

# A spatial decision support system for pipe-break susceptibility analysis of municipal water distribution systems

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## Abstract

Municipal water distribution maintenance is very important for sustainable urban development. Water pipe-breaks result not only in disrupting service but also in significant loss of water, which otherwise could have been sold to the consumer. In countries where water is scarce, such as South Africa, water losses can be detrimental to the living standard of people. Water pipe-breaks can furthermore cause extensive damage to nearby lower-lying properties.

Existing decision support systems available in the field of water distribution system maintenance mainly focus on leak detection and pipe rehabilitation/replacement strategies. These existing systems, however, do not address the actual causes of pipe-breaks.

This paper reports on the development of a spatial decision support system (SDSS) for pipe-break susceptibility analysis. The engineer (or public works administrator) can apply the SDSS to model the complex pipe-break phenomena in a municipal water distribution system in order to identify pipes susceptible to breaking. This should promote more informed decision-making on preventative maintenance measures to be taken and their prioritisation.

The SDSS has already been successfully applied to the water distribution system of Paarl (a medium-sized town in South Africa).

**Keywords:** pipe-break; pipe-break susceptibility analysis; water distribution system; pipe age; air-pockets; tree-roots; total break susceptibility, SDSS, GIS, fuzzy logic

## Introduction

This paper reports on the development of a spatial decision support system (SDSS) for pipe-break susceptibility analysis of municipal water distribution systems. The SDSS can identify pipes susceptible to breaking and therefore promote more informed decision-making on preventative maintenance measures to be taken and their prioritisation. The rate of pipe-breaks in a water distribution system can thus be reduced. Newly planned water distribution systems can similarly be tested with the SDSS for high pipe-break susceptibility. In this way designs can be altered or improved before commencing with the actual construction. The SDSS also has special functionality incorporated for pipe-break impact assessment with regard to water loss (i.e. the modelling of the outflow rate at pipe-breaks) and possible damage caused to nearby lower-lying property (such as structural damage and the ruining of swimming pools, gardens, carpets, etc.). These two impact assessment functionalities, however, will not be discussed in this paper, since the focus of this paper will be on pipe-break susceptibility analysis only.

The SDSS design is based on the concepts of information systems theory, fuzzy logic, object-oriented modelling and pipe-break theory. The pipe-break susceptibility analysis model of the SDSS is based mainly on existing pipe-break theory (which is a highly specialised field in civil engineering) and fuzzy logic (the modelling of complex, interrelated factors where partial truth, i.e. the grey area between true and false, plays a significant role). The model has been tested and calibrated successfully (Sinske, 2002) by comparing the model results with the actual pipe-break occurrence data collected and made available by the Paarl Municipality,

Western Cape Province, South Africa.

In the following sections the SDSS system functionality, the system architecture of the SDSS and finally, the system application are described.

## System functionality

The SDSS has special functions and operations to support the following pipe-break susceptibility analyses, viz. pipe age, air-pocket formation and damage to pipes by tree-roots. At this stage, with the available digital data on the study area, only these three important pipe-break causes can be modelled accurately with the SDSS. The SDSS has, however, been designed in such a way that it can easily be extended to model most of the other pipe-break causes such as corrosion, aggression, low/high temperature, temperature differentials, differential settlement, external impact and pressure surges (Morris, 1967; Böhm, 1993; Sinske, 2002).

The SDSS users (e.g. the system administrator, SDSS operator, SDSS analyst and public works administrator) can access the system functionality on different user access levels. The graphical user interfaces (GUIs) will adapt accordingly so that only the relevant user functionality is made available.

The SDSS furthermore provides powerful object-query functionality and manipulation operations to explore the solution space. The system supports fuzzy logic-based analysis. Functionality is also included to combine the results of separate analyses by using a multi-factor evaluation process.

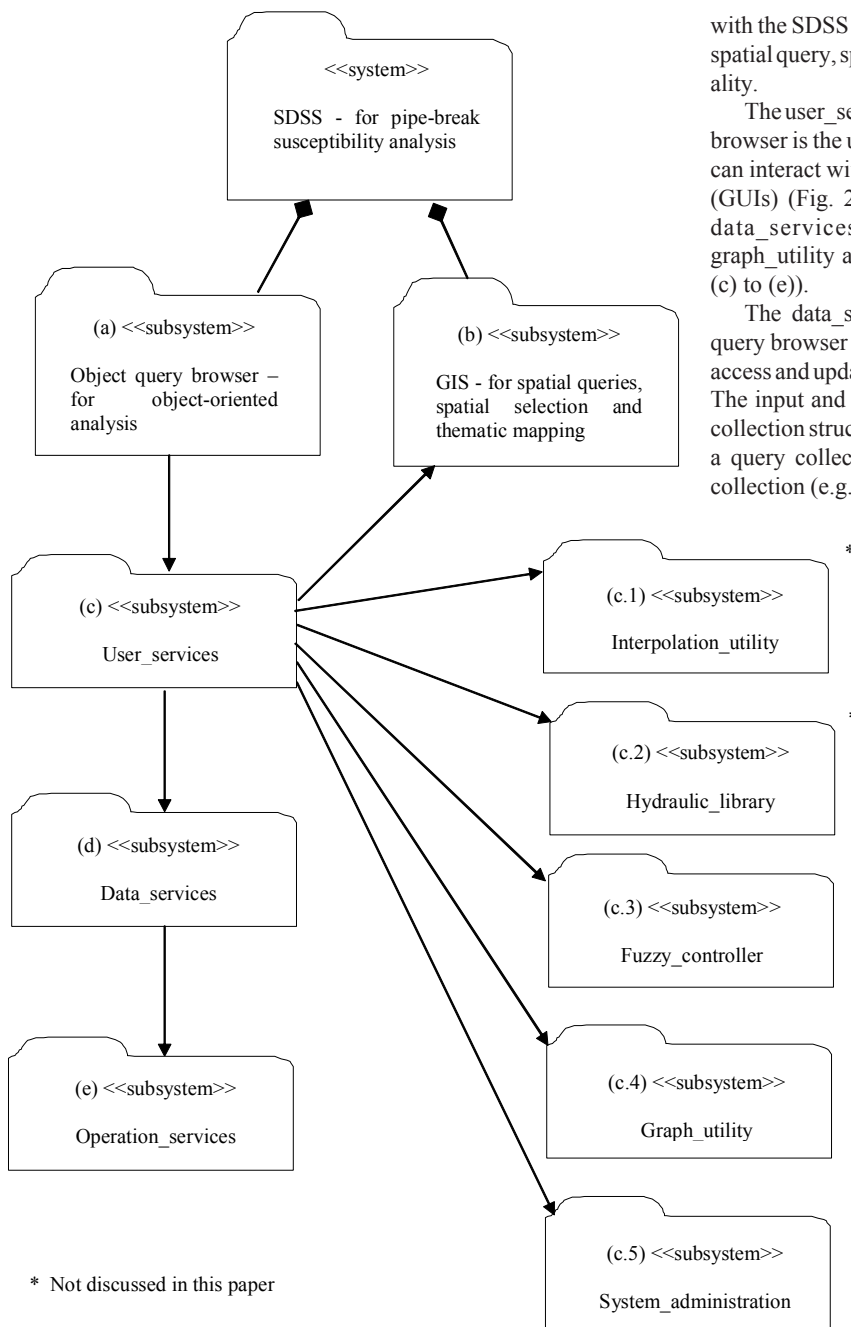
Additionally, the SDSS has functionality incorporated to compare model results with actual pipe-break occurrence. Hereby user-specified factor weights and the decision rules applied in the model can be calibrated.

Finally, graphs, cumulative distribution graphs and thematic maps of the model results can be compiled.

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**Figure 1**  
SDSS architecture

## System architecture

From a design architectural modelling view, the SDSS for pipe-break susceptibility analysis can be grouped into the subsystems as indicated in Fig. 1. This arrangement of subsystems can provide a platform to attain the aforementioned basic system functionality.

The SDSS for pipe-break susceptibility analysis is composed of two equally important subsystems, viz. an object query browser and a geographical information system (GIS) (Figs. 1 (a) & (b)). The object query browser (Fig. 2), which is written in Visual Basic for Applications (VBA), can be regarded as the control panel of the system from where all the query, manipulation and display functionality can be accessed. ArcView 3 from ESRI (Fig. 3) is linked

with the SDSS as GIS subsystem (Fig. 1 (b)) for providing the spatial query, spatial selection and thematic mapping functionality.

The user\_services subsystem (Fig. 1 (c)) of the object query browser is the user interface of the system with which the user can interact with the SDSS via the 7 graphical user interfaces (GUIs) (Fig. 2). The GUIs provide access to the GIS, the data\_services, operation\_services, fuzzy\_controller, graph\_utility and system\_administration subsystems (Fig. 1 (c) to (e)).

The data\_services subsystem (Fig. 1 (d)) of the object query browser contains functions and operations to maintain, access and update the data in the object-oriented data structure. The input and output data of the SDSS can be arranged in a collection structure known as query collections. Each object in a query collection can then also have an associated query collection (e.g. a pipe node has associated pipes connected to it). The functions to view and maintain the query collections and associated query collections can be accessed via the navigation GUI (Fig. 2) of the object query browser. The query collections can also be grouped via the navigation GUI in a tree-like structure for a better overview (Fig. 2).

The operation\_services subsystem (Fig. 1(e)) of the object query browser contains the special functions and operations for pipe-break susceptibility analysis. The SDSS users can access these functions and operations of the object query browser via the three sub-GUIs of the attributes GUI on different data access levels viz. pseudo-collection level, collection level and tree level (Fig. 4). The scope of the query will determine which data access level is to be applied.

The debug mode checkbox located in the attributes GUI (Fig. 4) can be checked. When the apply button is clicked, the program will temporarily stop and display the VBA editor with the program cursor located in the source code listing of the selected function or operation. The SDSS user can then customise the source code in an indicated editable region (i.e. customise the function/operation behaviour) and resume program execution.

The fuzzy\_controller subsystem A-B Flex 2.50a from Allen-Bradley Co. (Fig. 5) is linked to the SDSS (Fig. 1 (c.3)) to extend the object query browser functionality in order to support fuzzy inferencing (Klir and Yuan, 1995; Chang, 1997). Fuzzy inferencing is necessary for modelling of some complex, interrelated factors affecting pipe-break susceptibility. The fuzzy controller can be accessed from the fuzzy GUI of the object query browser (Fig. 6) where also the fuzzy input and output port variables should be specified.

The graph\_utility subsystem (Fig. 1 (c.4)), accessible via the graphs GUI of the object query browser, provides functionality to compile graphs and cumulative distribution graphs of the SDSS results (Fig. 7). The latter can be examined visually to find appropriate classification categories for the SDSS results.

The system\_administration subsystem (Fig. 1 (c.5)) provides

access to the administrative functions of the SDSS for managing the user names, passwords and corresponding user access rights. The GUIs of the SDSS will (at start-up) adapt according to the user profile of the user that is currently logged in, making only relevant functionality available. The system administrator can access the administration subsystem via the administration GUI of the object query browser.

### Pipe-break susceptibility analysis using the SDSS

The SDSS pipe-break susceptibility analyses taking into account the effects of pipe age, air-pocket formation and tree-roots will be discussed in turn. Model calibration will then be described followed by a presentation of the total pipe-break susceptibility analysis to model the combined effect of the three pipe-break causes.

### Susceptibility to breakage due to pipe age

The pipe-break susceptibility analysis due to age is a very straightforward analysis especially when digital records are available on the pipe installation and replacement dates. The SDSS operator can simply apply the quick query facility (Fig. 4) to query these date attributes to find the new and old pipes in the network. Two categories should be sufficient, since age is only a general indicator for pipe-break susceptibility (O'Day, 1983). Pipes can be considered as old if they are older than 25 years. This should not be taken as a fixed rule and is largely dependent on the type of environment the pipes have been in contact with.

If digital records on pipe age are not available then the year in which the residential areas were established in which the pipes are located, can be used to estimate the pipe age. The value of the pipe age attribute can be derived from the age of the residential area via a GIS overlay operation or a spatial selection operation (Sinske, 2002).

The results from an age analysis should always be used in conjunction with other pipe-break susceptibility analyses (see **Total pipe-break susceptibility**), since age alone is not a very accurate indicator of pipe-break susceptibility.

### Susceptibility to breakage caused by air-pockets

The SDSS is equipped with special query functions and manipulation operations to support pipe-break susceptibility analysis based on seven different types of air-pocket formations in a network, viz.:

- at long pipes with flat slopes
- at pipes with blank ends
- at pipes with changes in diameter
- at nodal high points

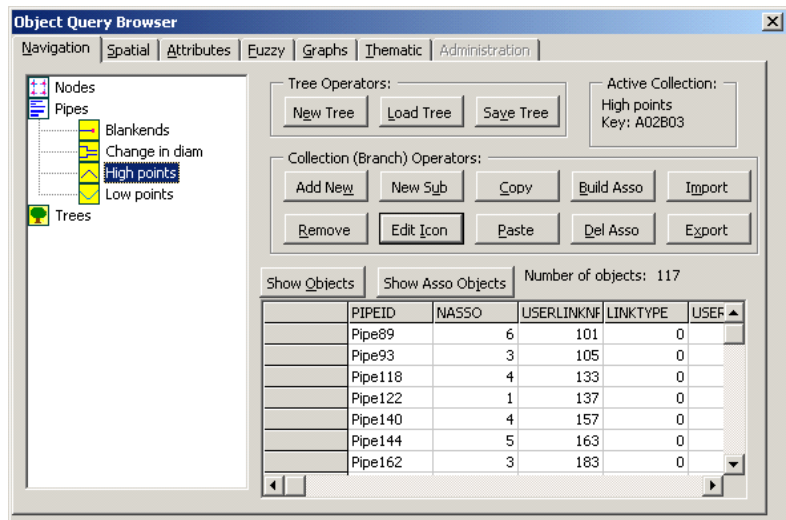


Figure 2  
Object query browser: Navigation GUI

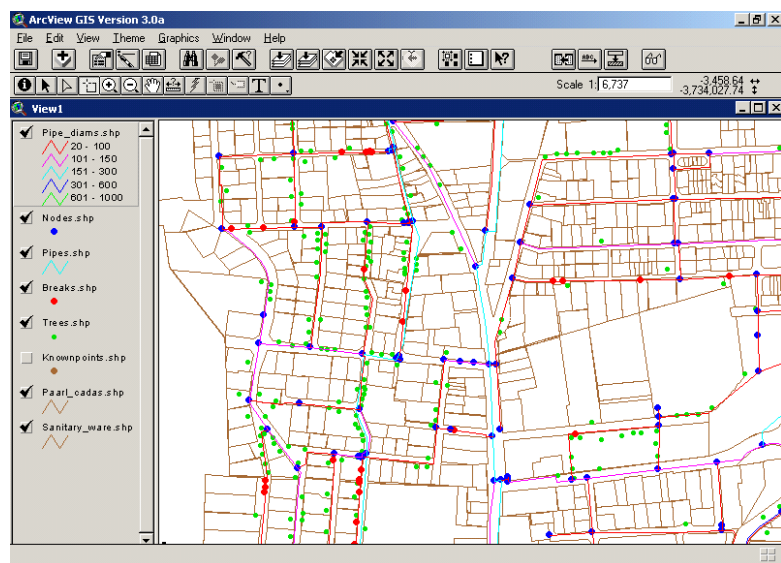


Figure 3  
Thematic mapping of query results in ArcView GIS

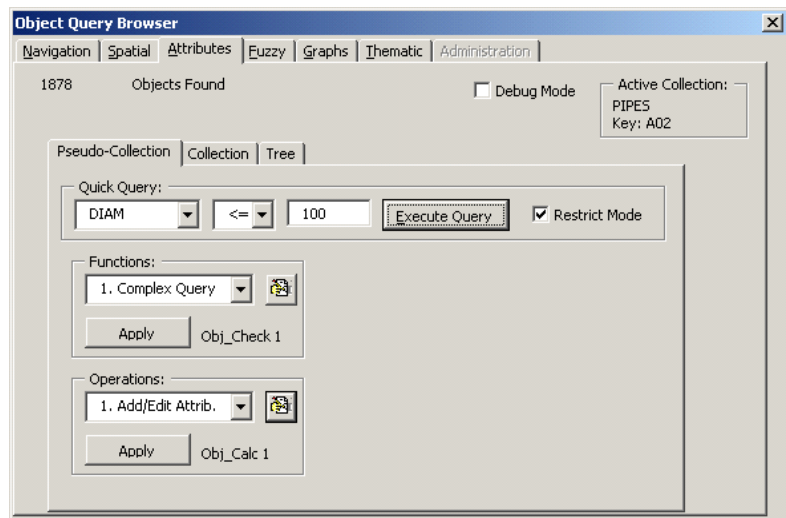


Figure 4  
Object query browser: Attributes GUI & Pseudo-Collection sub-GUI

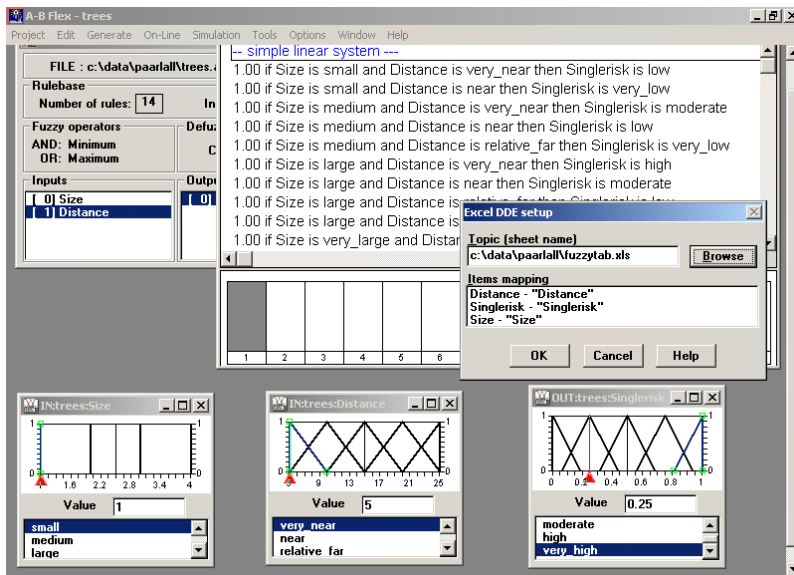


Figure 5  
A-B Flex fuzzy controller

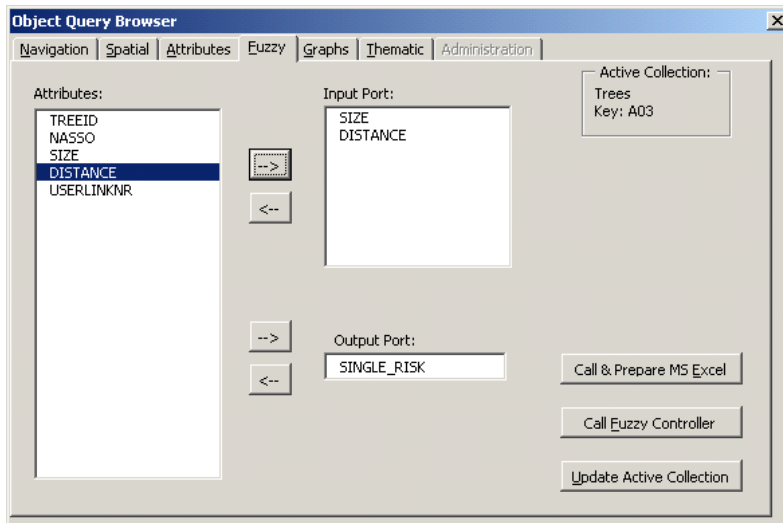


Figure 6  
Object query browser: Fuzzy GUI

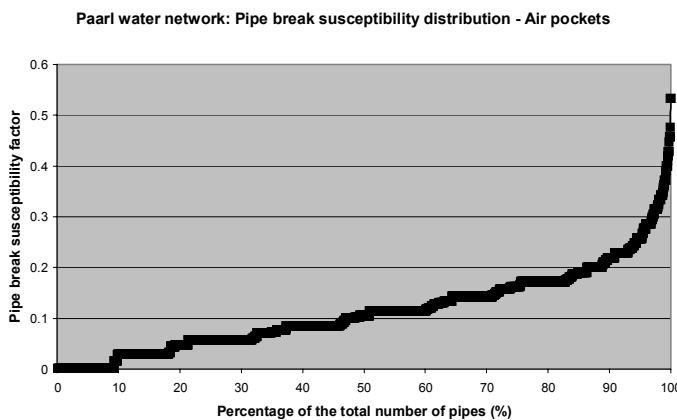


Figure 7  
Pipe-break susceptibility factor vs. percentage of total number of pipes

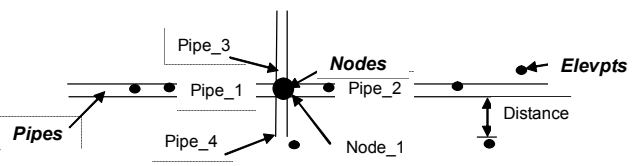


Figure 8  
Data objects and notation used for pipe-break susceptibility analysis – Air-pockets

- at nodal low points
- at high points along pipes
- at low points along pipes (Lescovich, 1972; Kottmann, 1995; Sinske, 2002).

The pipes in the network are categorised according to the 7 air-pocket formation types and then further subdivided into finer subtypes according to certain factors such as velocity, slope and diameter. The total pipe-break susceptibility (due to air-pockets) is calculated by collectively taking into account all the factors regarding air-pocket formation in the pipes, using a multi-factor evaluation process.

The data objects and notation used in an SDSS pipe-break susceptibility analysis, as a result of air-pocket formation, are shown in Fig. 8 and the unified modelling language (UML) use case diagram depicting the system usage is given in Fig. 9.

The SDSS operator (Fig. 9) should conduct a spatial join operation in ArcView between the Elevpts objects (containing the point objects with known elevation) and the Pipes objects (Fig. 8). The spatial join operation finds for each elevation point object the nearest pipe object and copies the results, viz. the calculated distance to the nearest pipe (Fig. 8) and the user link number of the pipe to the respective attribute fields of the elevation point object. The SDSS operator can then import the newly updated Elevpts attribute table into the object query browser via the navigation GUI (Fig. 2).

A simple **one-to-many** association between the objects in the Pipes collection and the objects in Elevpts must then be established for the pipe-break susceptibility analyses of air-pocket formation Types 6 and 7 (Fig. 9). This **one-to-many** association can be established by applying the standard association tool accessible from the navigation GUI (Fig. 2), and specifying Pipes as the main collection and Elevpts as the collection to be associated. The user link number attribute of the pipes should be specified for both association keys.

A **many-to-many** association must be established between the objects in the Nodes collection (the main collection) and objects in the associated Pipes collection, to be used in the Type 2, Type 3, Type 4 and Type 5 air-pocket formation checks (Fig. 9). The multiplicity of the association is important for subsequent mod-

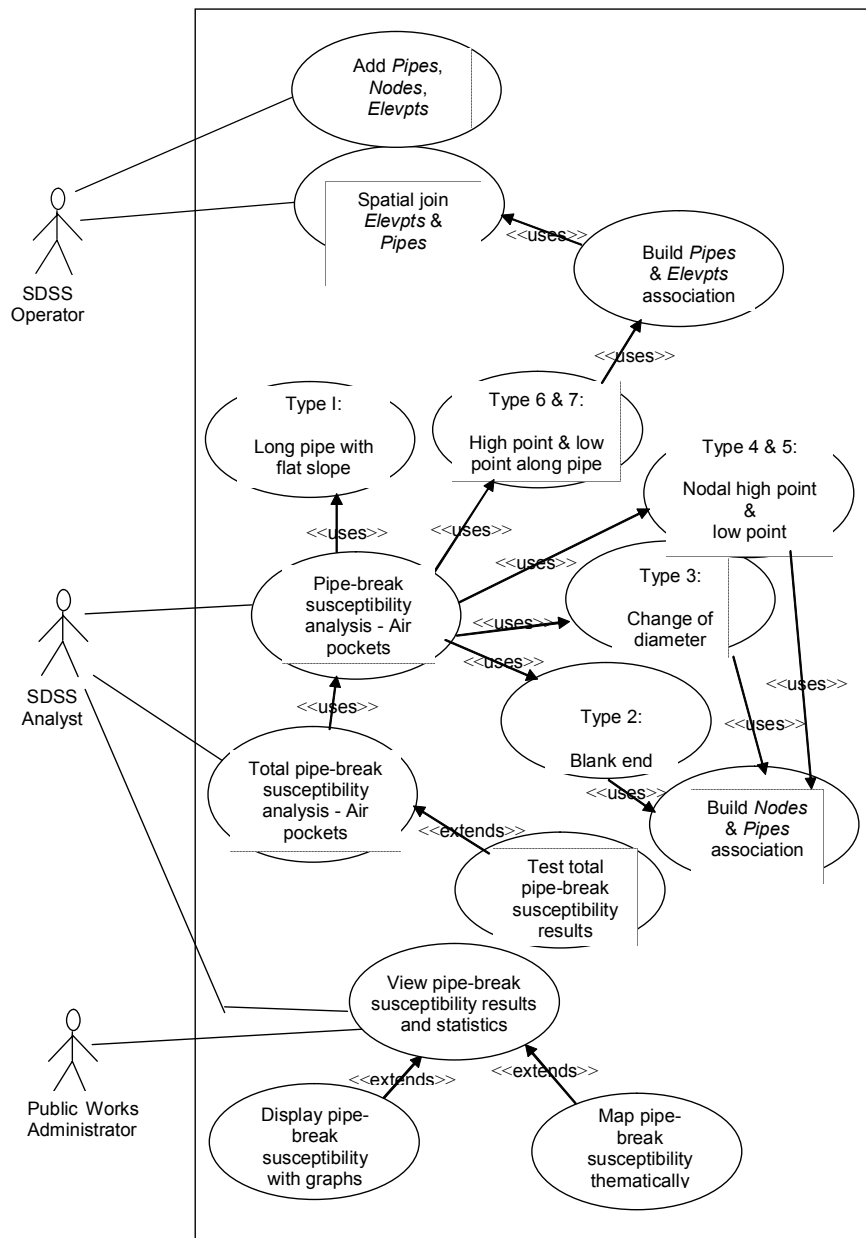
elling purposes and is as follows: (2—1...\*). This implies that each node can thus have one or more connected pipes and a pipe will always have two nodes, viz. a beginning node and an ending node. A node can have a minimum of one connected pipe, which will be the case when the node represents a blank end. The establishment of this special **many-to-many** association is somewhat complex, because the identification numbers (i.e. begin and end numbers) of both ends of a pipe should be compared with the identification number of the node. The association can be established by applying a special operation for building complex associations, which is accessible from the tree sub-GUI of the attributes GUI (Fig. 4).

Once these tasks have been completed the pipe-break susceptibility analyses for each of the 7 types of air-pocket formation can be carried out by the SDSS analyst (Fig. 9). The detailed classification of the subtypes is given in Table 1. The pipes can be classified according to the categories shown in this table by applying the quick query facility (Fig. 4) for the simpler queries, and a special function can be selected from the pseudo-collection sub-GUI (Fig. 4) for the more complex air-pocket analysis queries. A complex query can have a query domain that includes an associated collection and the query can also include derived values.

The SDSS analyst (Fig. 9) can summarise the results obtained from the individual pipe-break susceptibility analyses of Types 1 to 7, by applying a special multi-factor analysis operation to calculate a total pipe-break susceptibility factor (as the result of air-pockets) for each pipe in the Pipes collection. The multi-factor analysis operation is accessible from the tree sub-GUI (Fig. 4) and suitable factor weights (Table 1) should be assigned during execution of this operation. The multi-factor analysis operation will be discussed later in more detail (see **Total pipe-break susceptibility**).

Finally, the SDSS analyst (Fig. 9) can access the graphs GUI and thematic GUI of the object query browser to prepare the graphs and thematic maps (Fig. 3) for the public works administrator. A cumulative distribution graph of the total pipe-break susceptibility factors (Fig. 7) can be compiled via the graphs GUI. This graph can be examined visually to determine suitable upper-class intervals for pipes with high, very high and extremely high pipe-break susceptibility.

The parameters and factor weights used in the model can further be tested and calibrated by comparing the model results with actual pipe-break occurrences caused by air-pockets (see **Calibrating the model** below). The specified factor weights should ideally add up to one, but factor weights of certain air-pocket formation types may be reduced during the calibration process



**Figure 9**  
UML Use case diagram: Pipe-break susceptibility analysis – Air-pockets

when it is found that they have less influence, such as for example at nodal low points and low points along pipes (Table 1).

### Susceptibility to breakage caused by trees

The SDSS is further equipped with special query functions and manipulation operations for pipe-break susceptibility analysis with regard to damage to pipes by tree-roots. The tree size and its distance away from the pipe are the two important factors that must be taken into account when analysing pipe-break susceptibility caused by trees. The tree species should in fact also be taken into account. This will, however, require a detailed tree survey of the study area - which is costly - and is therefore not included in this version of the SDSS.

**TABLE 1**  
**Air-pocket formation types and subtypes**

Types and subtypes	Factor weight
<b>TYPE 1: LONG PIPES WITH FLAT SLOPE</b> Length ≥220; Diam ≤100; Velocity ≤0.7; -3 ≤Slope ≤3	
<b>TYPE 2: PIPES WITH BLANK ENDS</b> Type 2.1 All blank ends	$\frac{1}{7} \cdot \frac{1}{2} = \frac{1}{14}$
Type 2.2 Blank end pipes that slope downwards Diam ≤100; Velocity ≤0.6; -3 ≤Slope ≤1.5	$\frac{1}{7} \cdot \frac{1}{2} = \frac{1}{14}$
<b>TYPE 3: PIPES WITH CHANGES IN DIAMETER</b>	
Type 3.1 All changes in diameter	$\frac{1}{7} \cdot \frac{1}{5} = \frac{1}{35}$
Type 3.2 Medium changes in diameter (Max_diam – Min_diam) ≥50; Min_diam ≤100;	$\frac{1}{7} \cdot \frac{1}{5} = \frac{1}{35}$
Type 3.3 Large changes in diameter (Max_diam – Min_diam) ≥75; Min_diam ≤100;	$\frac{1}{7} \cdot \frac{1}{5} = \frac{1}{35}$
Type 3.4 Medium transition in diameter (Max_diam – Min_diam) ≥50; Min_diam ≤100;	$\frac{1}{7} \cdot \frac{1}{5} = \frac{1}{35}$
Type 3.5 Large transition in diameter (Max_diam – Min_diam) ≥75; Min_diam ≤100;	$\frac{1}{7} \cdot \frac{1}{5} = \frac{1}{35}$
<b>TYPE 4: PIPES WITH NODAL HIGH POINTS</b>	
Type 4.1 All nodal high points	$\frac{1}{7} \cdot \frac{1}{3} = \frac{1}{21}$
Type 4.2 Nodal high points & medium diameter Diam ≤150; Velocity ≤0.7;	$\frac{1}{7} \cdot \frac{1}{3} = \frac{1}{21}$
Type 4.3 Nodal high points & small diameter Diam ≤100; Velocity ≤0.7	$\frac{1}{7} \cdot \frac{1}{3} = \frac{1}{21}$
<b>TYPE 5: PIPES WITH NODAL LOW POINTS</b>	
Type 5.1 All nodal low points	$\frac{1}{7} \cdot \frac{1}{3} \cdot \frac{1}{3} = \frac{1}{63} *$
Type 5.2 Nodal low points & medium diameter Diam ≤150; Velocity ≤0.7;	$\frac{1}{7} \cdot \frac{1}{3} \cdot \frac{1}{3} = \frac{1}{63} *$
Type 5.3 Nodal low points & small diameter Diam ≤100; Velocity ≤0.7	$\frac{1}{7} \cdot \frac{1}{3} \cdot \frac{1}{3} = \frac{1}{63} *$
<b>TYPE 6: PIPES WITH HIGH POINTS</b>	
Type 6.1 All high points	$\frac{1}{7} \cdot \frac{1}{3} = \frac{1}{21}$
Type 6.2 High points & medium diameter Diam ≤150; Velocity ≤0.7;	$\frac{1}{7} \cdot \frac{1}{3} = \frac{1}{21}$
Type 6.3 High points & small diameter Diam ≤100; Velocity ≤0.7	$\frac{1}{7} \cdot \frac{1}{3} = \frac{1}{21}$
<b>TYPE 7: PIPES WITH LOW POINTS</b>	
Type 7.1 All low points	$\frac{1}{7} \cdot \frac{1}{3} \cdot \frac{1}{3} = \frac{1}{63} *$
Type 7.2 Low points & medium diameter Diam ≤150; Velocity ≤0.7;	$\frac{1}{7} \cdot \frac{1}{3} \cdot \frac{1}{3} = \frac{1}{63} *$
Type 7.3 Low points & small diameter Diam ≤100; Velocity ≤0.7	$\frac{1}{7} \cdot \frac{1}{3} \cdot \frac{1}{3} = \frac{1}{63} *$
Units: Diam [mm], Max_diam [mm], Min_diam [mm] Length [m], Velocity [m/s], Slope [%]	

\* All specified factor weights should ideally add up to 1. However, the weights can be reduced for certain types that have less influence such as at low points.

The data objects and notation used in an SDSS pipe-break susceptibility analysis - as the result of tree-roots are shown in Fig. 10 and the UML use case diagram depicting the system usage is given in Fig. 11.

The SDSS operator (Fig. 11) should establish a Trees collection by digitising the tree object data from an aerial photograph backdrop. The tree objects have a size attribute (Fig. 10) that must be quantified on an ordinal scale using the following discrete numbers (1 = small, 2 = medium, 3 = large and 4 = very large). The scale is based on the crown diameter (<7m = small, 7 to 14m = medium, 14 to 21m = large and >21m = very large).

The SDSS operator (Fig. 11) should conduct an ArcView spatial join operation between Trees and Pipes. The spatial join operation finds for each tree object the nearest pipe object (Fig. 10). ArcView automatically calculates the distance to the nearest pipe, as well as the user link number of the nearest pipe and stores the data in the Trees attribute table. The SDSS operator can then import the newly updated Trees attribute table into the object query browser via the navigation GUI (Fig. 2).

The SDSS analyst (Fig. 11) should also analyse the pipe-breaking influence each tree has on its nearest pipe. This pipe-breaking influence can be modelled by a fuzzy function (Sinske, 2002) that has two input fuzzy variables, viz. size and distance to nearest pipe and one output variable viz. single\_risk. The latter represents the pipe-break susceptibility as the result of a single tree. The A-B Flex fuzzy controller (Fig. 5), which is linked to the SDSS, can be called from the fuzzy GUI (Fig. 6). The recommended input membership functions for size and distance, the output membership function single\_risk and the rule base are shown in Fig. 5.

The SDSS analyst (Fig. 11) can further calculate the accumulated pipe-break susceptibility of each pipe, taking into account the pipe-breaking potential of all trees that are associated with the pipe. A **one-to-many** association must be established between each pipe and its associated trees. The link between the objects can be established by applying the standard association tool from the navigation GUI (Fig. 2), and specify Pipes as the main collection and Trees as the collection to be associated. The user link number attribute of the pipes should be specified for both association keys. The accumulated pipe-break susceptibility factor for a pipe can be obtained by applying a special operation that can be selected from the pseudo-collection sub-GUI of the attributes GUI (Fig. 4). The operation determines for each pipe the sum of all its associated pipe-break susceptibility factors (that are stored in the associated Trees collection). The operation implements a special formula that compares the pipe length with that of a typical short pipe segment and then adjusts the accumulated pipe-break susceptibility factor of the pipe accordingly. This adjustment is necessary to avoid that the long pipes in the network will get assigned unreal-

istically high pipe-break susceptibility factors, since the longer the pipe is, the greater is the chance that there will be trees located alongside the pipe that can cause pipe-breakage.

The SDSS analyst (Fig. 11) can further refine the model results. The Pipes collection, containing the calculated accumulated pipe-break susceptibility factors, may in the end be reduced to include only the small diameter pipes ( $d \leq 150$  mm). In this way the large diameter pipes, which have a higher section modulus and thus can resist the bending moment caused by the tree-roots, can be excluded from the high pipe-break susceptibility classification.

The SDSS analyst (Fig. 11) can finally prepare the statistics, graphs, cumulative distribution graphs (Fig. 7) and thematic maps (Fig. 3) that are of interest to the public works administrator. The model can be tested and calibrated further by comparing the model results with actual pipe-break occurrences caused by tree-roots (see **Calibrating the model** below).

### Calibrating the model

The SDSS applies complex models to identify and classify pipes with high break susceptibility. If there is data available on pipe-break occurrences regarding the location and break causes, then the pipe-break susceptibility analysis models of the SDSS can be tested and calibrated.

The pipe-break occurrence data can be imported into the object query browser of the SDSS and then be grouped into separate collections according to the recorded pipe-break causes. The query results collections from a pipe-break susceptibility analysis can be associated with the pipe-break occurrence collection by applying the standard association tool from the navigation GUI (Fig. 2) of the object query browser. An attribute common to both collections, such as the user link number of the pipe, can be used as an association key to establish the **one-to-many** association between each pipe and its associated breaks. At first the pipe-break susceptibility results and occurrence data should be associated for single pipe-break causes only, i.e. the testing and calibration should at first be done for a single pipe-break cause, before attempting to test and calibrate multi-

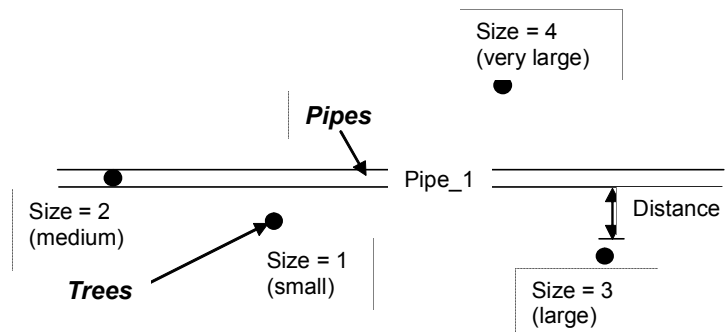


Figure 10  
Data objects and notation used for pipe-break susceptibility analysis – Trees

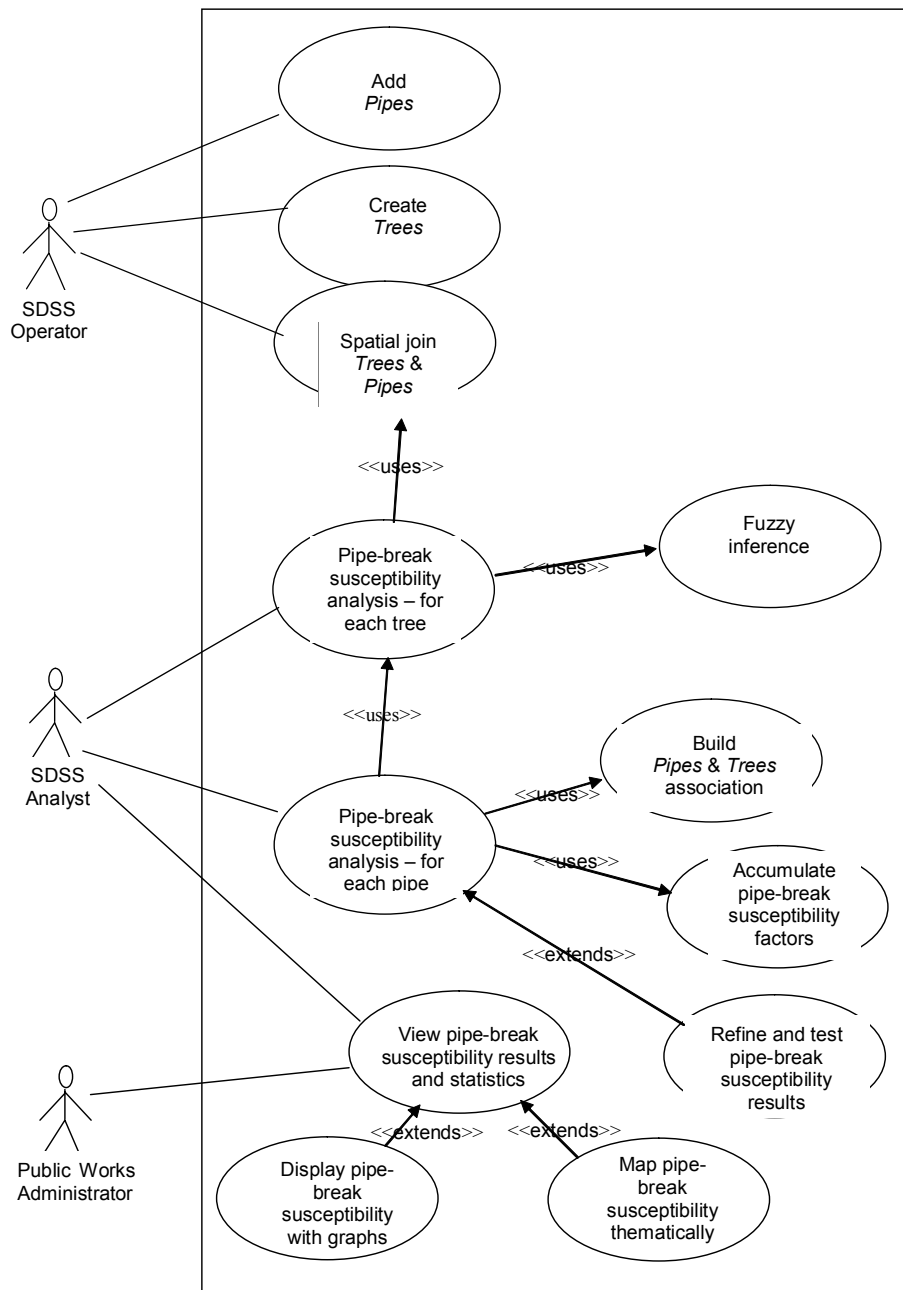


Figure 11  
UML Use case diagram: Pipe-break susceptibility analysis – Trees

Categories and subcategories	Factor weight
<b>1. PIPES WITH HIGH BREAK SUSCEPTIBILITY - AGE</b> Age ≥ 25 (years)	
<b>2. PIPES WITH HIGH BREAK SUSCEPTIBILITY - AIR-POCKETS</b>	
2.1 High break susceptibility Total_airbreak ≥ 0.1	$\frac{1}{3} \cdot \frac{1}{3} = \frac{1}{9}$
2.2 Very high break susceptibility Total_airbreak ≥ 0.16	$\frac{1}{3} \cdot \frac{1}{3} = \frac{1}{9}$
2.3 Extremely high break susceptibility Total_airbreak ≥ 0.3	$\frac{1}{3} \cdot \frac{1}{3} = \frac{1}{9}$
<b>3. PIPES WITH HIGH BREAK SUSCEPTIBILITY - TREES</b>	
3.1 High break susceptibility Tree_risk ≥ 0.5	$\frac{1}{3} \cdot \frac{1}{3} = \frac{1}{9}$
3.2 Very high break susceptibility Tree_risk ≥ 1.5	$\frac{1}{3} \cdot \frac{1}{3} = \frac{1}{9}$
3.3 Extremely high break susceptibility Tree_risk ≥ 2.0	$\frac{1}{3} \cdot \frac{1}{3} = \frac{1}{9}$

ple pipe-break causes.

When testing or calibrating the pipe-break susceptibility model, the model calibration statistics consisting of the following three factors should be evaluated collectively:

- The **sharpness** factor is a measure to evaluate the size of the query results collection in relation to the total number of pipes in the network. The smaller the factor, the ‘sharper’ (or ‘finer’) is the query results collection. The sharpness factor is defined as:

$$\frac{\text{Number of pipes in query results collection}}{\text{Total number of pipes in network}} \quad (1)$$

- The **success rate** factor indicates how many breaks of the actual pipe-break occurrences the model was able to predict. The larger the factor is, the better the model prediction. The success rate factor is defined as:

$$\frac{\Sigma n_{\text{Asso}}}{\text{Total number of pipe-break occurrences}} \quad (2)$$

where:

$\Sigma n_{\text{Asso}}$  is the total number of associated pipe-break occurrences for the query results collection.

- The **reliability factor** indicates how many pipes in the active query results collection have in fact broken. The larger the factor is, the better the reliability. The reliability factor is a control measure to check if the model is defined correctly. In the extremely high pipe-break susceptibility categories the reliability factor should be almost 1 (or 100%), confirming that

almost all pipes identified by the SDSS that are in these extremely high categories have indeed broken. The reliability factor is defined as:

$$\frac{\Sigma n_{\text{Asso}}}{\text{Number of pipes in query results collection}} \quad (3)$$

A special operation, that implements the three model calibration factors, can be selected from the collection sub-GUI of the attributes GUI (Fig. 4).

### Total pipe-break susceptibility

Pipe-break seldom occurs as the result of a single cause; there is usually a combination of pipe-breaking causes responsible for the break. A total pipe-break susceptibility analysis should therefore be conducted with the SDSS.

The query outputs (pipe collections) resulting from the aforementioned pipe age, air-pockets and tree analyses can typically be grouped into high, very high and extremely high pipe-break susceptibility categories (Table 2). Suitable factor weights for defining the importance of each category and subcategory should then be assigned (Table 2). A total pipe-break susceptibility analysis, taking into account the combined pipe-break susceptibility due to pipe age, air-pockets and trees, can be conducted by applying the special multi-factor analysis operation from the tree sub-GUI of the attributes GUI (Fig. 4). The operation iterates through all the pipes in the network and checks whether each pipe is a member of the high, very high, and/or extremely high category (it is possible for a pipe to be member of all three of these categories). An accumulated weighted evaluation factor is then calculated for each pipe representing the total pipe-break susceptibility of the pipe.

The factor weights specified in the total pipe-break susceptibility analysis can also further be tested and calibrated as described in the previous section, provided there are suitable data available on pipe-break occurrences in the water network.

### Conclusions

The SDSS described in this paper is a very useful tool to model the complex pipe-break phenomena in a municipal water distribution system. The SDSS pipe-break susceptibility results (especially those obtained via calibration with the actual pipe-break occurrences) can give a municipality valuable insights into the specific pipe-break causes in their water network. Using this model preventative maintenance can be carried out more effectively and an appropriate maintenance strategy can be planned and implemented. The pipe failure rate can thus be reduced saving the municipality pipe repair costs, which otherwise could amount to large expenditures annually. Newly planned water distribution systems can also be tested with the SDSS by identifying pipes with high break susceptibility (which will in this case mainly be the result of air-pockets). In this way designs can be altered or improved before commencing with the actual construction.

The SDSS currently supports pipe-break susceptibility analysis based on three pipe-break causes, viz. pipe age, air-pocket formation and tree-roots. The scalable architecture of the SDSS, however, allows for system extension to also support other pipe-break causes. The SDSS can test a water distribution system for seven different air-pocket formation types. Fuzzy logic-based



analysis can be conducted to determine pipe-break susceptibility as a result of nearby trees. The SDSS further has multi-factor analysis functionality to calculate the total pipe-break susceptibility taking into account the combined effect of pipe age, air-pockets and tree-roots. Incorporated into the model is also functionality for pipe-break impact assessment (not discussed in this paper) with regard to water loss and damage caused to nearby lower-lying property. The reduction of water losses in a municipal water distribution system should be of utmost importance to water-scarce countries such as South Africa.

A new ArcGIS version (ESRI, 2001) of the SDSS package is in the final stages of development, whereby the object query browser of the SDSS will be linked with ArcView 8. The object query browser, which has been written in VBA, will be fully integrated with the GIS, since it can run directly from the built-in VBA editor of ArcView 8.

## References

- BÖHM A (1993) *Betrieb, Instandhaltung und Erneuerung von Wasserleitungen*. Vulkan, Essen.
- CHANG C (1997) *Fuzzy-Logic-Based Programming*. World Scientific Publishing, Singapore.
- ESRI (2001) *What is ArcGIS?* ESRI, Redlands, CA.
- KLIR GJ and YUAN B (1995) *Fuzzy Sets and Fuzzy Logic: Theory and Applications*. Prentice-Hall, Upper Saddle River, NJ.
- KOTTMANN A (1995) Pipe damage due to air-pockets in low pressure piping. *3R Int.* **34** 11-16.
- LESCOVICH JE (1972) Locating and sizing air-release valves. *J. AWWA* **64** (7) 457-461.
- MORRIS RE (Jr.) (1967) Principal causes and remedies of water main breaks. *J. AWWA* **54** (7) 782-798.
- O'DAY DK (1983) Analyzing infrastructure conditions – A practical approach. *Civil Engineering, Am. Soc. Civ. Eng.* **53** (4) 39-42.
- SINSKE SA (2002) A Spatial Decision Support System for Pipe-Break Susceptibility Analysis and Impact Assessment of Municipal Water Distribution Systems. Ph.D. (Geography and Environmental Study) Dissertation, Univ. of Stellenbosch, Stellenbosch.

