

PEOPLE-CENTRED APPROACHES TO WATER AND ENVIRONMENTAL SANITATION

**A GIS based spatial decision support system for modelling
contaminant intrusion into water distribution systems**

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The paper presents a GIS based spatial decision support system for modelling contaminant intrusion into water distribution system. Three models have been developed to simulate the process and risk of contamination. A seepage model predicts the contaminant zone of pollution sources and the change of concentration during migration through soil. A pipe condition assessment model ranks the condition of water pipe in terms of the potential of contaminant ingress. An ingress model combines the geometry algorithm with contaminant zone to obtain the potential pollution areas of water distribution pipe. The three models were integrated with ArcView GIS for supporting decision making for risk mitigation. Zone VIII of water supply system in Guntur, India was selected for the case study. The contaminant ingress potential and potential pollution area of water pipes were displayed as thematic maps in GIS. The areas resulting in high risk were identified from the GIS maps. The availability of resources for maintenance activities are limited in developing countries. Thus GIS based spatial decision support system helps to achieve maximum risk reduction.

Introduction

Water distribution system (WDS) is an important component of urban water supply system which conveys water to the consumer from the sources. These systems constitute a substantial proportion of the cost of a water supply system, in some cases as much as half the overall cost of the system. Drinking water transported through such distribution networks can undergo a variety of water quality changes in terms of physical, chemical, and biological degradation. Understanding the sources and process of water quality degradation during distribution has become a priority for water authorities.

Water quality variation during transportation in distribution networks may be attributed to two main aspects of reasons. One is internal degradation, and the other is external intrusion. The internal factors including physical, chemical, and biological reaction with pipe material that degrades water quality. Furthermore, recent evidence has demonstrated that external contaminant intrusion into water distribution network may be more frequent and of a great important than previously suspected. Both continuous and intermittent water distribution network might suffer from the contaminant intrusion problem, and the intermittent systems were found more vulnerable of contaminant intrusion. Intermittent systems of water supply, meets to a great extend the water demands of the public, especially when the available water is less. But since the pipes are often under no or negative pressure, there are always chances of contaminant intrusion.

In developing countries water quantity available for supply generally is not sufficient to meet the demands and one of the most common methods of controlling demand is the use of intermittent supplies (where water supplied only a

few hours a day). A serious problem arising from intermittent supplies, which is generally ignored, is the associated high level of contamination. This occurs in networks where there are prolonged periods of interruption of supply due to negligible or zero pressures in the system. The sources of contaminant intrusion into water distribution network are many and various. But leaky sewer pipes, foul water bodies, and open drainage may be the primary sources for water distribution networks contamination.

By establishing the factors that are most related to contamination, it may be possible to develop control measures to minimise the risk of contaminant intrusion, and improve the management of water quality in drinking water distribution networks. This requires a decision support system (DSS) for source-process-receptor analysis considering both water distribution network and the possible contamination sources. Such decision support systems require handling large amount of data, for which Geographical Information Systems (GIS) will be the best tool. The conjunctive application of GIS and DSS technologies are often known as spatial decision support system (SDSS), which are a class of computer systems aiding decision makers with problems that have a spatial dimension (Walsh, 1992). GIS is a general-purpose technology for handling geographic data in digital form, with the ability to preprocess data into a form suitable for analysis, to support analysis and modeling directly and to postprocess of results (Goodchild, 1993). GIS Technology has been applied for solving various problems in water distribution system. Schindler and Garrard (1999) found that GIS technology can be used to store and retrieve an inventory of the WDS assets. They also described the use of GIS for providing on line monitoring to identify customers at the risk of low pres-

sure in South West Water Services Ltd. The paper discussed a procedure to reflect the overall pressure regime in GIS. It also describes how GIS can be used to operate the system in predictive mode. Yazdan (1998) developed a GIS based predictive tool which can be used to reduce maintenance by increasing the preventive and predictive activities. For a particular entity, the predictive modelling tools, comprised of a collection of techniques, can be used to determine the likelihood of failure or failure rate.

A SDSS was developed in this paper by integrating modelling tools with ArcView GIS. GIS for extracting information to generate model inputs and display model outputs spatially. Three models have been developed to support assessing the risk of contaminant ingress into water pipe, i.e., contaminant seepage model, pipe condition assessment (PCA) model and contaminant ingress model. Contaminant seepage model (Yan and Vairamoorthy, 2004) simulates the movement of contaminant in the soil from pollution sources to water distribution pipes. The output from this component will be the contaminant zone (CZ) of pollution sources and the variable concentration of contaminant during its migration through the soil. Pipe condition assessment component ranks contaminant ingress potential for water pipe. The proposed PCA model (Yan and Vairamoorthy, 2003) accounts for both certainty and uncertainty factors through using fuzzy based techniques. The distance base multi-criteria decision making (MCDM) method - fuzzy composite programming (FCP) has been used for PCA. Contaminant ingress model (Yan and Vairamoorthy, 2002) identifies locations along the water distribution pipes where it is likely that contaminants may enter. Combining the outputs from the above two models with geometry algorithms, it will be possible to calculate pollution prone areas (PPA), affecting the water distribution pipes.

The objective of the study reported here were to develop an integrated model by combining contaminant ingress models and ArcView GIS to determine the locations that are prone to contamination, to apply the integrated model to real world water supply system and to evolve strategies for management of water supply, and mapping of risk areas using GIS.

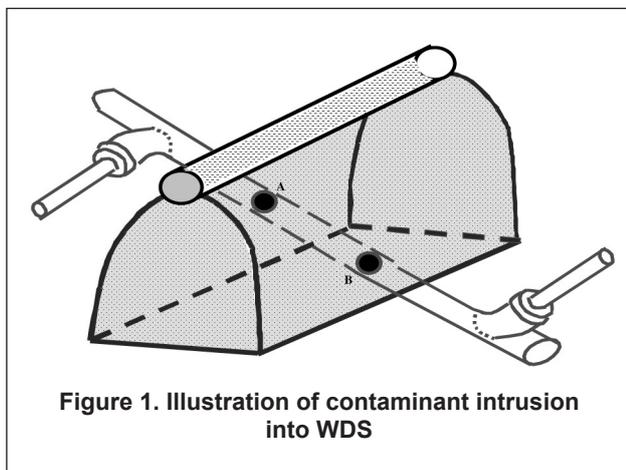


Figure 1. Illustration of contaminant intrusion into WDS

Integration of mathematical modelling tools and GIS provides a feasible and affordable approach for many water utilities for analyzing the system and assessing the risk. The applicability of the developed SDSS has been applied to zone VIII of the Guntur water distribution system, India.

Methodology

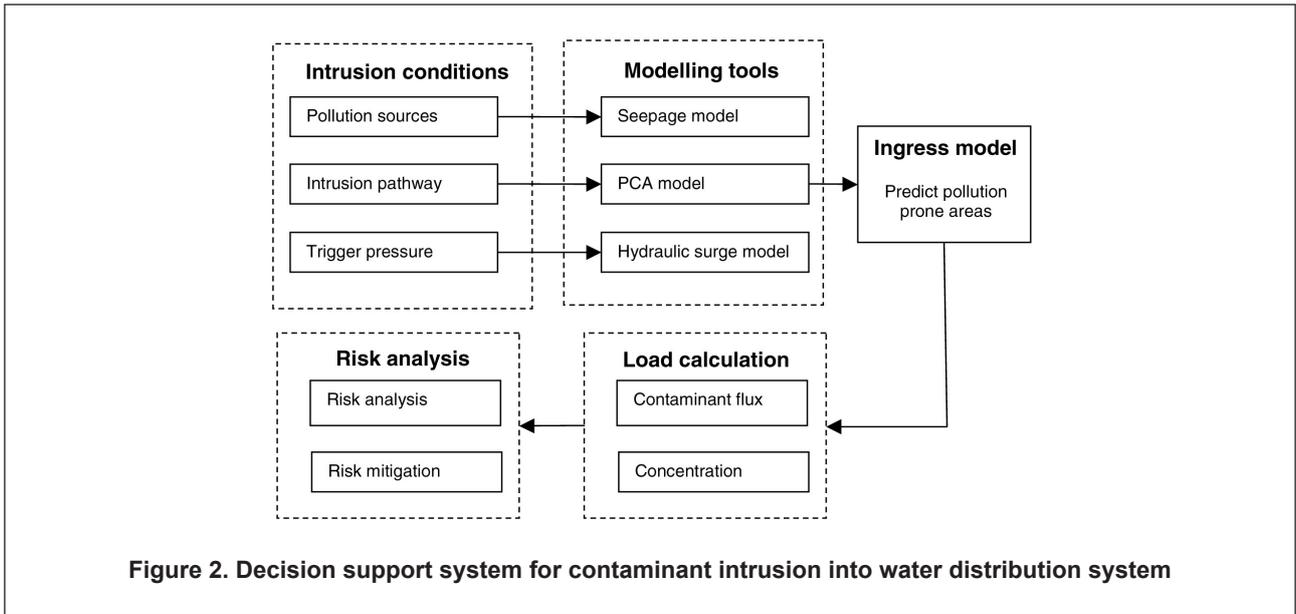
Figure 1 gives the illustrations of contaminant intrusion into WDS where considers a water distribution pipe passing underneath a pollution sources (for example a leaky sewer). Contaminant from the pollution source seepages through soil and migrates to drinking water pipe which is potential contaminant for intrusion when other conditions are met simultaneously (such as cracks and internal pressure for water pipe). The pollution sources usually develop a contamination zone (CZ) shown as envelop in Figure 1. Therefore if the water pipe or part of water pipe is within CZ, there is a potential for contaminant intrusion into water pipe through the cracks.

According to the conceptual formulation established above, contaminant might intrude into water distribution pipe provided that the following conditions are met simultaneously:

- Contaminant source.
such as leaky sewer, polluted water bodies etc.
- Intrusion pathway.
Portal along water pipe for contaminant entry such as crack, leaks, etc.
- Trigger pressure.
The external pressure of contaminant must be higher than the internal pressure of water flow by which contaminant can entry into water distribution pipes.

Among the above three conditions that essential to contaminant entry, the first two are necessary for both continuous and intermittent system, but the last condition (trigger pressure) may vary because of the different characteristics of these two systems. The intermittent water distribution systems are empty during most hours of the day when contaminant might enter. Whereas the continuous water distribution networks are pressurized all the time where no means for contaminant intrude except hydraulic transient occurs resulting in low or negative pressure. Hydraulic transients are pressure waves that propagate in the pipe system as a response to abrupt changes in water flow, which can result in high pressure to burst a pipe or cause low or even negative pressure to bring undesirable material into distribution systems.

The relationship of the three conditions for contaminant intrusion and the associated models for prediction of such conditions can be illustrated in Figure 2. The modeling tools are used to investigate the conditions that are necessary for contaminant intrusion into water distribution network. More specifically, contaminant seepage model predicts contamination zone (CZ), which is the potential contaminant source and the associated contaminant concentration. This components concerns numerical modeling water flow and



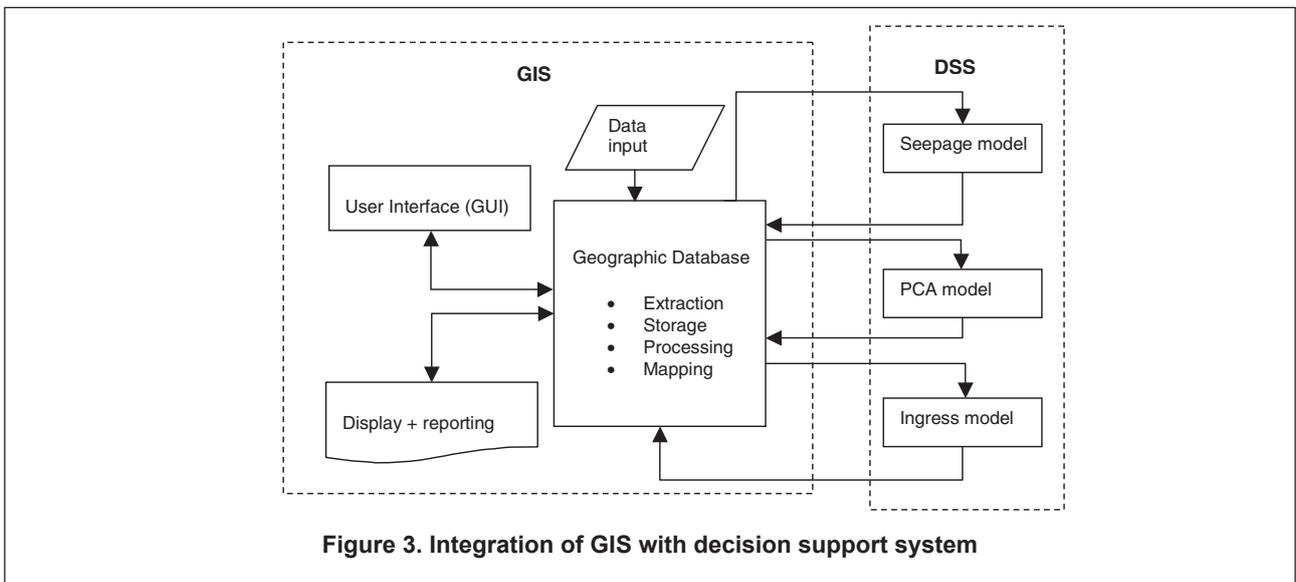
contaminant transport in unsaturated soil. Two-dimensional, second-order, parabolic partial differential equations (PDEs) i.e. Richard equations and advection-diffusion equations that account for water flow and contaminant transport respectively has been solved numerically using adaptive method of line (MOL). Numerical adaptive method of line is more suitable for modelling such purpose since that water flow and contaminant transport in unsaturated soil has a sharp water content moving front.

Water pipe condition assessment model evaluate the potential of contaminant ingress into water pipe. There are many factors attributing to the deterioration of water pipes among which many are vague and of imprecise information. The proposed water pipe assessment model ranks the condition of water pipe accounts for both certainty and uncertainty factors by using fuzzy based techniques. The distance base multi-criteria decision making (MCDM) method - fuzzy composite programming (FCP) has been applied to combine

multi-level pipe condition indicators to form a single indicator to rank the condition of pipe.

For continuous water distribution system, a surge model is required to simulate the internal pressure change due to which hydraulic transient occurs in water distribution network resulting in low or negative pressures. Thus an opportunity exists where contaminated water exterior to pipe could enter when low or negative pressure condition occurs. For intermittent water distribution system, the system will empty many hours of the day providing outdoor for contaminant intrusion during non-supply hours.

Contaminant ingress model identifies locations along the water distribution pipes where it is likely that contaminants may enter. Combing the outputs from the above two models with spatial analysis, pollution-prone area that affecting the water distribution pipes can be located in water distribution systems.



The three components have been integrated into GIS platform. GIS provides model inputs extracting data from Geographical database. The modeling results are presented in GIS graphic user interface (GUI) that shows the potential areas that threat to contamination and ranking of water pipe ingress potential. The risk of contamination is obtained by overlaying these two model output themes. The interaction between mathematical models and GIS is outline in Figure 3. The load calculation and risk analysis is embodied into ingress model.

The Risk Builder Model

The risk builder model as shown in Figure 4 is written with the view to supply it as an extension to the commercial GIS software Arc View. The model is written in Avenue macro language of Arc View GIS. The contaminant ingress and pipe condition assessment models are integrated with this model using the tight coupling approach. The extension adds a new document named "RiskBuilder" to the Arc View. The user friendly model interface helps the user in loading the input data, editing the input data, displaying the input themes, generating the input files to run the contaminant ingress and pipe condition assessment models. It also helps in visualizing the results generated both in table format and in map the form.

The model mainly consists of four main menus namely, Data Preparation, Ingress Model, Pipe Condition Assessment and Risk Assessment. These menus are added to the RiskBuilder document of the Arc View. The RiskBuilder document also contains shortcut buttons and tools from which you can directly execute certain scripts rather than from pull down menus.

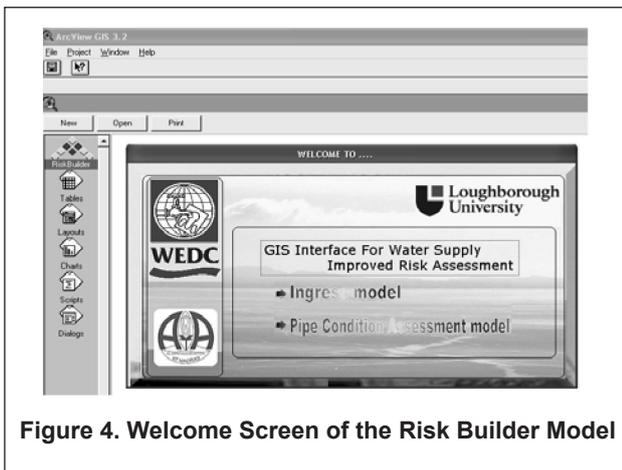


Figure 4. Welcome Screen of the Risk Builder Model

Data Preparation: The *Data Preparation* menu shown in Figure 5 helps in adding the themes with their respective attribute data to the view. This menu also helps in modifying/editing the attribute values of the themes. This menu also helps in creating new themes and tables from the ASCII data files.

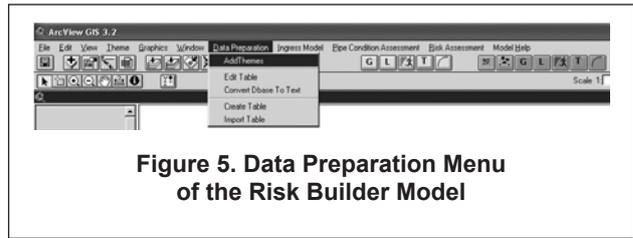


Figure 5. Data Preparation Menu of the Risk Builder Model

Ingress Model: The *Ingress* menu given in Figure 6 guides the user through various steps from data definition, input file generation to the output display in tabular and map form.

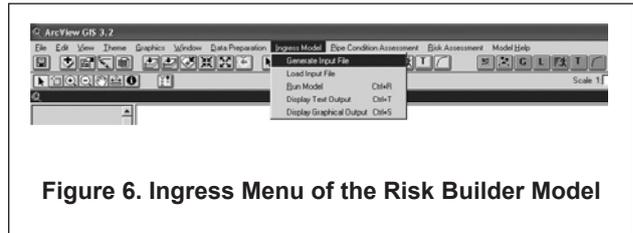


Figure 6. Ingress Menu of the Risk Builder Model

Once the data is loaded with the help of *Data Preparation* menu, the *Generate Input File* menu shown in Figure 7 helps in defining the data files and tables. The defined input themes and their respective attribute data is then used to generate the input data file for Ingress model which is then saved to the location preferred by the user (Figure 8, 9 and 10). The input data file is then loaded using the *Load Input File* menu (Figure 11). The Ingress model is executed through the *Run Model* menu. The resultant output file is stored in the location as preferred by the user. This output file can then be displayed in the tabular format using the *Display Text Output* or in the map format using the *Display Graphical Output*. The map display output helps in visualising the result of the contaminant ingress zones in much better wave than viewing the output file in the tabular format. The Display Map Output generates new shape file from the ingress output showing those pipe areas which will be under contamination.

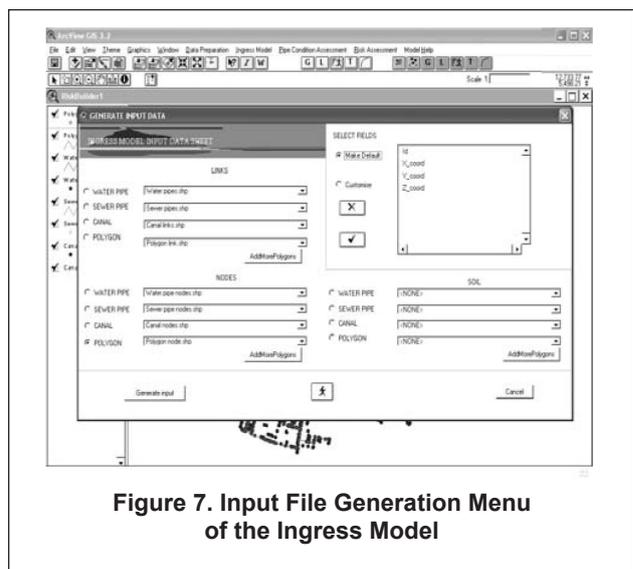


Figure 7. Input File Generation Menu of the Ingress Model

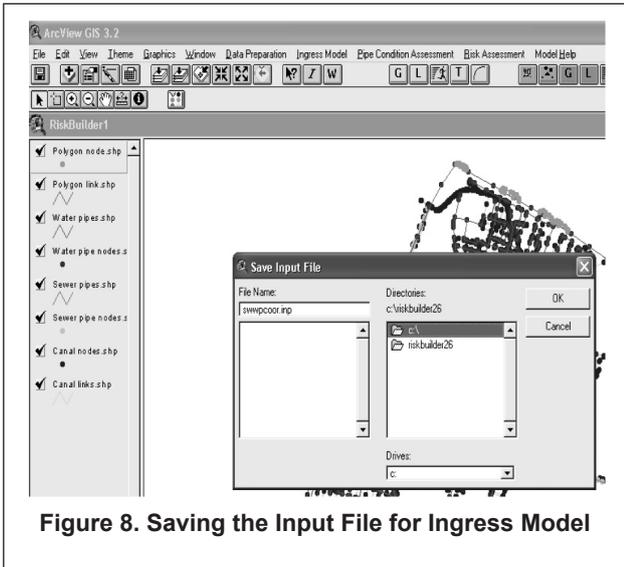


Figure 8. Saving the Input File for Ingress Model

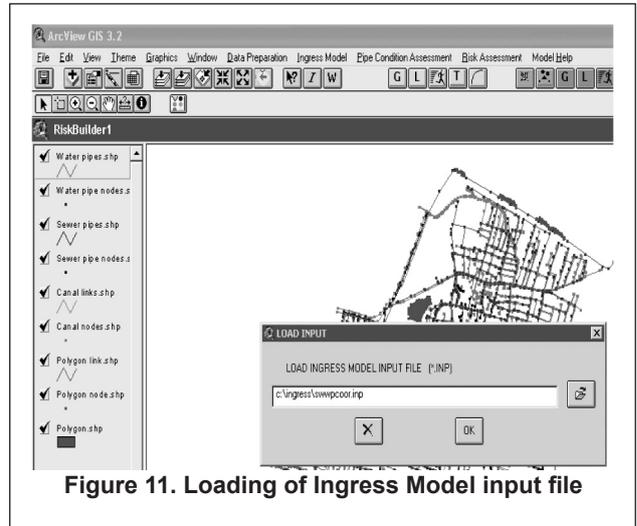


Figure 11. Loading of Ingress Model input file

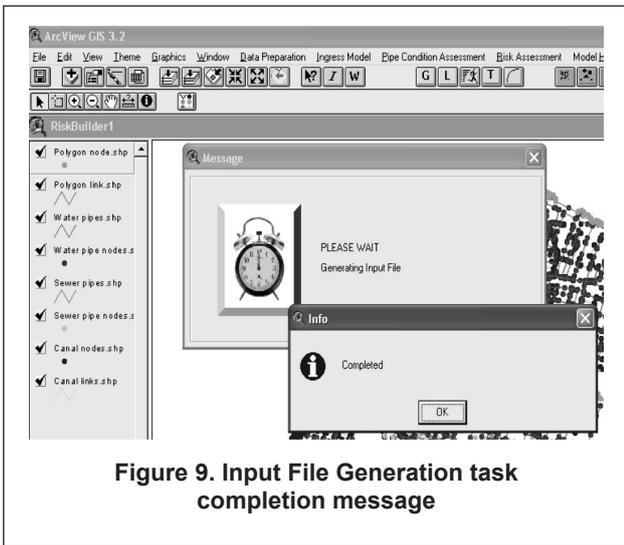


Figure 9. Input File Generation task completion message

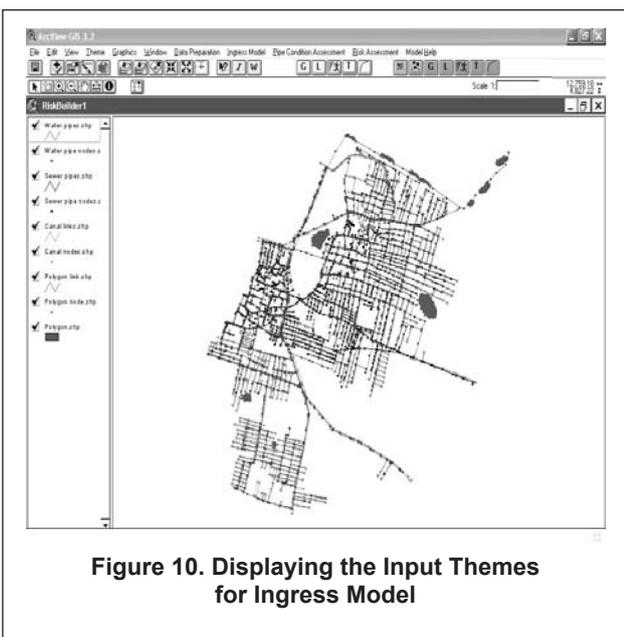


Figure 10. Displaying the Input Themes for Ingress Model

Pipe Condition Assessment: The *Pipe Condition Assessment* menu (Figure 12) guides the user through various steps from data definition, input file generation to the output display in tabular and map form. The data is loaded with the help of *Data Preparation* menu, the functions and weights to the pipes are assigned using the *Generate MF* (Figure 13) and *Generate Weightings* menus (Figure 14) respectively. *Generate Input File* menu (Figure 15) helps in defining the data files and tables. The defined input theme and its attribute data is then used to generate the input data file for Pipe Condition Assessment (PCA) model which is then saved to the location preferred by the user. The input data file is then loaded using the *Load Input File* menu (Figure 16). The PCA model is executed through the *Run Model* menu. The resultant output file is stored in the location as preferred by the user. This output file can then be displayed in the tabular format using the *Display Text Output* or in the map format using the *Display Graphical Output*. The graphical output displays the water distribution network map divided into 11 different categories starting from Extremely Bad to Extremely Good depending on the condition of the pipes assessed by the PCA model.

Risk Assessment: The *Risk Assessment* menu overlays the two output themes from Ingress model and Pipe Condition Assessment model and generates new theme called risk theme which shows which part of the pipe network is in High, Medium or Low Risk.

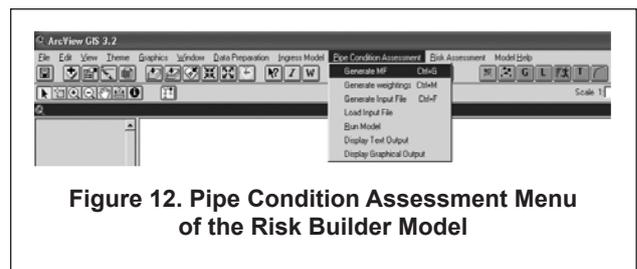


Figure 12. Pipe Condition Assessment Menu of the Risk Builder Model

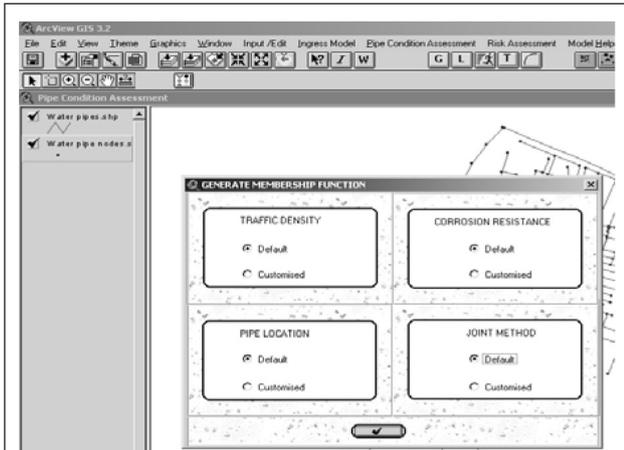


Figure 13. Generating Membership Function for Pipe Condition Assessment

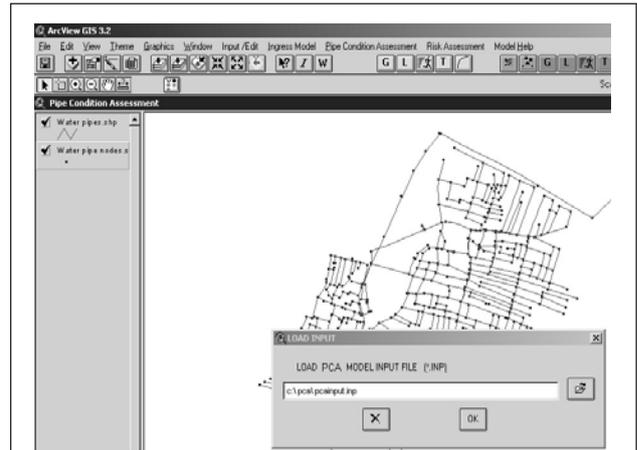


Figure 16. Loading the Input File for Pipe Condition Assessment

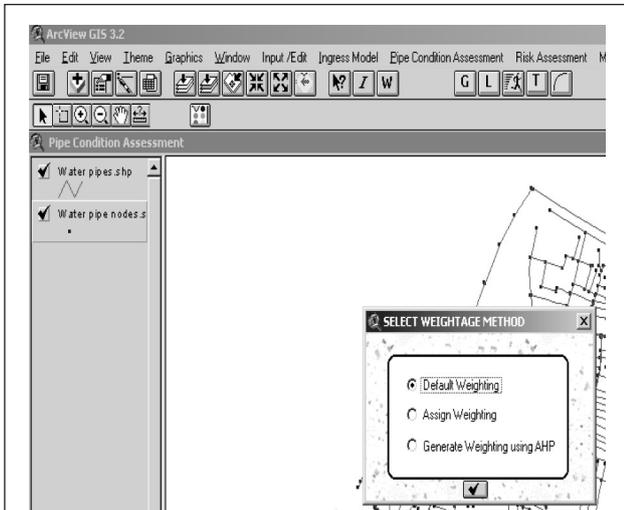


Figure 14. Generating the Weights for Pipe Condition Assessment Model

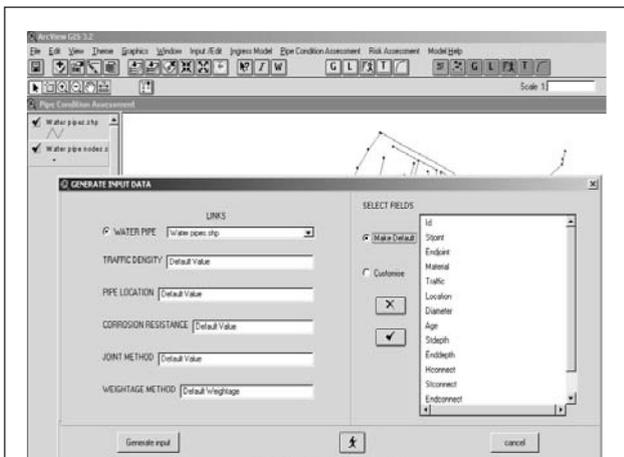


Figure 15. Generating the Input File for Pipe Condition Assessment

A Case Study

The developed spatial decision support system has been applied to a case study area in Guntur city, India. Water contamination frequently occurs in this area due to the lose integrity of water distribution system and the adverse conditions where pipes are laid. There is a need for decision making tool to locate the areas of contamination and analyze risk of contaminant ingress into water pipe. GIS based SDSS provides better solution for such purpose.

Study Area

The site chosen for study is B. R. stadium zone in Guntur City, Andhra Pradesh, India. As in most parts of the country, intermittent water supply system is adopted here. Water is supplied through pipe networks for 1 hour per day. Zone VIII have a population of about 60,000 and area of 4 km². Various pollution sources existing in this zone are prone to contaminate drinking water supply. For example, there are various points along the pipe network where it passes through open drains; laid under foul water bodies; the sewage water flows just over the pipes. Frequent occurrence of contamination in water distribution system has been reported in this zone.

The underground sewer pipe runs almost parallel to or even above the water supply pipelines. If the drinking water pipe had developed a crack or leak (this is unavoidable in most system), the sewage enters the pipeline leading to contamination. The sewer network only covers a small part of zone VIII as a result most sewage is directly discharged into open drains (canal). Considerable amount of seepage occurs from open drains. Since the open drains are at ground level, always there is a potential of seepage reaching water supply pipes leading to contamination. Stagnated water is found at the depressions especially during rain. Water supply lines passing beneath such water bodies are at risk of contamination.

Leakages in water distribution system are common phenomena in this area. Frequent leakages from sewer

networks have also been observed. As the field survey revealed, there occurs 7-8 pipe leakages a day. Also there are frequent leakages and overflows from sewer pipes and drains due to blocks. There are pipelines passing directly through open drains. Contamination of water, by mixing of sewage with drinking water supplied was reported at many locations in zone VIII. These features reveal the high level of risk involved in water supply system of the zone. Since, majority of the population depends on public water supply; any contamination in the network affects large number of people.

Potential Pollution Areas

The contaminant seepage model produces the contaminant zone of pollution sources. Geometry algorithm is employed for spatial analysis of water pipe and contaminant zone. As a result, contaminant ingress model determines the areas along water distribution pipe that are prone for contaminant ingress. These potential pollution areas will be the possible points required for monitoring or taking action to mitigate the risk. Additional analysis e.g. pipe condition assessment is required in order to assess the risk of such potential contamination posed on drinking water distribution systems.

The GIS Risk Builder is applied to this case study area for risk analysis of contaminant intrusion into water distribution pipe. The three layers of pollution sources i.e. sewer network, open drains (canal) and foul water bodies and the layer of water distribution system have been displayed as different themes in ArcView GIS, as shown in Figure 10. The Risk Builder generate input file for ingress model by extracting information from these four thematic maps. Then the Risk Builder runs the Ingress Model and displays the output within GIS as an additional theme namely "Areas of Contamination". The output of ingress model is shown in Figure 17.

Contaminant Ingress Potential

Water distribution pipes are in different condition due to their variety in physical, environmental and operational

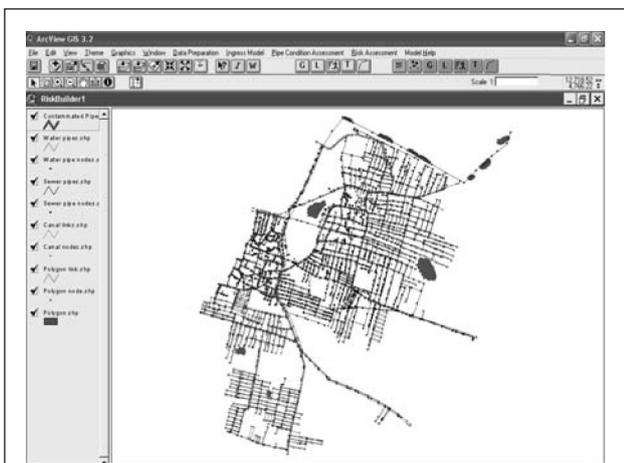


Figure 17. Displaying the Results of Ingress Model

condition. The risk of contaminant intrusion into water pipe depends on the condition of water pipe in addition to the potential pollution areas. A water pipe condition assessment model is developed and integrated into Risk Builder to assess the possibility for contaminant intrusion into water distribution pipes.

The water pipe is clustered into different groups according to their similarity in condition. In this case study, fuzzy classification is used to classify water pipe into 11 groups range from extremely bad to extremely good. A fuzzy membership function is assigned to each group to distinguish water pipe condition in a vague fashion. Therefore each pipe has a membership function consisting 11 discrete values representing the membership belonging to a certain group. These 11 groups are displayed in ArcView GIS as a theme named "Ingress Potential", as shown in Figure 18.

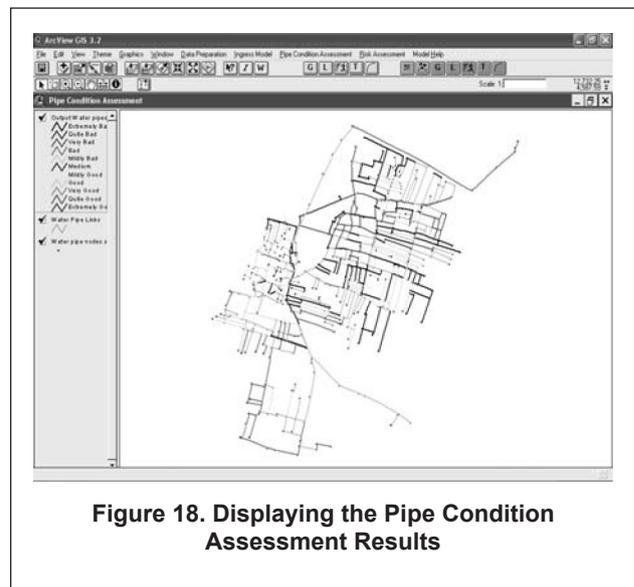


Figure 18. Displaying the Pipe Condition Assessment Results

Risk Assessment

GIS based risk assessment proves to be an efficient decision support system, especially involving a bulk amounts of spatial data. It provides an easy way to display spatial data and interpret spatial modelling results. The risk of contaminant ingress into water pipe is obtained by overlaying the two themes of potential pollution areas and contaminant ingress potential. The risk for contamination is ranked as three levels, i.e. high, medium and low. The thematic map is shown in Figure 19.

Summary and Conclusions

The objectives of the study were to develop a spatial decision support system for contaminant intrusion into water distribution system. The developed SDSS was applied to a real world water supply system to obtain risk areas of contamination.

For this purpose, three models have been developed to assess the risk of contaminant ingress into water distribution system are integrated into ArcView GIS using tight coupling

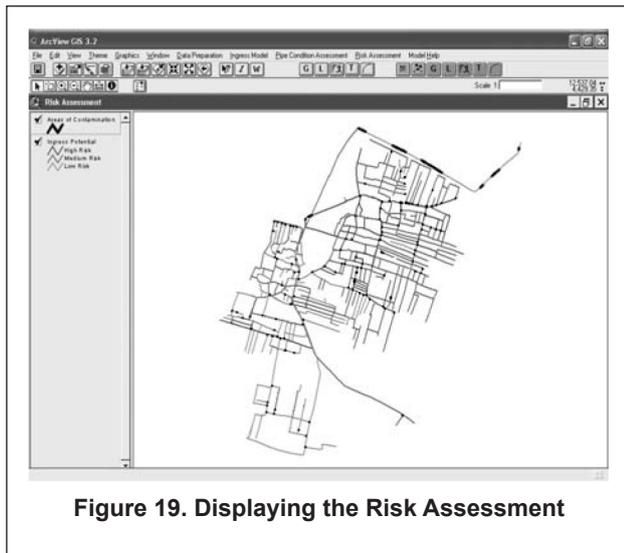


Figure 19. Displaying the Risk Assessment

approach. The data required for analysis was retrieved from the GIS tables and the results were appended to the tables and displayed as thematic maps. The developed modelling tools and software package have been applied to a water distribution network in Guntur, India. Thematic maps have been generated from the model outputs showing the areas of contamination, the ingress potential and the risk of contaminant ingress.

The developed SDSS package provides useful tools for water utilities to manage their water distribution asset. The developed pipe condition assessment model ranking the water pipes in terms of their deterioration is useful to prioritize water pipe rehabilitation under tight financial constraints. The ingress model predicts the areas of contamination which will assist engineers to choose the point for water quality monitoring. The risk obtained from coupling the above two outputs enables engineers to prioritise locations in water distribution system for risk mitigation.

It is anticipated that the developed SDSS for risk management of contaminant intrusion into water distribution system will find ultimate application in water utilities, especially in developing countries where intermittent water supply are norm. The developed modelling tools facilitated within GIS will aid engineers to improve the understanding of contamination occurrence in water distribution system.

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Note

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