Deuerlein, Jochen; Wolters, Andreas; Meyer-Harries, Lea; Simpson, Angus Ross Graph decomposition in risk analysis and sensor placement for water distribution network security 12th Annual Conference on Water Distribution Systems Analysis 2010, Tucson, Arizona, United States, 12 Sep-15 Sep 2010 / Kevin E. Lansey, Christopher Y. Choi, Avi Ostfeld and Ian L. Pepper (eds.): pp. 394-411

Graph decomposition in risk analysis and sensor placement for water distribution network security

Jochen Deuerlein[1], Andreas Wolters[2], Lea Meyer-Harries[3] and Angus R. Simpson[4]

[1]3S Consult GmbH, 76133 Karlsruhe, Germany; *Email: deuerlein@3sconsult.de*
[2]3S Consult GmbH, 80333 Munich, Germany; *Email: wolters@3sconsult.de*
[3]3S Consult GmbH, 80333 Munich, Germany; *Email: meyer-harries@3sconsult.de*
[4]School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide SA 5005, Australia; *Email: asimpson@civeng.adelaide.edu.au*

Abstract

Over the last decade considerable research in water distribution network modeling has focused on the security of water supply against terrorist attacks. In this paper, specific issues of urban and regional distribution systems as to their vulnerability against terrorist attacks with CBRN (chemical, biological, radiological, nuclear) substances, detection methods and emergency plans are investigated.

As a first step, a risk analysis is carried out based on topological properties of different parts of the network, classification of building developments and customers. The decomposition of the network graph enables the differentiation of network components (into treed components, blocks and bridges). Following this subdivision, the different impacts and detection characteristics can be assessed. The results of the risk analysis can be used for the creation of risk maps. The specific differences of urban (mainly looped) and regional (mainly branched) supply networks are discussed.

The decomposition of the network graph can be further used for reducing the problem size of the sensor allocation problem by pre-selection of events with little impact and aggregation of the network model. The main ideas are demonstrated by use of the example network 2 of the Battle of the Water Sensor Networks (BWSN).

The crucial point of all sensor networks is that a full coverage of the system won't be reachable and there will be a considerably long time to detection. An alarm is not actually generated until the toxic substance has passed a sensor. In this study another approach is proposed. The case of intrusion of the toxic substance by pumping against the pressure of the network will be considered. This event is considered as a "positive" leak. Leak detection methods that are normally used for the observation of pipelines are applied to the investigation of the water hammer event caused by the intrusion. Finally, conditions for the practical applicability of the method will be put up for discussion.

Keywords
Network security, risk analysis, graph decomposition, sensor allocation, water hammer analysis, water quality sensors

1. INTRODUCTION

Since the tragedy of September 11 in 2001 research in water distribution modeling has been affected by the security of drinking water supply systems against contamination by terrorists and natural hazards. At the center of research activities has been consideration of the development of sensor networks as early warning systems for contamination events. A large number of researchers from all over the world have tackled this complex issue to the main part by formulating and solving a mathematical optimization problem.

In 2006 the Battle of the Water Sensor Networks (BWSN) was undertaken as part of the 8th WDSA conference in Cincinnati (Ostfeld et. al. 2008). The goal was to develop algorithms that are capable of calculating a sensor network that performs best for different objectives including: (1) minimizing the expected time of detection, (2) minimizing the expected population affected, (3) minimizing the expected consumption of contaminated water prior to detection and (4) maximizing detection likelihood. The methods of the different research groups were tested for two example network models: network 1 with 126 nodes and 158 pipes and network 2 with 12523 nodes and 14822 pipes ("Ostfeld et al. BWSN files", 2010). The results have shown that the objective functions (1) to (3) are correlated and competing with function (4). Another outcome was that "general guidelines cannot be set".

There are many influencing factors that vary from network to network. The consideration of the larger network 2 has shown that especially the criteria of maximizing the detection likelihood causes misleading results. For future research, the development of worst case scenarios is claimed that allow for a more efficient calculation. Examples network 1 and network 2 have already led to a huge number of scenarios that had to be investigated. The full event matrix of the smaller network already contains 37152 events. For the larger network the scenarios were randomly chosen.

The intention of this paper is not to provide a new sensor allocation tool. In the first part of the paper the outcome of the hydraulic and risk analysis of urban and regional supply systems is presented. In contrast to the BWSN where contamination scenarios are simulated at all nodes of the network model (full event matrix) or randomly chosen (larger networks) in our case a scenario based approach has been used. Identification and classification of feasible intrusion points and studying the impacts of contamination is firstly addressed. The risk of contamination at different locations has been determined by interviews of local water supply utility managers and on site-inspections. For the estimation of the impact, a hydraulic simulation model is used. Finally, worst case scenarios shall be defined and distinguished from less important scenarios. It will be shown that the graph theoretical characterization of incident locations supports the estimation of impact of a contaminant intrusion.

In the second part of the paper, based on the outcome of the scenario based risk analysis, a proposal is given for the reduction of problem size in the common sensor allocation problem. Since details of the pipe systems of the affiliated project partners are not able to be published, the results are demonstrated by use of network 2 of the BWSN. The network is subdivided into tree, bridge and looped block components. It turns out that tree structures should be excluded from application of sensor allocation algorithms using mathematical optimization since they are mostly responsible for non-detections. A decrease in calculation time can be further achieved if separated blocks are identified in a preliminary analysis and the information is used for solving the allocation problem.

Even well-planned contaminant warning systems with a large number of well-positioned sensors cannot avoid that a certain time span exists between intrusion and detection or in the worst case even non detections. Therefore in the last section of this paper the question of alternative detection methods that support water quality sensor networks is posed for discussion. As an example the detection of small water hammer events caused by unauthorized input of mass into the system is presented. This approach can be imagined as a leak detection method with a negative leak (inflow). Conditions for the practical applicability of the approach are discussed.

The research presented in this paper is part of the joint research project STATuS which is funded by the German ministry for education and research (BMBF) and has started in autumn 2009. The acronym STATuS stands for "Security of Drinking Water Supply with Respect to CBRN-threat scenarios". In this scenario based research, the central water supply systems are threatened by chemical, biological, radiological and nuclear substances that can come into the drinking water by natural hazards or by terrorist attacks. The objective of the research project is helping water supply utilities and administration to increase the security of the population against toxic agents in the drinking water by implementation of a comprehensive and scenario based risk analysis and the development of prevention and protection measures. The preliminary first part of STATuS is being undertaken by five German institutions from research and industry. Important issues are the selection of chemical and biological agents that can be used for terrorist attacks against the central water supply and the development of detection methods.

The part of the research that is described in this paper includes addressing the most important threat scenarios, detection and development of emergency plans. In Germany, there exist distinct systems of urban and regional water supply. Often communities with their own water resources have additional connections to regional suppliers for security and reliability reasons. Although both kinds of systems consist of the same assets including pipes, tanks and fittings there a differences in operation and control that shall be emphasized in this project.

2. RISK ANALYSIS AND SELECTION OF INTRUSION SCENARIOS

2.1. Overview

Due to their distributed nature water supply systems are vulnerable against manipulation and intended contamination by intrusion of toxic matter into the distribution systems. Central buildings like water treatment facilities and storage tanks meanwhile show a high level of security measures and are often controlled by security services. In contrast, the distribution network with its hundreds or thousands of kilometers pipe length could be a target for terrorist who want to destroy the belief of the population in a secure life, or for an actor who simply wants to kill as many people as possible.

There are many combinations of different possible locations for the intrusion of the attack, duration, toxicity of substance and availability of sensors that are able to reliably detect toxic concentrations of the substance. In addition, the topological structure of the network plays an important role. The coverage of all different combinations would require the investigation of a huge number of scenarios. For that reason a pre-selection needs to be made that is based on analysis of available access points to the system and the decomposition of the network graph.

The risk analysis in this section does not consider sensor networks for the following reasons. Firstly, there exist substances that cannot be detected by available sensors. Secondly, results of the part of the research project STATuS that includes the classification of substances based on their toxicity, availability and stability within water for identifying the most dangerous chemical, biological and radio nuclear agents are not available yet. Therefore the risk analysis here focuses on hydraulic and topological properties of urban and regional supply systems only. For the contamination scenarios the worst case is assumed where the concentration of substance is always above a lethal level.

2.2. Graph Decomposition of the BWSN network 2

As mentioned above the German network models of the project partners need to be kept confidential and therefore are not shown in this paper. For an explanation of the results of the study, the example network 2 from the BWSN is used. Figure 1 shows the decomposition of this network into the three subgraphs including forest, bridges and grid. The forest consists of several trees; the grid includes all looped subgraphs, the so called blocks that are characterized by the presence of loops. The bridge components are the connections of the blocks (Deuerlein 2008).

Please note that for consideration of different input sources (tanks, reservoirs, etc.) the input nodes are connected with a virtual ground node by virtual links. The justification for this is the fact that a node that is connected to at least two sources can be supplied by an alternative path if one connection fails. The network graph together with the virtual links is called augmented network graph. For more details the reader is referred to Deuerlein (2006).

After a general definition of risk in the following section the different graph theoretical properties of the network nodes being possible locations for contaminant intrusion are discussed and ranked as to the impact of an intrusion.

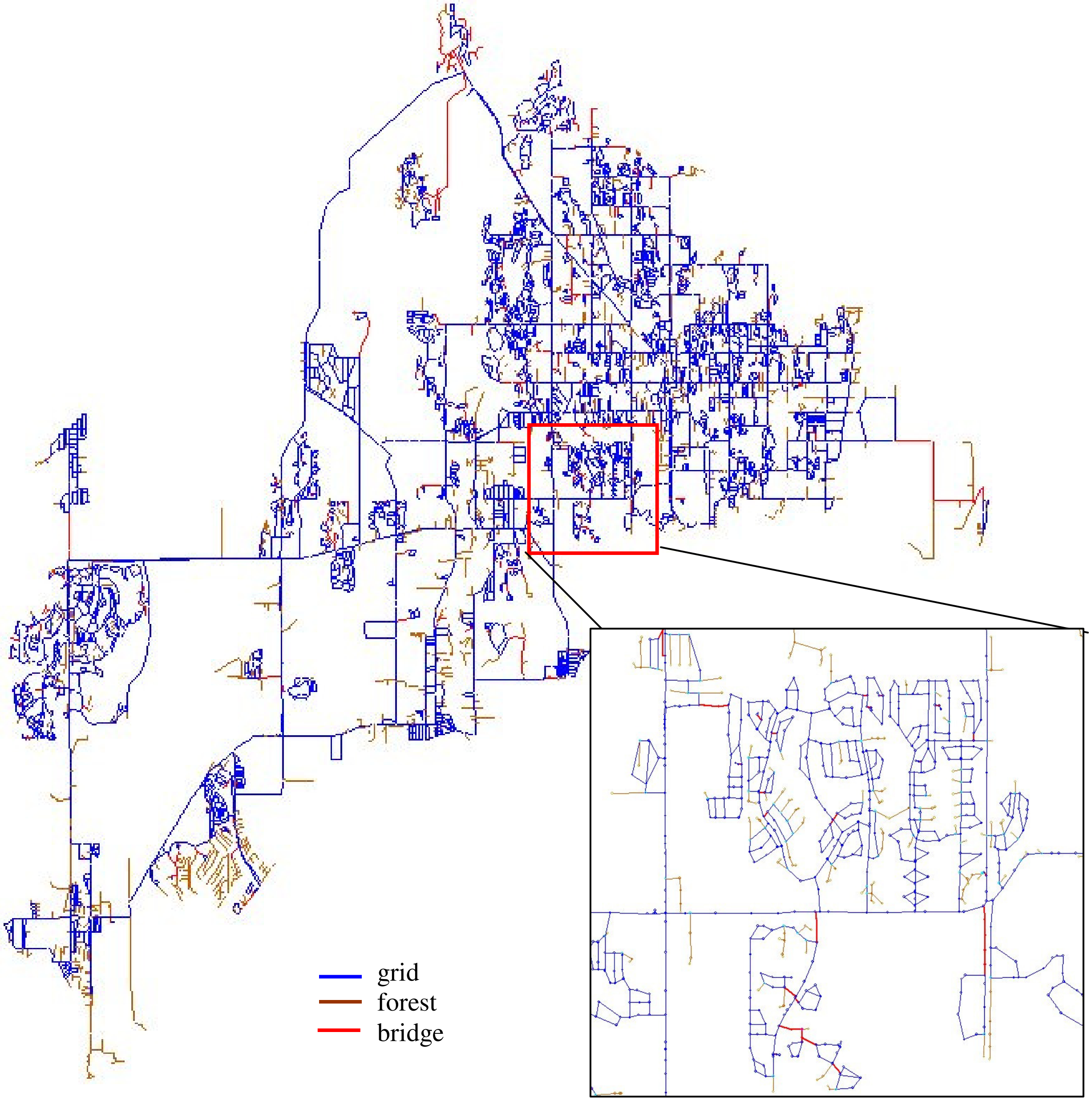


Figure 1. Graph decomposition of network 2 of the BWSN (12529 nodes, 14493 pipes, 1798 km)

2.3. Definition of risk

For the investigation of the contamination scenarios the following assumptions are made:

1.) Detection by sensors is not considered. As a worst case it is assumed that for the toxic substance no technical detection methods are available. The only detection is the occurrence of consumers becoming symptomatic (worst case scenario).

2.) It is further assumed that the lethal concentration is exceeded over the whole time of intrusion. Fluctuations in concentration and reactions within the pipe systems are out of the scope of this paper.

3.) The choice of the toxic substance is also not important here. It could be a chemical, biological or radioactive agent.
4.) The intrusion starts at a certain point in time t_0 and lasts to the time point t_1. During the intrusion time it is assumed that a constant rate of mass is input into the water distribution system.

In general the definition of risk is difficult since there are many influencing factors (Jiang, 2002). Following the definition of Smith (1999) the risk of a dangerous event *i* is the product of its impact Imp_i and the likelihood of occurrence P_i.

$$R_i = \mathrm{Imp}_i \cdot P_i \tag{1}$$

In this paper, the impact of the intrusion of toxic matter at a certain location *i* is defined as the volume of contaminated water. The likelihood of occurrence is estimated by the accessibility of the location, detection likelihood of the manipulation at this location and the attractiveness as target. The different criteria are described in more detail below. The formulation of risk is similar to the impact in TEVA-SPOT (Threat Ensemble Vulnerability Assessment and Sensor Placement Optimization Tool, Berry et al. (2009)) that includes already a weighting factor for the probability of an incident.

Impact of contamination

The impact can be formulated as the volume of contaminated water which is directly correlated to the number of people exposed. After a contamination incident the concentration of toxic mass in the contaminated water volume may vary due to fluctuating demands and pipe flows. However, under the simplifying assumptions 1.) and 2.) above the infected volume can be used as a measure of impact:

$$V_{c,i} = \int_{t_0}^{t_1} \sum_{j=1}^{n_s} Q_{o,j}(t)dt \tag{2}$$

where $V_{c,i}$ is the contaminated water volume that leaves node *i*, t_0 is the time of the beginning of the intrusion, t_1 is the end of intrusion and $Q_{o,j}(t)$ are the pipe flows that leave node *i* at time *t*.

As an example imagine that a biological agent with no available sensor and long incubation time is used. Then the probability that all people who have consumed water from the contamination source become symptomatic is very high. Neglecting leakage losses, all the contaminated water reaches the consumer. The detection is possible only when the first consumers become symptomatic.

The dominant parameters of Eq. (2) are the flows $Q_{o,j}(t)$ leaving node *i* at a certain time *t* and the duration $\Delta t = t_1 - t_0$ of contamination. With application of a time extended hydraulic simulation model the flow can be calculated. Its fluctuation is driven by varying demands of the consumers. For the definition of a worst case scenario $V_{c,i}$ has to be maximized. Whereas the flows are mainly determined by rigorous properties like network graph topology and hydraulic characteristics of the pipes the duration of contamination depends on other non-hydraulic criteria that are also important for the estimation of the likelihood of occurrence. A selection is described in the following.

Accessibility of the intrusion point

When we are working with hydraulic simulation models we are usually thinking in terms of links and nodes. The water comes into the system at a node and is transported through the links representing pipes, valves and pumps before it leaves the system at a node. However, in reality different buildings or fittings hide behind the nodes. There are different access points to the pipe system. In Germany the pipes usually lay about one meter under ground and it would be difficult to access them without being detected. However, there exist other access points such as manholes for valves and hydrants that can be accessed pretty easily. The risk analysis should take into account those differences.

Attractiveness (from a terrorist's point of view) of objects that can be threatened from the intrusion point

Some locations including religious centers, military and/or governmental buildings might be at a higher risk than others if the actor has good knowledge about the pipe systems. Thus a selected building or selected people could be threatened.

Detection likelihood

Some parts of the network can be accessed easily but the likelihood of detection of intrusion is also very high. For example if a manhole is located in a high traffic street the probability that the intrusion will be observed is higher than for a location in the basement of private home or a manhole that is located in a park or forest.

Summary of risk

The criteria listed here is not necessarily complete. The evaluation of risk implies the availability of more than just hydraulic data. Building density, the type of building, socio-economic data as well as the exact knowledge of access points to the pipe network are important for the estimation of the probability of an incident. Those data can be often gained from existing GIS-systems. It is almost impossible to estimate the probability of an incident in accordance with the formulation of risk in Eq. (1). Therefore in our case a points system has been introduced for classifying the different locations.

This additional information is not available for the example system network 2 and it is not possible to reveal the networks of our project partners. In the following, the most important threat scenarios classified as to their incident locations are described based on consideration of different topological characteristics.

2.4. Water storage and water treatment facilities

Water storage and water treatment facilities are very important locations for central water supply systems and thus are a worthwhile target for terrorists. As consequence, in recent years new security systems have been developed and installed at those locations. These systems include cameras, automatic alarms and security personnel that control the facility. Nevertheless, 100 percent security cannot be guaranteed. Security holes could be possibly found by terrorists. A point of weakness is often the personnel running the facility.

The intrusion of toxic matter into a storage tank that cannot be detected by available sensors represents the worst case scenario with regard to its impact. The average fluctuating water volume of storage tanks ranges from 25% for large tanks to 100% for smaller tanks ($V < 2000\ m^3$). With the intrusion of toxic substances into a storage tank the terrorist reaches the largest coverage of the network. If for example the whole network is supplied by just one tank and by construction of the network and the storage volume it is guaranteed that the fluctuating volume is consumed during one day. Most of the population can be contaminated by just one threat. It is also very easy for the terrorist to pre-calculate the dose of the substance that effects lethal concentration. In addition, if the entire zone is supplied by one tank there are no dilution effects and the only mechanism that can effect a change in concentration is by chemical reactions and degradation processes.

2.5. Distribution Network (urban systems only)

The most vulnerable part of the water supply system in terms of accessibility is the pipe network. Urban water supply networks often reach pipe lengths of more than 1000 kilometers. In Germany, the pipes are usually installed about one meter below the ground. However there exist numerous points of access to the pipes. Considered as most important for urban systems are 1) valve chambers located in manholes at important connections; 2) fire flow hydrants that are spread over the entire system and can be accessed easily; 3) house connections that join the public water supply network with the house installations and are located on private ground.

Let us consider the house connections in more detail. They usually include back flow preventers prohibiting the public supply lines from private area borne contamination. However these fittings are built for preventing accidentally induced contaminations. If somebody knows a little about sanitary installations they could easily manipulate the backflow preventer. But this is only the first step. In the second step they must bring the substance from the basement of the house into the distribution network. Therefore a pump is needed. Usually the flow direction is from the distribution lines within the street to the house. The flow direction must be altered by the input of a more or less large amount of water that has to be pumped against the common flow direction. The total volume of the pipes of the house connection has to be replaced. And this is the difficult point. Often the branched house connection subnetworks consist of a considerable length of pipeline. That means that if somebody wants to introduce a toxic substance via a house connection they firstly have to collect a quantity of water. The water needed for reversing the flow direction cannot be withdrawn from the house connection pipes since in this case the water will only be pumped in circles and the contaminated water would reach only the actor himself.

That could lead one to assume that house connections are not as vulnerable, however, that really depends on the structure of the network. How far is the house from the looped system? A house connection line with a 1 ½ inch diameter pipe and a length of 100 m has a volume of only 0.114 m^3. This amount of water is easily storable in small tanks in the basement.

For the calculation of risk - the accessibility is very high and detection likelihood very low in the basement of a private home. For the other two access points, hydrants and manholes, the likelihood of detection of unauthorized manipulations increases drastically but the risk is still less than that of a storage tank. For example if the actor impersonates a staff member of the water supply utility and puts a tent over the hydrant he may have several hours prior to detection.

It is assumed that the intrusion point has been selected by those criteria including accessibility and observability or just by accident without considering whether the hydrant or the house connection is within the looped or the branched system. However, for an estimate of the consequences of an attack and possible security measures it is very important to distinguish between various locations within a network including bridges, looped blocks and trees.

Intrusion at house connection/hydrant/manhole – graph theoretical bridge

Graph theoretical bridge links are often important pipes that connect a looped subsystem downstream to an upstream looped system. Bridge pipes are often part of the flow system within a large network. All the water that is supplied to the downstream network flows through the bridge pipe. Therefore those pipes are particularly vulnerable against contamination. For the calculation of a contamination scenario the systems downstream of the bridge can be considered independently from the rest of the network with the intrusion point as water source. Since there is no mixing with water from other sources dilution is impossible. If the time span of intrusion exceeds the flow time from the contamination to its furthest downstream user the total subnetwork is affected by contamination of high concentration.

Intrusion at house connection/hydrant/manhole – looped system

Within the looped part of the network the spread of the substance is more diffuse. The flow directions and the area affected at a certain time after the substance has been added depend on the load conditions and the operation of the network at the time of the intrusion and afterwards. After running an extended period simulation flow routing can be calculated for each time step. It consists of a linked list of nodes where for each node its upstream users and downstream users are stored. For each time step the set of successors of each node can be determined. An upper bound for the influence area of contamination is the union of the sets of successors of each time step.

Please note that just one time extended period simulation is needed. Traversing through the flow routing list can be done very time efficiently even for very large network models. The influence area represents the worst case scenario for an infinite time of intrusion. The specific time that is needed for reaching all downstream users can be also easily calculated from the flow routing by summing the travel times from the contamination node to its furthest downstream users.

Displaying the results sometimes leads to misinterpretations. Often the area of influence is relatively small. However the graphics may be misleading. It is not the size of the area that is as critical for its lethal impact but rather the volume of water that is consumed by the population. If for example, the attack is within a central urban area like a downtown area with tall buildings and a large population density the area may look small but the water volume consumed might be very large. The worst case scenario is the intrusion at a central pipe that is a little downstream of the input node (e. g. storage tank) with a dose that leads to lethal concentrations over a time span that is longer than the flow time from the intrusion point to its furthest downstream node.

Intrusion at house connection/hydrant/manhole – branched system

House connections at the end of a branched subsystem are often characterized by good accessibility and low detection likelihood (end of a road, etc) for the actor. However, under normal conditions without input of a considerable amount of water volume the impact of a contamination is very small since the plume of the contamination is limited to the small network part at the downstream end. As explained above, the only way for the actor to overcome this local limitation is to pump the toxic matter into the system after it has been dissolved in a considerable amount of water that is large enough to replace the pipe volume of the tree structure. The impact of such an event could be avoided by installing back flow preventers (check valves) at places that are difficult to access and for which the flow direction is clearly known from their topological properties (for example all links that belong to bridges and trees).

2.6. Summary of results and comparison of urban and regional systems

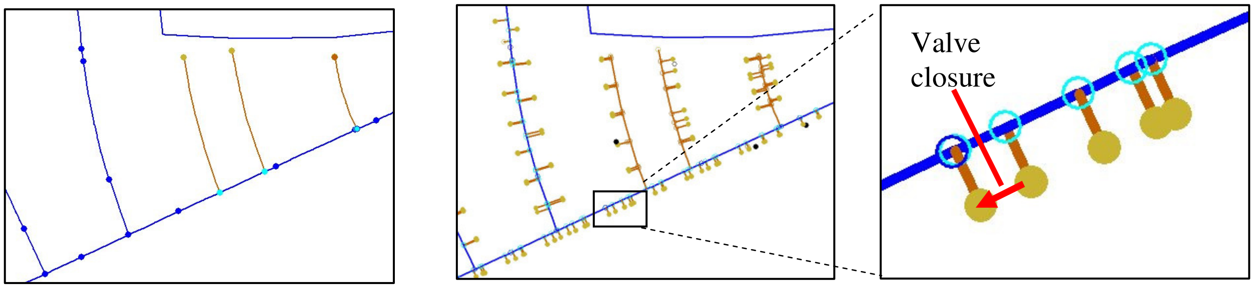
In the sections above various threat scenarios have been discussed that are more or less likely if we compare urban supply systems and regional ones. In the following the results are summarized.

Urban system:

Six different contamination locations were studied: a storage tank, the end node of a branched supply line, two nodes within the looped system and two nodes on bridge links. As expected according to its impact the worst case scenario is the contamination of the storage tank. The example system studied in the research project has only one tank supplying the whole area and the volume is far more than one day's demand of the entire supply zone. It is only a matter of time when all people are drinking contaminated water.

The worst case scenario for the contamination through a house connection is when the actor is able to build a bypass from two house connections that are directly connected to the looped part of the network or a bridge (Figure 2). The higher the pipe flow (in general this is correlated to the distance to a storage tank or reservoir) the worse is the impact. The detection likelihood is very low. The dosage can be run over days without detection.

A house connection at the end of a graph theoretical tree structure is less vulnerable due to its local character. Two exceptions exist: if the actor is able to dissolve the contaminant in a large water volume, which for instance might be arranged by flooding of the basement. In this case the replacement of the water volume of the tree structure can overcome the local limitation. However, the mixing with fresh water at the root node reduces the concentration.



Simplified network model

1:1 network plan

Bypass with dosage pump

Figure 2. House connection lines with possible cross connections

Another important issue is that branched tree structures are very well suited for targeted attacks. If the actor identifies an upstream node of the house connection of his target he can be sure that the contaminated water will arrive with initial concentration. No dilution effects are to be expected and the uncertainty of not knowing where the water flows in looped parts does not exist. Detailed knowledge of the pipe system and an understanding of pipe flow would be necessary by the actor.

Regional systems:

The study of a regional system has focused on incidents in manholes and storage tanks solely. The topology of the network is less complex. It is assumed to consist of a tree like structure with only few demand nodes, which are representing water storage tanks being the connections to the urban distribution networks. There are no house connections in the system and access points are limited to the manholes for isolation valves, ventilation and draining of the pipes. In each manhole is a tap for cleaning which provides an access point to the pipe system. The water utility estimates as highest risk the manipulation of intermediate tanks. They are often located in isolated areas in the forest and only visited for inspection from time to time. A large volume of water could be infected within a comparably short time. The sensor allocation problem in this case is straight forward. Upstream of each storage tank of the customers must have a sensor installed.

The hydraulic studies include the simulation of impacts of incidents at manholes and tanks. The most important difference to urban systems is in terms of the demand characteristics. The customers of the regional supplier have contracts that allow them to take a maximum amount of water and a minimum that is 10 % of the maximum. The crucial point is that they can take the water whenever they want. In effect that means that the supplier has to provide the maximum amount of water every day. However, it is not guaranteed that there are any withdrawals at all. As a result no demand patterns exist that are available and that can be used for the estimation of actual demands. This problem can be avoided by use of SCADA-Systems only that provide real-time data of flow measurements in the system.

3. SENSOR ALLOCATION BY USE OF GRAPH DECOMPOSITION

In the last section graph theoretical properties of different locations in water distribution network have been used for the estimation of the risk of a contamination event. Under the assumption that there are no sensors available for the detection of the substance only worst case scenarios have been studied. In this section, based on the results of the risk analysis, graph theory will be used for simplifying the sensor allocation problem. Ostfeld et al. (2008) mention amongst others two important research challenges for the improvement of existing optimal sensor network design models:

1) The full event matrix becomes large for real-life-applications. Randomly chosen event matrices lead to different solutions and non-detected events are excluded. Therefore procedures are required that support computing optimal sensor networks for rare subsets with extreme impacts
2.) Because of the size of the sensor placement problem for real networks aggregation algorithms are needed that simplify the network but deliver the same results for network hydraulics as well as water quality as the original system.
The two points are addressed in the following by a classification method for contamination events that is based on the topological properties of the network graph.

3.1. Forest subgraph of the network

Let us first consider the forest portion of a water distribution system. In the network in Figure 3, it consists of 1459 trees with a length of 398.6 km pipeline (22.2 % of the total network length of 1798 km).

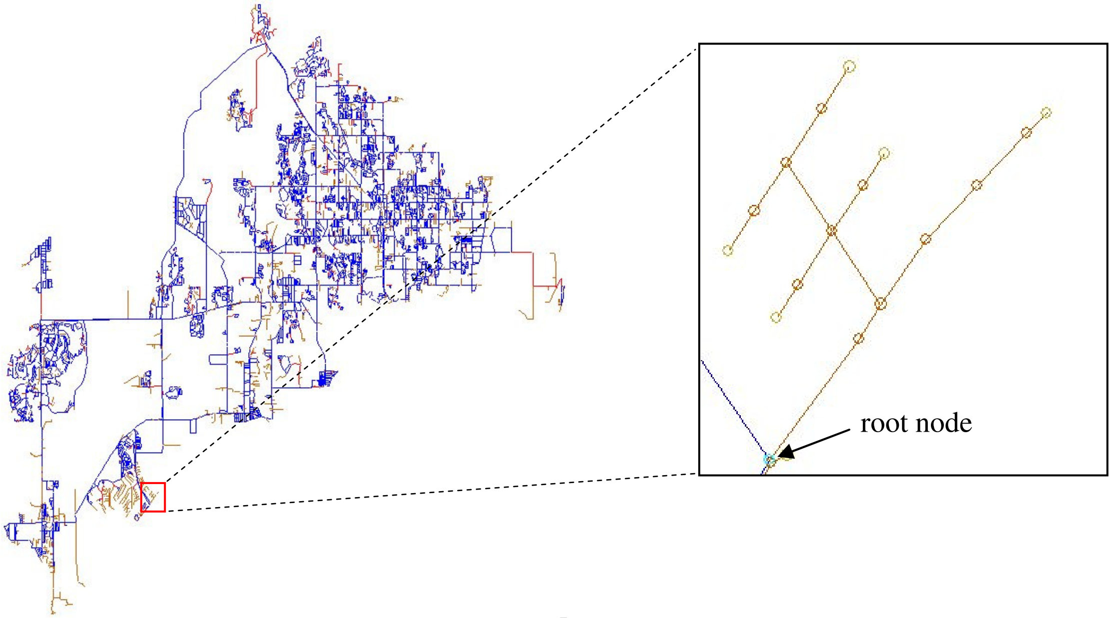


Figure 3. Tree Structure (17 nodes, 16 pipes, 1.9 km)

It is assumed that an intrusion theoretically can take place at every node. Contamination events with low mass input can be detected if and only if a sensor is in the same tree downstream of the input node. The contaminated water plume is limited to the tree structure. A full coverage of the selected tree in Figure 3 with no non-detection events requires a total of five sensors at the end nodes. In general, the number of sensors required n_S can be calculated by $n_S = n_P - n_B$ where n_P is the number of path elements (pipe sequence without bifurcation) with possible input of contaminant and n_B is the number of bifurcation nodes (nodes with more than two pipes connected). In our example that means that we had to install sensors in 1459 tree subnetworks for full coverage of the network. As already mentioned by Ostfeld et al. (2008) the sensor optimization problem often results in non-detections for intrusion. This can be explained by the existence of tree structures within the network.

In addition to the huge number of sensors required for full coverage of the forest subgraph another shortcoming of the location of sensors in trees is the very long time to detection. For source tracking the tree nodes are poorly suited as well since, under the assumption of conservative behaviour of the contaminant and input upstream within the tree, all the nodes have the same concentration of mass. Therefore a much better choice for the installation of a sensor is the root node of the tree because it belongs to both the tree and the network upstream. Consequently, our suggestion is to exclude the forest structure from the algorithmic sensor allocation problem. Exceptional cases, e.g. if a very important building (hospital, military and/or governmental buildings) belongs to the network forest, they should be treated by engineering judgement. In the next section the network is simplified by removing the forest. For the further analysis only the core of the network graph will be investigated.

3.2. Core subgraph of the network and separated blocks

In general, the core part of the water distribution systems consists of looped blocks that are connected by bridge components or single articulation points. The bridge subgraphs have similar properties to the trees of the forest. For all the pipes of the bridge subgraphs, the flow direction is known without hydraulic calculation. A contamination event influences the components only downstream. For the investigation of contaminant scenarios within the sensor allocation problem the looped blocks of the grid can be studied separately. Three cases have to be distinguished.

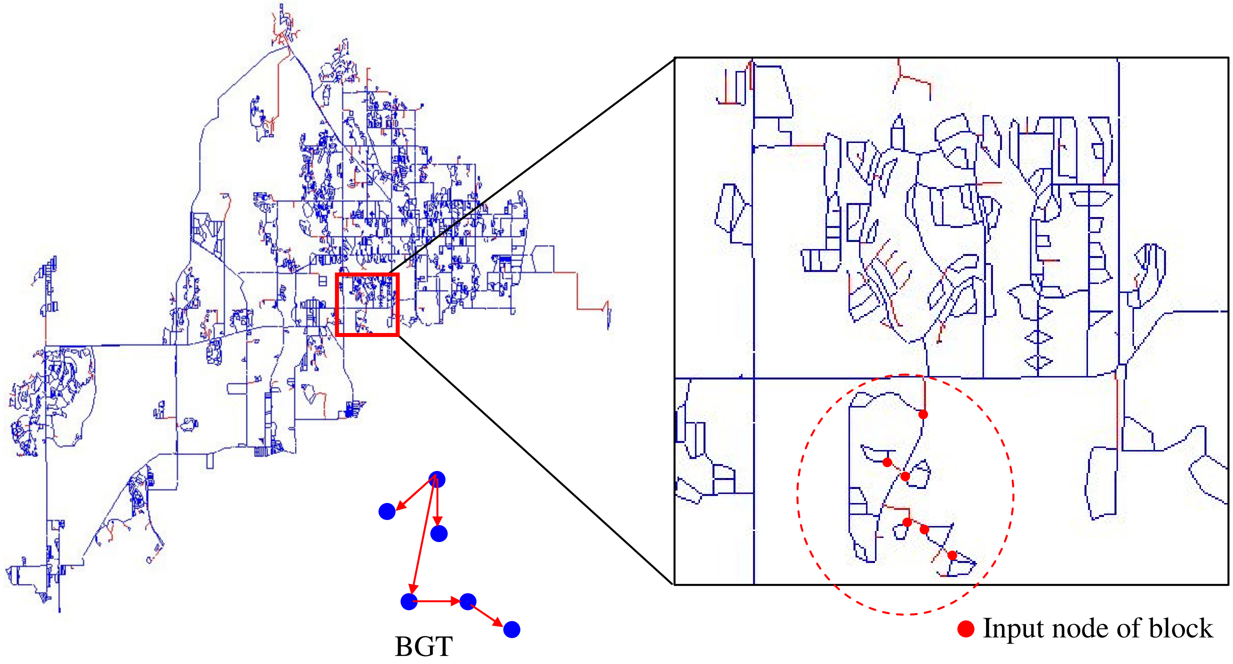


Figure 4. Core of network 2 of the BWSN (9059 nodes, 11023 pipes, 1399 km)

In the first case, the contamination is assumed to be within the same block which is investigated for sensor placement. Since the flow direction in the bridge that connects the block with its upstream block is always the same there is no way for the concentration to reach the upstream block with one exception: a large amount of water is pumped into the system in order to replace the total water volume of the pipes of the block and reverses the flow in the bridge component. This case will be treated separately in the following section. Under the assumptions of the BWSN (Battle of the Water Sensor Networks) with an input volume of 125 L/h the substance will spread through the pipes and to nodes of the block only. In this case, the block can be treated like a separate network with an input reservoir at the connection node between the block and the bridge. In the red marked area in Figure 4, a sequence of blocks that are connected by bridges is shown for the BWSN-network 2.

The second case includes a contamination event in a downstream block. Here, the current block is not affected at all and needs no further investigation. In the third case the contamination source is assuemed to be in an upstream block. The contaminated water enters the block at the connection node. The block itself can be treated again as separate network with a contamination of its input node (the worst case scenario for the block). Depending on the size of the block and the number of people that are affected by a contamination of the block it can be decided if a sensor allocation problem is solved for the block.

Whereas a contamination in the block does not affect the upstream blocks at all there is a feedback between a sensor in the block and the contamination in an upstream block. The contaminated water enters the block via the bridge and can be detected by the sensor. Therefore the downstream block cannot be simply neglected. However, the information you can gain from more than one sensor in downstream blocks is just the same as for that of the first sensor reached. The water that enters the block is “channelled” by the bridge. A possible workaround is: the feedback can be considered by placing a sensor in the simplified network at the connection node representing all the sensors within the block that have been determined in the calculation before. The time delay that represents the time that the contamination front needs from entering the block to the alarm of the first sensor has to be considered at the connection. If there was no sensor calculated only the total consumption of the block has to be added to the connection node guaranteeing identical hydraulic behaviour of the full and the reduced system as well as keeping the same number of people exposed.

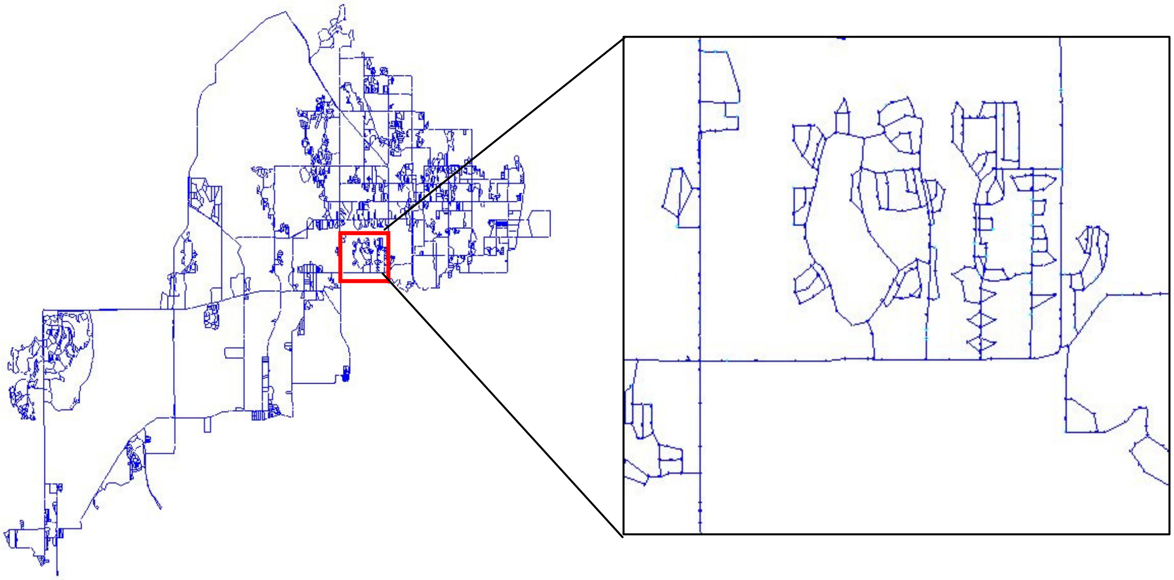


Figure 5. Main block of network 2 of the BWSN (6961 nodes, 8404 pipes, 1093 km)

A more practical solution follows from the observation explained above. The bridges are very well suited for the installation of sensors because of the following reasons. The bridge pipes are bottle necks for the subsequent blocks. All the water consumed within the block comes through the bridge pipe. Another important issue is that if a contamination is detected at a bridge pipe, the block can be easily isolated because only one valve has to be closed. A sequence of detection followed by a closure of the valve can protect the whole block subnetwork by closing only one valve.

In a similar way to the trees of the forest it can be decided by engineering judgment if the block is large enough and if it is worth installing sensors within the block. For optimal allocation of sensors numerical algorithms like TEVA-SPOT can be applied to the separated block network. The blocks are investigated in the direction from the leaves to the root of the so called block graph tree (Deuerlein 2006). The remaining system, after removing all subsequent blocks, is the main block of the network that includes all storage facilities and input points (Figure 5). The reduced system has 6961 nodes and 8404 pipes.

3.3. Identification of path elements within blocks

A further reduction of candidates for sensor placements and threats can be made by considering only the path nodes of the network graph. A path node is simply defined as a node that connects at least 3 pipes. A path element reaches from one path node to the next path node. All the nodes in between are called inner path nodes. Whereas the path nodes determine the connectivity of the whole block a path element with its inner path nodes can be treated as local subsystem. If both, hydraulics and water quality at the path nodes are known the calculation of the inner of the path is straight-forward and can be done locally without consideration of the rest of the network. As a consequence, the best coverage of the network can be reached by monitoring the water quality at path connecting nodes. Therefore we propose that for the sensor allocation problem, the feasible locations for sensors are reduced to the set of path nodes. For the main block of the BWSN example 2 the number of nodes can be reduced by 58 % (see Figure 6).

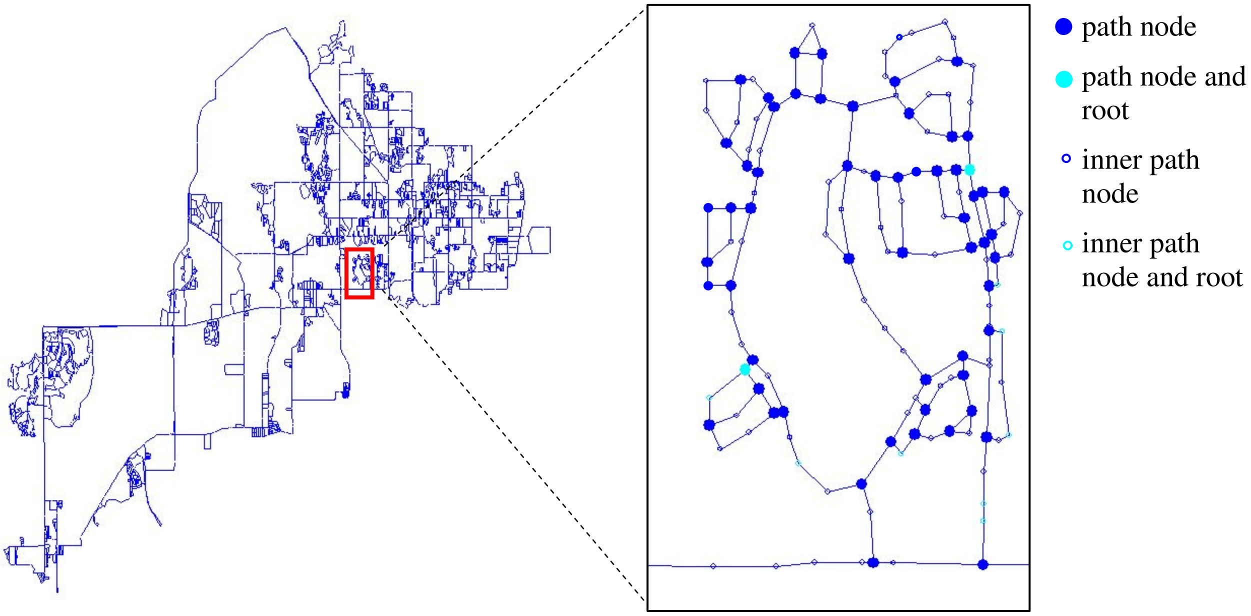


Figure 6. Path nodes and paths of the main block of network 2 of the BWSN (2936 path nodes, 4379 paths, 1093 km)

4. OTHER DETECTION METHODS

In the last section ideas for the simplification of the algorithmic problem of calculating optimal water quality sensor networks for the detection of contamination incidents were presented. However, due to often long response times of quality sensor alarms and their dependency on the kind of substance used it is appealing to develop other methods that are capable of sensing manipulations on the pipe system. For the observation of oil and gas pipelines online leakage detection methods are widely-used. Highly sensitive pressure sensors with very short sampling intervals in combination with deterministic (or statistical) leak detection software supports the quick identification of unusual behaviour and pressure waves that coincide with sudden appearance of a leak (Kasch, 2007).

Such classic leak detection methods are only applicable for detecting CRBN attacks when the pressure signal-noise distance is large enough. The signal is the pressure peak caused by the attack. The noise is the normal pressure fluctuation due to both fluctuating/stochastic demand and tracing pump and valve controller. To cause a signal peak at all, the CRBN attack must be done by pumping or injecting contaminated water volume into the system. To rise above the noise the contaminated water volume must be large enough and the pumping/injecting has to be done fast enough. The idea is to implement an early warning system for detection of the pressure waves that are caused by the input of substance and that can be metered by a common SCADA system. The input of dissolved contaminant is detected as a negative leak. As part of the research project STATuS, selected input scenarios have been studied by the use of water hammer calculation of the intrusion scenarios. The desired outcome of the theoretical investigation should include information whether it is worth following this approach. In case of a positive result the study will be extended by field tests. Different scenarios have been studied for both the urban and the regional supply systems. Two examples are given below.

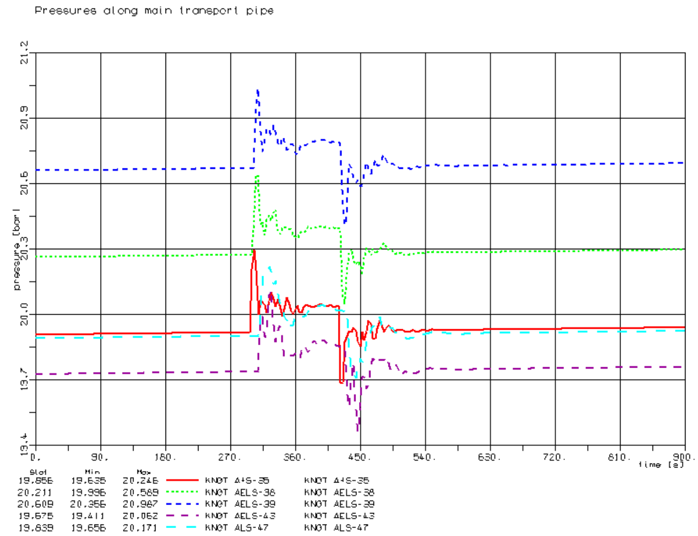


Figure 7: Pressure waves at different locations of the regional system

In Scenario 1, which is a regional system: An amount of 1 m³ is pumped into the main transport pipe from an installation in a valve chamber manhole within a time span of two minutes. The resulting water hammer with a sudden increase in pressure of about 4 m at the beginning of the insertion and the pressure drop at the end of about the same amount propagates through the entire system. Alternation effects are not observed until the reflection of the pressure wave at the tanks at the end of the system. Figure 7 shows the calculated pressures for a time interval of 15 minutes at different locations distributed over the whole system.

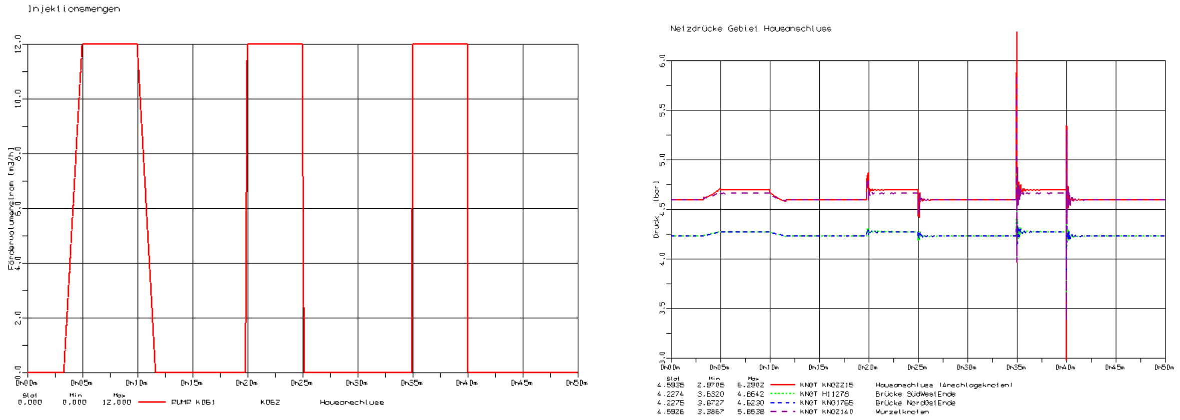


Figure 8: Influence of different starting times of the injection pump

In Scenario 2, for an urban system: In this scenario different starting times of the injection pump are considered. An amount of 1 m³ is pumped into the system (at the end of a treed component). The starting time of the pump that is used for injection of the contaminant is varied between 1 s and 100 s. The injection itself lasts five minutes. The left diagram in Figure 8 shows the plot of the input flow of the pump increasing linearly from zero to 12.0 m^3/h for the starting times 100 s, 10 s and 1 s. The right diagram of Figure 8 shows the system response (pressure measurements at different locations).

As it can be seen the long starting time of 100 s leads to a small increase in pressure during the time of injection which is not detectable in a real system where the pressures are permanently varying. With reduction of the starting time to 10 s and 1 s the water hammer that is caused by the sudden start of the pump causes a pressure head raise of 3 m and 17 m, respectively. In this case the incident could be detected by SCADA readings. A special characteristic of such a short injection incident by a pump is the appearance of positive and negative pressure drops in sequence. However, the quick energy dissipation in a looped urban system results in very short time intervals during which the pressure wave can be observed. As a consequence the pressure readings must have a high resolution in time in order to avoid non-detections.

5. SUMMARY AND CONCLUSION

The results of a scenario based investigation of security against terrorist attack with CBRN-substances of two German water supply networks have been presented qualitatively. The characteristics of different incident locations as to their accessibility as well as their topological position have been described. It turned out that different locations are better suited for different purposes that the terrorist might try to achieve. If for instance the attack is against a specific location (army, government, hospital, company, …) the branched parts of the network are preferable because the terrorist can be sure that the contaminant reaches its target. In contrast within the looped systems the spread of the substance is not easily predictable and dependent on the flow conditions which are in turn dependent on the demand pattern and the actual operation of the system at the time of intrusion.

The decomposition of the network graph also explains non detections in existing sensor placement algorithms like TEVA-SPOT and can be used for the reduction of the number of intrusion points and the simplification of the problem by aggregation. The detection of all possible incidents in the branched forest subgraph of a real network is impossible in practice since a huge number of sensors would be needed. For the mathematical model the forest should be excluded. A further simplification can be reached by considering looped blocks separately and reducing the number of incident locations and possible sensor placements to the path nodes of the graph. If required a local analysis of a path element (sequence of pipes between two path nodes) can be added.

Since quality sensors are not available for all agents and the delay in time between the incident and the detection cannot be eliminated even for well planned and optimized sensor networks the question for alternative detection methods has been posed. An initial idea for detection of the water hammer that is caused by an insertion pump has been presented. However, those methods are constrained to incidents that are executed with high pressure pumps. They are not applicable to detect incidents that are executed over a comparably long time and with low input pumping pressure or contamination of storage facilities. As a consequence those methods are not suited for substitution of sensor networks but possibly may be used to supplement sensor networks. More research is needed to better define appropriate criteria for usage.

In our opinion one important shortcoming of existing methods for contaminant detection is that the mathematical models are all based on offline simulations. However, the applicability and reliability of contaminant warning systems combined with hydraulic simulation models for early warning systems is crucial to real-time modeling. The real impact of a contaminant injection including the geographical coverage and the number of exposed people are all affected by the current water demand load and operation of the system. Offline hydraulic solvers are not applicable as operational tools because results generated by hydraulic calculations may strongly distinguish from the actual state of the physical system. Online-simulation tools are required that are capable of capturing the actual state of the system in seconds. Source identification and quick decisions on emergency measures like isolation of contamination, notification of population, flushing of contaminated pipes can be well-directed only if this information is provided by a process accompanying hydraulic solutions that always has the ability to reflect the current hydraulic state of the system with all its changing boundaries.

Acknowledgements

The research presented in this paper is part of the project STATuS (Support Code: 13N10623) that is funded by the German Ministry for Education and Research (BMBF).

References

Berry, J.; Boman, E.; Riesen, L. A.; Hart, W. E.; Phillips, C. A.; Watson, J.-P.; Murray, R. (2009). User's Manual TEVA-SPOT Toolkit Version 2.3. *Report EPA 600/R – 08/041A National Homeland Security Research Center, Office of Research and Development.* Download, April 13th 2010 at: www.epa.gov/NHSRC/pubs/600r08041a.pdf.

Deuerlein, J. W. (2008). Decomposition model of a general water supply network graph. *Journal of Hydraulic Engineering,* ASCE, 134(6), 822 - 832.

Deuerlein, J. W. (2006). Efficient supply network management based on linear graph theory*, Proceedings of the 8th Annual Water Distribution System Analysis Symposium*; Cincinnati, Ohio, USA; August 27-30.

Jiang, B. (2002). Risk Management and the Office of Homeland Security's Antiterrorism Task. *The Online Journal of Peace and Conflict Resolution* 4.2: 30 – 36.

Kasch, M. (2007). Performance Characteristics of Deterministic Leak Detection Systems. *3R International, Special 2007(1)*, 65-69.

Ostfeld, A.; Uber, J. G.; Salomons, E.; Berry, J. W., Hart, W. E.; Phillips, C. A.; Watson, J.-P.; Dorini, G.; Jonkergouw, P.; Kapelan, Z.; di Pierro, F.; Khu, S.-T.; Savic, D.; Eliades, D.; Polycarpou, M.; Ghimire, S. R.; Barkdoll, B. D.; Gueli, R.; Huang, J. J.; McBean, E. A.; James, W.; Krause, A.; Leskovec, J.; Isovitsch, S.; Xu, J.; Guestrin, C.; VanBriesen, J.; Small, M.; Fischbeck, P.; Preis, A.; Propato, M.; Piller, O.; Trachtman, G. B.; Wu, Z. Y.; and Walski, T. (2008). The Battle of the Water Sensor Networks (BWSN): A Design Challenge for Engineers and Algorithms*; Journal of Water Resources Planning and Management*, 134 (6), 556 – 568.

"Ostfeld et. al. BWSN files." Download Section: Benchmarks. Centre for Water Systems, University of Exeter, http://centres.exeter.ac.uk/cws/downloads/cat_view/28-benchmarks, Download, April 19th 2010.

Smith, P. (1999). "Managing Risk as Product Development Schedules Shrink," *Research & Technology Management* 25-32 (September-October 1999).