes ranging in diameter from 60mm to 600mm.

There are various locations along the pipe network that the pipes pass through open drains and at these locations the sewage water often flows over the drinking water pipes. Since, the majority of the population depend on public water supply, any contamination in the network is likely to affect large number of people.

Also during the non-supply hours, at many locations the public uses hand-pumps or even electric pumps to draw out water remaining in the pipes. Also illegal pumping of water from the pipeline during normal supply causes lower pressures at downstream locations These pumping activities can pull in sewage from the leaking sewer pipes or contaminated water from the open drains. It is sucked into the drinking water pipelines through the leaks (at joints, damaged pipes or valves). Usage of this contaminated water has reportedly caused health hazards in the past..

In Zone VIII, almost 99% of the households are connected to either open-drains or sewer pipelines or both. Occasionally, due to the malfunctioning of the treatment plant, the sewage is unable to flow away thus causing blockages in the sewer lines, which in turn leads to leaks at weaker joints.

Considerable amount of seepage of contaminated water occurs from open drains. Since the open drains are at ground level, there is a potential of this seepage reaching water supply pipes. Stagnation of water is a common feature especially during rainy seasons. Water supply lines passing beneath such water bodies are also at risk of contamination.

Methodology

A Water Quality Model can be integrated with the GIS tool to analyse and simulate the hydraulic behaviour of, and water quality in, the pipe networks. Using the GIS tool, the area and number of families affected by deterioration in water quality can be determined. Conventional methods of analysis of a water distribution system impose specified quantities of demand at the nodes and compute the corresponding residual heads. But in most cases there is a head dependent outflow, instead of pressurized flow at demand points (nodes). The latter assumes that sufficient water is available at the nodes and demand is always met. Srinivasa Reddy and Elango (1989) proposed a methodology, which takes into account the residual head versus flow relationship where there is no control on the outlet. The appropriateness of the methodology was demonstrated using examples, including a 'bullet network' (Srinivasa Reddy and Elango (1989)). The results from this study were used to evaluate the capability of EPANET 2.0 (Rossman, 1994) in handling head dependent flow at outlets. The bullet network explain in the above paper was simulated using EPANET. The results were identical. Thus, EPANET 2.0 was chosen as the tool for simulating water quality variation in the water distribution system under study (Rossman et al., 1996).

The methodology used in the study reported here consists of three phases. The first phase involves integration of the pipe network analysis model with GIS. The network analysis model is used to simulate the propagation of contaminant through the network in order to identify the affected sections of the network at any point in time. The integrated model is then applied to water supply network of zone VIII in Guntur city and this constitutes the second phase. In the third phase, a suitable decision support system has been developed for the risk assessment in the water distribution network.

ArcGIS Desktop 8.3 software package developed by ESRI (Environmental Systems Research Institute, Inc.) is used for mapping the network and the other geographic features of Zone VIII. the water supply network analysis model was integrated to ArcGIS using the macro editor provided for visual basic application. This retrieves required data from the attribute tables of features (pipes, nodes etc.) of the map and creates the input for the network analysis model. After successful running of the model, it loads the results to the attribute table of appropriate features in the map. Then using the spatial analyst tool of ArcGIS, the contamination prone areas are identified. The results are then displayed in the GIS interface.
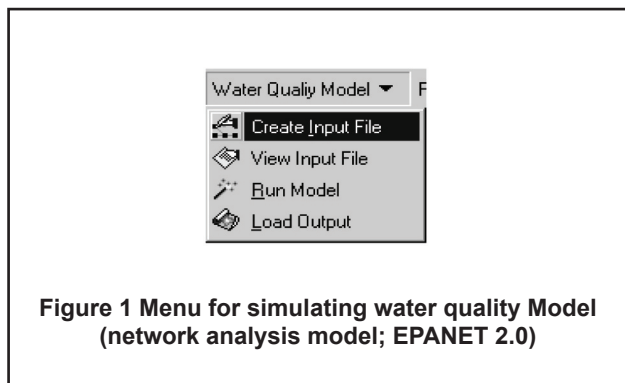
Thematic maps were created for different features of the study area. In GIS, all thematic maps are associated with an attribute table, which contains the properties of every element of the feature class (thematic maps). Each field in the attribute table represents a particular property. More fields are required to fully describe the network as required by EPANET. There are certain fields, which are essentially required for the simulation of network analysis model (e.g.:- Start Node and End Node for links, pipe diameter etc.). These fields are to be populated for the creating the proper input file. Certain fields are also required for loading the results (Flow rate, velocity etc.).

The units of the values entered in the fields depend upon the unit system chosen for the analysis. There are two main types of units for EPANET, viz US customary units and SI Metric units. Option was given to choose the unit system while creating the input file in the integrated model, which sets the unit for all the parameters. More information on the input file format and other information for running the simulation are available at the help section in the EPANET 2.0 software package.

### Integrating Network Analysis Model (EPANET) with GIS

ArcGIS provides for changing or creating toolbars and menus in the work environment. Custom commands can be created with VBA (Visual Basic Application) in ArcMap using the object library. New objects are created and codes are attached to them to accomplish particular set of actions. Custom made toolbars and menus can be saved to a template (*.mxt in ArcMap). All maps made in a particular template will have all the custom made commands saved to the template and will be available every time that the map is opened.

A template has been created to save the new toolbars and menus for integrating the water supply network analysis tool. All the maps created for analysis of water supply networks were made in this template. The menu for water quality modelling is depicted in Fig. 1. It consists of four commands namely, 'Create Input File', 'View Input File', 'Run Model' and 'Load Output'. The command, 'Create Input File', will create a text file in the input file format specific to EPANET 2.0.

Clicking on to the command will open up a dialog for retrieving appropriate data from the themes (Fig. 2). The data required are derived from the related shape files (representing the themes or layers in ArcMap) from appropriate fields in its attribute tables. The fields contained in the attribute tables of the selected theme are listed in the combo box next to each parameter. The field that contains the value corresponding to the parameter required, is to be selected for each combo box in the dialog box. There are two options for hydraulic analysis viz. *pressurized flow analysis* and the *head dependent flow analysis*. For head dependent flow analysis, the flow coefficient values are to be added to the attribute tables as required by EPANET.
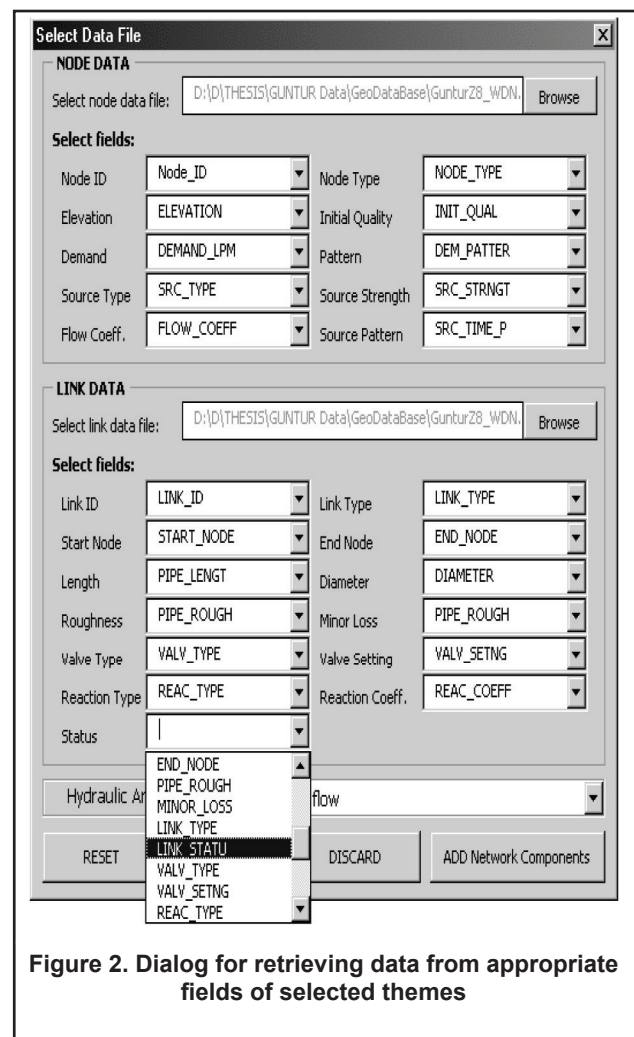
Figure 2. Dialog for retrieving data from appropriate fields of selected themes

After choosing the necessary options, clicking to the *"ADD Network Components"* button, enables adding the network parameters to the default input file. After adding the network components, another dialog box as shown in Fig.3, opens up automatically for choosing the option for analysis. This is similar to the normal EPANET interface. For each tab in the dialog, short notes are given at the bottom of the dialog. Clicking the *"Create Input File"* button completes the crea-

Figure 1 Menu for simulating water quality Model (network analysis model; EPANET 2.0)

tion of input file and a message box is displayed thus the input file created can be viewed using the *"View Input File"* command from the *Water Quality Model* menu. The default input file can also be saved in a different filename.
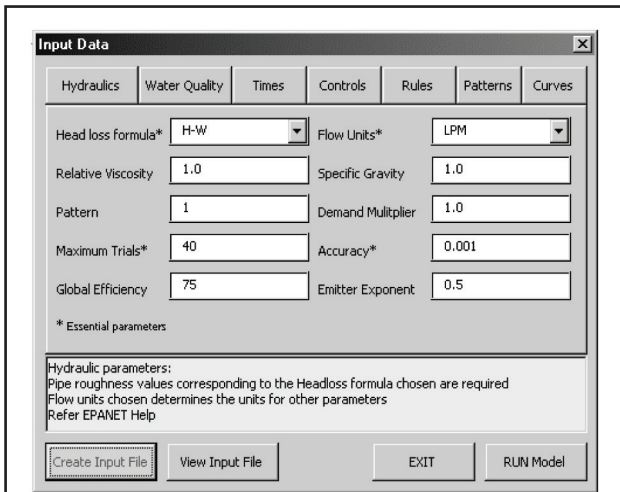

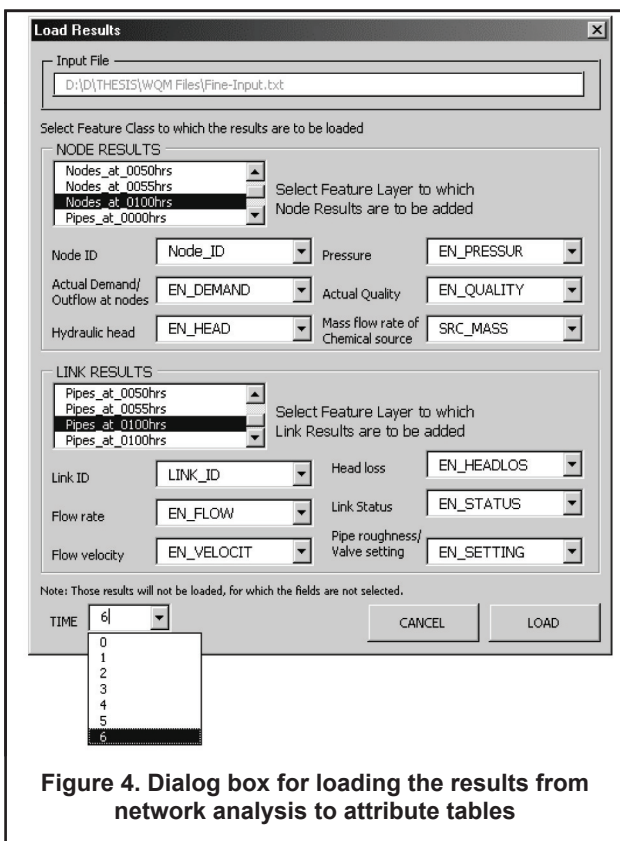**Figure 3 Dialog for choosing the analysis options**

Figure 4. Dialog box for loading the results from network analysis to attribute tables

Once the input file is created, the network can be simulated using the *"Run Model"* command from the menu. An input file other than the default input file can be chosen in the dialog that appears. A different name may be given for

the report file. The "RUN" button in the dialog triggers the simulation. It generates a message, whether the run was successful or not. If the run was unsuccessful, the report file can be viewed for error checking. The errors need to be rectified before any further simulation or loading of results.

Once the model runs successfully, the results can be loaded to the attribute table of the thematic maps in the current map document in ArcMap. This implies that the maps need to be added as layers to the current map document. Activating the *"Load Output"* command from the menu brings up the dialog for choosing the fields to which the results are to be loaded (Fig. 4). The dialog lists the themes already loaded into the map. The combo boxes list the fields available in the tables. Respective fields can be chosen for both node and link results. The time period, for which the results are to be loaded, is also to be chosen from the lowermost combo box in the dialog. After loading the results, the representation of the layer was changed to show the variation in chemical concentration.

Water Quality Analysis for Study Area
The water supply network of the study area was simulated for analyzing the water quality conditions for four different cases. The menus and commands developed as explained above were used for the analysis. The four cases are:

Case 1: Contamination at a single node – Instantaneous intrusion (Plug flow intrusion)

Case 2: Contamination at a single node – Continuous intrusion

Case 3: Contamination at multiple nodes – Instantaneous intrusion (Plug flow intrusion)

Case 4: Contamination at multiple nodes – Continuous intrusion

Node no. 534 was chosen as the contaminated node for cases 1 and 2. This is a location where the sewer line is crossing the pipelines. It is assumed that in case 1, a particular amount of contaminant has entered into the pipeline through a leak at this point. It is also assumed that for the first five minutes from the start of water supply, the contaminant concentration is 100 mg/l at the point of intrusion. The contaminant intrusion stops once water supply resumes because of higher pressure within the pipeline compared to the outside environment.

For case 2, the node 534 is assumed to have continuous intrusion into the pipeline, resulting in the contaminant concentration of 100mg/l in water for the first five minutes after resuming water supply and 10mg/l for the rest of the time for which water is supplied. This is the case when the pressure inside the water pipeline is not sufficient to keep the contaminant outside the pipe. But since the pipe is not empty, the intrusion rate will not be as high as when there was no water in the pipe. Thus it was taken as about 10 percent of the initial intrusion rate.

Case 3 and 4 consider similar situations, but the contaminant intrusion occurring at two different nodes. Node no. 589, which is close to a foul water body, and node no. 487, which is crossed by a sewer line, were chosen for these two
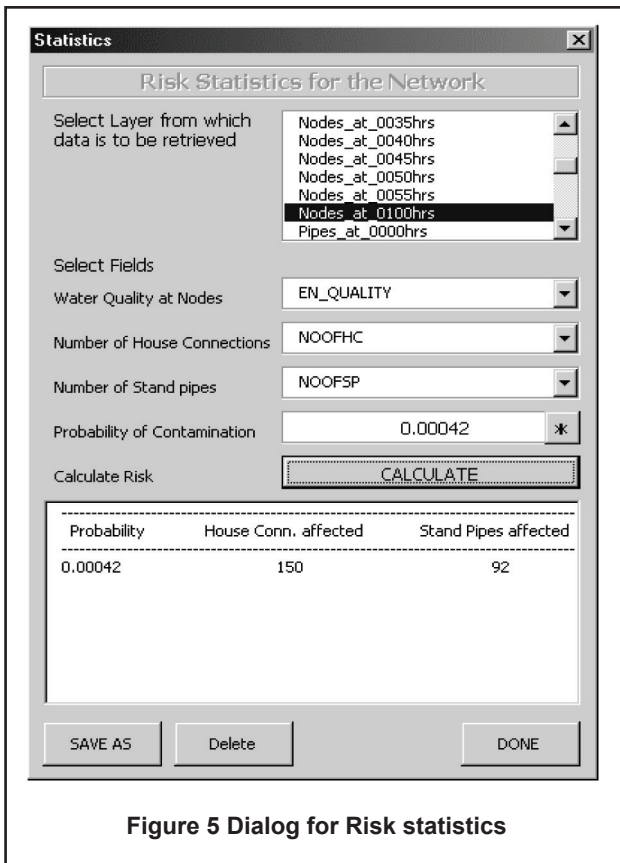
Figure 5 Dialog for Risk statistics

cases. The resulting contaminant concentration in the water and the pattern of variation in intrusion rate was considered same as that of the previous cases.

Water quality simulation for the water supply network of Zone VIII of Guntur was done with the following parameters.

• Analysis was done for head dependent flow at outlets (nodes). The flow coefficient value for the outlets was assumed on an average as 40, where flow unit is litres per minute (LPM) and head in metres. (Flow coefficient value of 40 corresponds to the orifice constant 0.82 and opening diameter of 15mm)

• The node assumed to be affected by contamination (Node no. 534, 589 and 487 in different cases as described in the methodology) is set to be contaminated by a non-reactive contaminant with resultant initial concentration of 100mg/l. The node was set as a "set-point" source with the contaminant being present at the node in the initial five minutes for plug flow cases (cases 1 and 3). For continuous intrusion cases (cases 2 and 4) the contaminant concentration was 100mg/l for the initial 5 minutes and 10mg/l for the rest of the time period.

• Extended period simulation was done for a time period of one hour with a time interval of 10 minutes.

Risk Analysis

One additional menu – Risk Assessment – was added in the GIS template (*.mxt) for fault tree analysis and to retrieve

data from attribute tables about number of house connections and standpipes affected by contamination.

The "Statistics" command in the menu activates the statistics dialog box shown in Fig.5. The purpose of this is to retrieve the data from the attribute tables, the number of house connections and stand pipes in the network affected by contamination. Similar to earlier cases, here also the appropriate feature class and corresponding fields are to be selected from the lists given in the dialog window. Probability of contamination can be either typed in or obtained from the fault tree. On clicking the "CALCULATE" button, the total number of house connections and standpipes at which the chemical concentration is greater than zero is calculated and displayed in the space below.

Spatial Analysis of Results

Various options are available in GIS for spatial analysis of the results. ArcMap provides the "Spatial Analyst" tool for different types of spatial analysis. The inverse distance-weighted method was used to create a buffer region surrounding the nodes affected by contamination. This is according to the assumption that people living within a certain distance from the node will use the water from a particular node. The area covered by the buffer can be measured to understand extend of contamination.

Results and Discussions

Thematic maps of the study were prepared in ArcGIS Desktop 8.3 and the attribute tables were modified by adding the additional fields required. Water supply network analysis model, EPANET 2.0 was integrated to the GIS environment using Visual Basic scripts as explained in the methodology. The input file for EPANET was successfully created from the interactive and user-friendly menus and commands developed. Also the model was simulated using the input file created. The results of water quality analysis for the different cases and various time intervals were loaded to the attribute table of the corresponding thematic maps. After loading to the attribute tables the results were displayed in map using suitable colours to show the variation of contaminant concentration at the affected nodes.

A buffer was created for the contaminated nodes for a distance of 100m around the node. This is under the assumption that people within this distance from the node uses water from those nodes. This was done using the spatial analyst tool in ArcGIS, with the Inverse Distance Weighted (IDW) method of interpolation. This gives the area surrounding a node, likely to be affected by the contamination as shown in Figs 6 and 7.

Retrieving Statistics of Contaminated Nodes

After simulation of the water quality model and loading the results the information on the affected population were obtained. The total number of household connections and standpipes to the nodes affected by contamination was retrieved from the GIS database. This includes all the con-
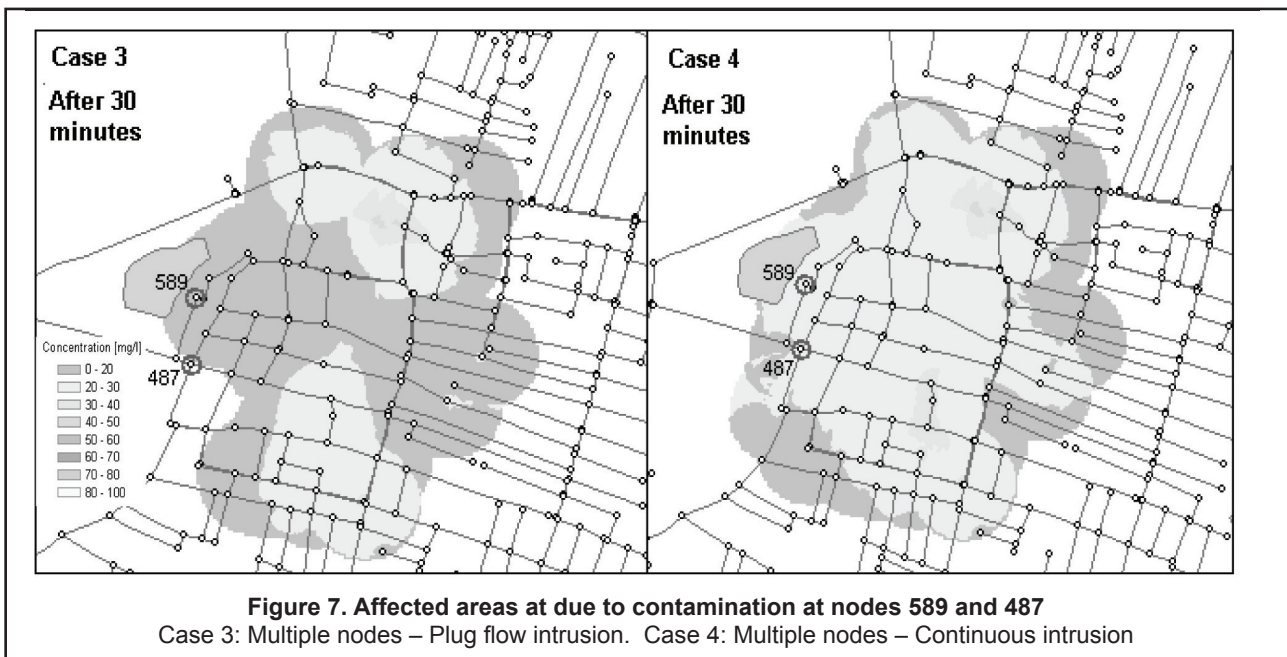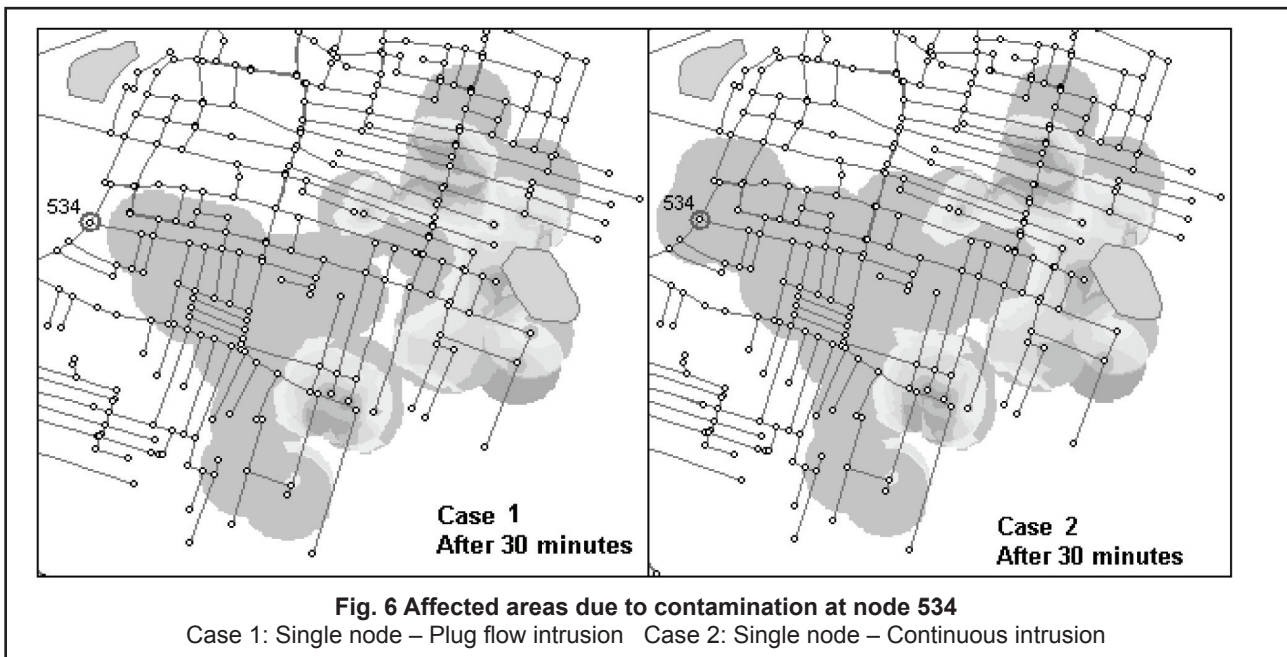
nections from the nodes with contaminant concentration greater than zero. The number of affected connections at different time intervals was obtained and variation is shown in Fig 8. It can be seen from this figure that the continuous intrusion has affected a greater number of nodes compared to plug flow intrusion at any time interval. Also the location of the contaminated node has significant effect on the number of affected nodes. For example, in case 1, node no. 534, which supplied water to a large number of downstream nodes, was contaminated resulting in a greater number of affected nodes compared to case 3. The results obtained for plug flow intrusions (cases 1 and 3) are to be closely analysed. The results displayed show affected nodes at each time intervals. In these cases the nodes affected earlier in the time period may not be considered as affected nodes later, as intrusion is stopped and fresh water starts flowing through those nodes after sometime. But there are chances of health hazards during the time for which the nodes were affected. Thus the actual number of affected nodes will be between the number of nodes affected in the case of plug flow intrusion and that for continuous intrusion.

Maps generated showing the area affected due to contamination also gives insight to the extent of contamination.

The maps are created by assuming that people within a radius of 100m from a node have access to water from that node and are interpolated using the Inverse Distance Weighted method of spatial analysis in ArcGIS.

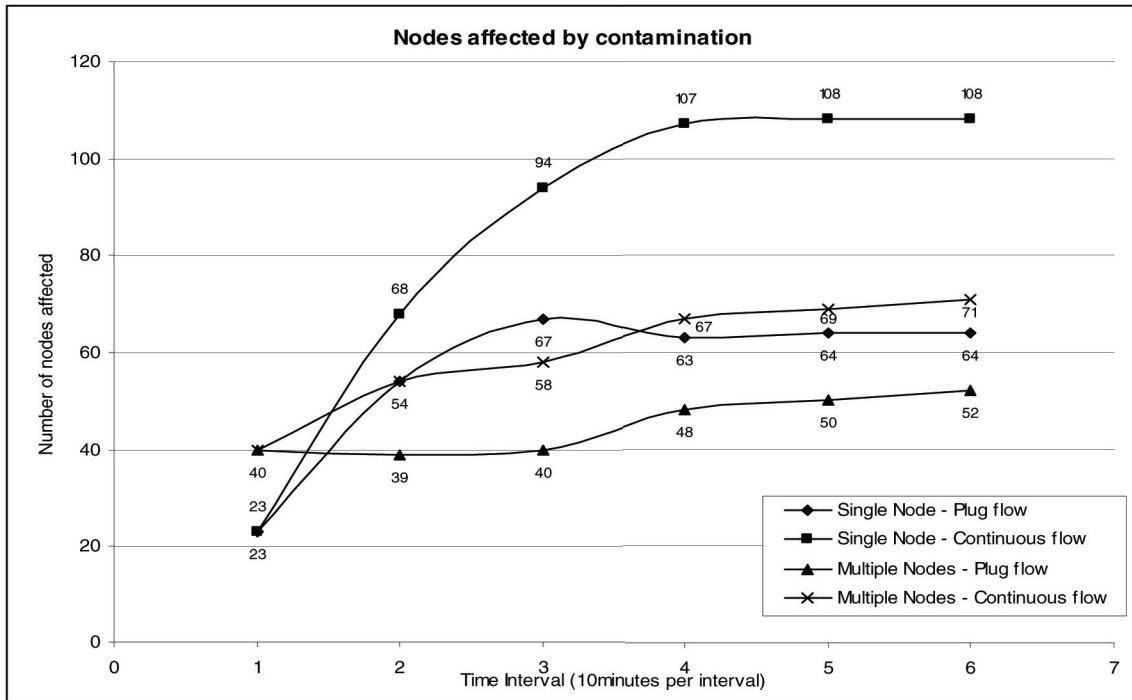These results are important in the final decision-making.

Fig. 6 Affected areas due to contamination at node 534
Case 1: Single node – Plug flow intrusion   Case 2: Single node – Continuous intrusion

Figure 7. Affected areas at due to contamination at nodes 589 and 487
Case 3: Multiple nodes – Plug flow intrusion. Case 4: Multiple nodes – Continuous intrusion

Figure. 8 Statistics of nodes affected by contamination during 1 hour simulation

Figure 9. Alternate path for water flow to nodes bypassing the contaminant affected node (534).

These maps give a better picture of the spread and intensity of contamination over a time span. The final decision on the management policy is to be made by considering the number of nodes, and hence the number of people affected by different events of contamination.

Determination of Alternate Connectivity for the Affected Nodes

In the trial simulation, node no. 534 was assumed to be a leakage point that allowed contaminant intrusion into the water supply pipe. In pracice node 534 would need to be

isolated to prevent contamination as well as to allow repair the leakage.

Using the network analysis tool in ArcGIS, the connectivity to various nodes from the tank, in case of blocking of a part of the network, can be examined. Blocking of part of water supply network to repair the leakage or to prevent contamination continuing can be simulated. It is possible to use the software to investigate whether there is an alternate route to supply water to the downstream nodes.. This is essentially required for the maintenance work to be undertaken that will affect large numbers of people for a long time. If re-routing of the water through the network is possible it will saves money spent on tankers and other alternative means of water supply. The network analyst tool of GIS is used for this analysis. Fig 9 depicts the results of this analysis if node 534 is assumed to be contaminated and is then isolated. Thus 3 pipes that are connected to node 534 were blocked (indicated by an X mark on the pipe), and the target nodes were marked (target nodes are marked as squares). Then the network analysis tool was used to check whether the downstream nodes are connected to the tank through an alternative route. The thicker lines show a possible route to the down stream nodes. Suitable planning before undertaking the maintenance work saves time and money. Determining the alternative routes for rerouting the water supply avoids the need for supply of water by tankers.

Many times it requires case specific decisions to be made. For example; which failure event to be given importance at any point of time? In such cases, the area affected by contamination by the particular event of contamination has to be considered, which can be rapidly obtained from the water quality analysis with GIS. This gives the area to which the contamination has spread. Then depending upon the importance of the area, population density, presence of schools or hospitals etc. decisions can be made on events that require immediate attention.

Thus GIS based risk assessment proves to be an efficient decision support system. It provides an easy way of deciding upon the activities that need to be undertaken immediately, especially in situations of limited resource availability.

Conclusions

From the study reported here, the following conclusions are arrived at.

- Integration of network analysis models with GIS software aids provides a useful decision making tool for water supply management.
- Head dependent flow in intermittent water supply systems can be handled with EPANET 2.0 by imposing the emitter status to the nodes.
- GIS mapping helps in easy prioritization of maintenance activities.

The study can be further extended by detailed investigation of the parameters for network analysis using EPANET. The flow coefficient values may be determined by field experiments. Also the actual concentration of contaminant intrusion and reaction rates can be included in the analysis to get more realistic results. Incorporating information and locations of various features in the map, which will augment the risk assessments, can further enhance GIS maps. An investigation on the type of health hazards due to contaminated water and its classification also enhance the decision making process.

References

Kalbermatten, J. (1989). "Watertech United States: A program for helping developing nations," J. AWWA, 81(10), 39-44.

Rossman, L A (1994) "EPANET Users' Manual", United States Environmental Protection Agency, Centre for Environmental Research Information, Cincinnati, Ohio.

Rossman, L A. and Boulos P F. (1996) "Numerical Methods for Modelling Water Quality in Distribution Systems: A Comparison," Journal of Water Resources Planning and Management, Vol 122(2), pp: 137 – 146

Schindler, D.F. and Garrard, T.P. (1999) "GIS as an active management tool," Water Industry Systems: Modeling and Optimization Applications, Vol. II. Research Studies Press Ltd. Baldock, Hertfordshire, England pp: 97 – 102

Srinivasa Reddy, L.S., Elango, K. (1989). "Analysis of water distribution networks with head-dependent outlets," Civil Engineering Systems, Vol 6(3), pp: 102-110.

Contact address

S Mohan
Professor
Environmental & Water Resource Engg. Division
Department of Civil Engineering
IIT Madras, Chennai 600 036
India

Danimon K
M.Tech Student
Environmental & Water Resource Engg. Division
Department of Civil Engineering
IIT Madras, Chennai 600 036
India

K Vairavamoorthy
Senior Programme Manager
Water, Engineering Development Centre (WEDC)
Department of Civil and Building Engineering
Loughborough University
UK