Identification of Possible Contamination Sources Using Reverse Hydraulic Simulation

By Elad Salomons [1] and Avi Ostfeld [2], Member ASCE

[1] Director, OptiWater (http://www.optiwater.com), 6 Amikam Israel St., Haifa 34385, Israel; PH and FAX: +972-54-2002050; E-mail: selad@optiwater.com

[2] Associate Professor, Faculty of Civil and Environmental Engineering, Technion – I.I.T, Haifa 32000, Israel; PH +972-4-8292782; FAX +972-4-8228898; email: ostfeld@tx.technion.ac.il

Keywords: contamination identification, source detection, water security, water distribution

Abstract

In case of a contamination in a water distribution system the water quality sensors should ring the alarm bells. Once a contamination is detected by one or more sensors, the immediate question is what is the source or sources of pollution. Assuming the network's hydraulics are known, this paper describes a method of using a reverse hydraulic and quality simulation to identify all of the networks nodes that can "reach" a specific set of sensors at a given time. Using real time SCADA data a hydraulic simulation of the system is performed up to the detection times and the hydraulic simulation results are reversed. Then, a theoretical water quality simulation is performed with tracers injected at the node associated with the sensors that detected the contamination. The algorithm tracks and records the tracers upstream to find all possible contaminating nodes. By using a superposition technique for all possible contaminating nodes, the algorithm can find the most likely set. The algorithm may suggest the location of the contamination source while providing information regarding safe areas in the network. This methodology is fast enough to be used in real time and simple to implement. The methodology is demonstrated through a simple example application.

Introduction

Since the events of 9/11 2001 in the US there is a growing concern around the world over the security of water distribution systems. Water distribution systems are spatially diversed and thus are inherently vulnerable, with one of the most serious threats considered to be a deliberate terrorist contamination injection at one of the network nodes.

To reduce the risk to public from such a threat, protective actions need to be undertaken. Those include two foremost actions: improving the system physical security (e.g., fences, guarding, surveillance instrumentations, etc.), and sensors placement. If all system nodes could be reliably monitored then the maximum level of safety would have been gained. This is obviously not possible, and thus to cope with this constraint various methodologies for monitoring stations layout design were developed (e.g., Kessler et al. 1998; Al-Zahrani and Moied 2001; Woo et al. 2001; Ostfeld and Salomons 2004; Berry at al. 2005, 2006; Propato 2006).

Once monitoring stations are placed, a complimentary model should provide the ability to solve the contamination source identification problem of revealing the characteristics of a contaminant intrusion: its location, starting time, duration, and mass rate. Such a tool is required for both immediate police actions and system response activities such as contaminant containment and public warning announcements.

Previous work on contamination source identification for water distribution systems used various approaches: Shang et al. (2002) suggested an input-output model which provides information about the relationships between water quality at input and output locations by tracking water parcels, and moving them simultaneously along their paths; Laird at al. (2005) presented an origin tracking algorithm for solving the inverse problem of contamination source identification based on a nonlinear programming framework; Preis and Ostfeld (2006) introduced a hybrid approach for contamination source identification in water distribution systems using a coupled model trees – linear programming scheme; Laird et al. (2006) addressed the non-uniqueness difficulty of the outcome of the nonlinear model of Laird et al. (2005) by incorporating a mixed-integer quadratic program to refine the solutions provided by the nonlinear formulation; Preis and Ostfeld (2007, 2008), and Zechman and Ranjithan (2009) suggested a genetic algorithm (Holland, 1975) framework for contamination source detection.

The methodology presented in this study solves the problem of contamination source identification for water distribution systems using reverse hydraulic modeling.

Methodology

The idea of reverse hydraulic modeling for contaminant source identification is extremely simple and efficient: once a contaminant has been detected at a sensor location, a hydraulic simulation is performed from a user defined time up to the detection time. First, the hydraulic results are reversed (i.e., consumers become sources, sources become consumers, and the flow quantities and directions are reversed). Second, a tracer is injected at the location and time of the detection and a water quality simulation is performed using the reversed flows for a duration defined by the user. All nodes the tracer reaches are potential sources of contamination. Those nodes identified as a result of reverse hydraulics through multiple sensors, correspond to the most likely locations and times of the contaminant source intrusion. The methodology is best demonstrated using a simple example application.

Example application

The example application layout is shown in Fig. 1 (Ostfeld et al., 2008). The system is subject to a varying demand pattern of 96 hrs, consists of 126 nodes, 168 pipes, one constant head source, two tanks, two pumps, and eight valves. The system full EPANET input file is available at http://centres.exeter.ac.uk/cws/benchmarks where the complete data (e.g., pipe diameters, demands, pump curves, etc.) can be downloaded.

To test the methodology two sensors (Fig. 1) are placed at JUNCTION-18 and JUNCTION-68, and a contaminant is injected at JUNCTION-22 at 12:55 AM for a duration of five minutes. As a result, a contamination plume is being spread in the network, reaching JUNCTION-18 at 05:20 AM and JUNCTION-68 at 08:00 AM. Reverse hydraulics is thus invoked at JUNCTION-68 at 08:00 AM and at JUNCTION-18 at 05:20. The backwards time duration is set to 8 hrs (i.e., until 12:00 midnight). Fig. 2 shows the Contamination Source Detection (CSD) program interface used for this task.

Fig. 3 describes the results of this experiment: at time 05:00 AM (top left corner of Fig. 3) three possible contamination source locations are identified with "one sensor detection" (i.e., an alarm indication of one sensor); at 02:45 AM six contamination sources are detected yet with only one sensor detection; at 01:00 AM five possible contamination sources are found with one sensor detection, but also one location with both sensors detection, which also refers to the exact location and time of the intrusion; at 00:40 AM six one sensor detection locations are revealed and three "all sensors detection locations". The later are all in the vicinity of the true contamination source position at JUNCTION-22.

Conclusions

A simple and powerful contamination source identification methodology based on reverse hydraulics was described and demonstrated. The method is able to identify quickly and accurately possible contamination sources. Further developments of the proposed scheme for real life networks are currently been undertaken.

Acknowledgements

The substantial contribution of Danny Weintrob to the algorithm development and application is highly acknowledged.

References

Al-Zahrani M. and Moied K. (2001). "Locating optimum water quality monitoring stations in water distribution system." In Bridging the Gap: Meeting the World's Water and Environmental Resources Challenges, Proceedings of the ASCE annual conference on Water Resources Planning and Management, published on CD.

Berry J. W., Fleischer L., Hart W. E., Phillips C. A., and Watson J. P. (2005). "Sensor placement in municipal water networks." Journal of Water Resources Planning and Management Division, ASCE, Vol. 131, No. 3, pp. 237-243.

Berry J. W., Hart W. E., Phillips C. A., Uber J. G., and Watson J. P. (2006). "Sensor placement in municipal water networks with temporal integer programming models." Journal of Water Resources Planning and Management Division, ASCE, Vol. 132, No. 4, pp. 218-224.

Holland J. H. (1975). "Adaptation in natural and artificial systems." The University of Michigan Press, Ann Arbor.

Kessler A., Ostfeld A., and Sinai G. (1998). "Detecting accidental contaminations in municipal water networks." Journal of Water Resources Planning and Management Division, ASCE, Vol. 124, No. 4, pp. 192-198.

Laird C. D., Biegler L. T., van Bloemen Waanders B. G., and Bartlet R. A. (2005). "Contamination source determination for water networks." Journal of Water Resources Planning and Management Division, ASCE, Vol. 131, No. 3, pp. 125-134.

Laird C. D., Biegler L. T., van Bloemen Waanders B. G. (2006). "Mixed-integer approach for obtaining unique solutions in source inversion of water networks." Journal of Water Resources Planning and Management Division, ASCE, Vol. 132, No. 4, pp. 242-251.

Ostfeld A. and Salomons E. (2004). "Optimal layout of early warning detection stations for water distribution systems security." Journal of Water Resources Planning and Management Division, ASCE, Vol. 130, No. 5, pp. 377-385.

Ostfeld A. et al. (+ 34 co-authors) (2008). "The battle of the water sensor networks: a design challenge for engineers and algorithms." Journal of Water Resources Planning and Management Division, ASCE, Vol. 134, No. 6, pp. 556-568.

Preis A. and Ostfeld A. (2006). "Contamination source identification in water systems: a hybrid model trees - linear programming scheme." Journal of Water Resources Planning and Management Division, ASCE, Vol. 132, No. 4, pp. 263-273.

Preis A. and Ostfeld A. (2007). "A contamination source identification model for water distribution system security." Engineering Optimization, Vol. 39, No. 8, pp. 941 - 951.

Preis A. and Ostfeld A. (2008). "A genetic algorithm for contaminant source characterization using imperfect sensors." Civil Engineering and Environmental Systems, Vol. 25, No. 1, pp. 29 - 39.

Propato M. (2006). "Contamination warning in water networks: general mixed-integer linear models for sensor location design." Journal of Water Resources Planning and Management Division, ASCE, Vol. 132, No. 4, pp. 225-233.

Shang F., Uber J. G., and Polycarpou M. M. (2002). "Practical back-tracking algorithm for water distribution system analysis." Journal of Environmental Engineering, ASCE, Vol. 128, No. 5, pp. 441-450.

Woo H. M., Yoon J. H., and Choi D. Y. (2001). "Optimal monitoring sites based on water quality and quantity in water distribution systems." In Bridging the Gap: Meeting the World's Water and Environmental Resources Challenges, Proceedings of the ASCE annual conference on Water Resources Planning and Management, published on CD.

Zechman E. M. and Ranjithan R. (2009). "Evolutionary computation-based methods for characterizing contaminant sources in a water distribution system." Journal of Water Resources Planning and Management Division, ASCE, Vol. 135, No. 5, pp. 334-343.

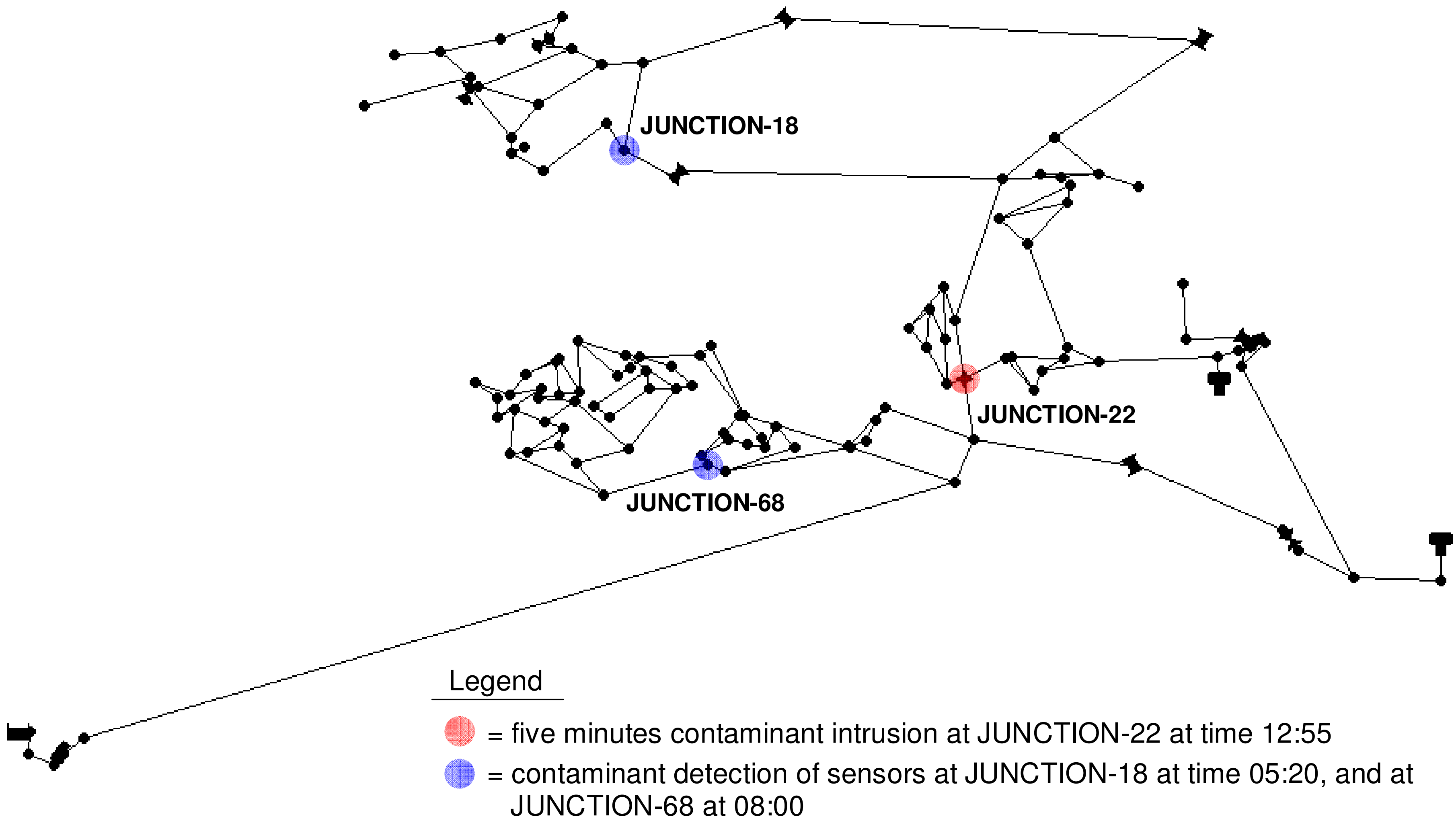

Fig. 1: Example application layout (Ostfeld et al., 2008)

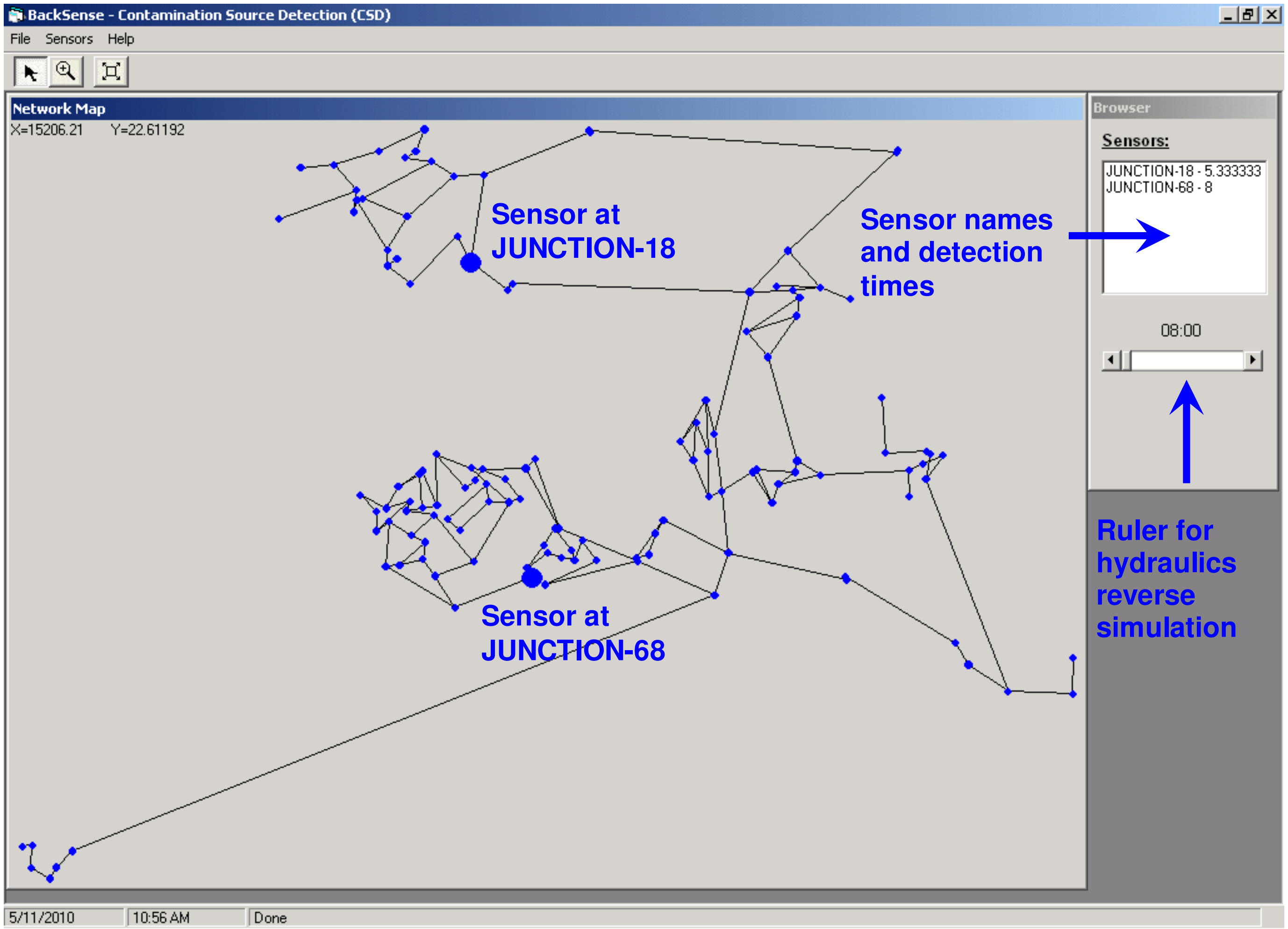

Fig. 2: Contamination Source Detection (CSD) program interface

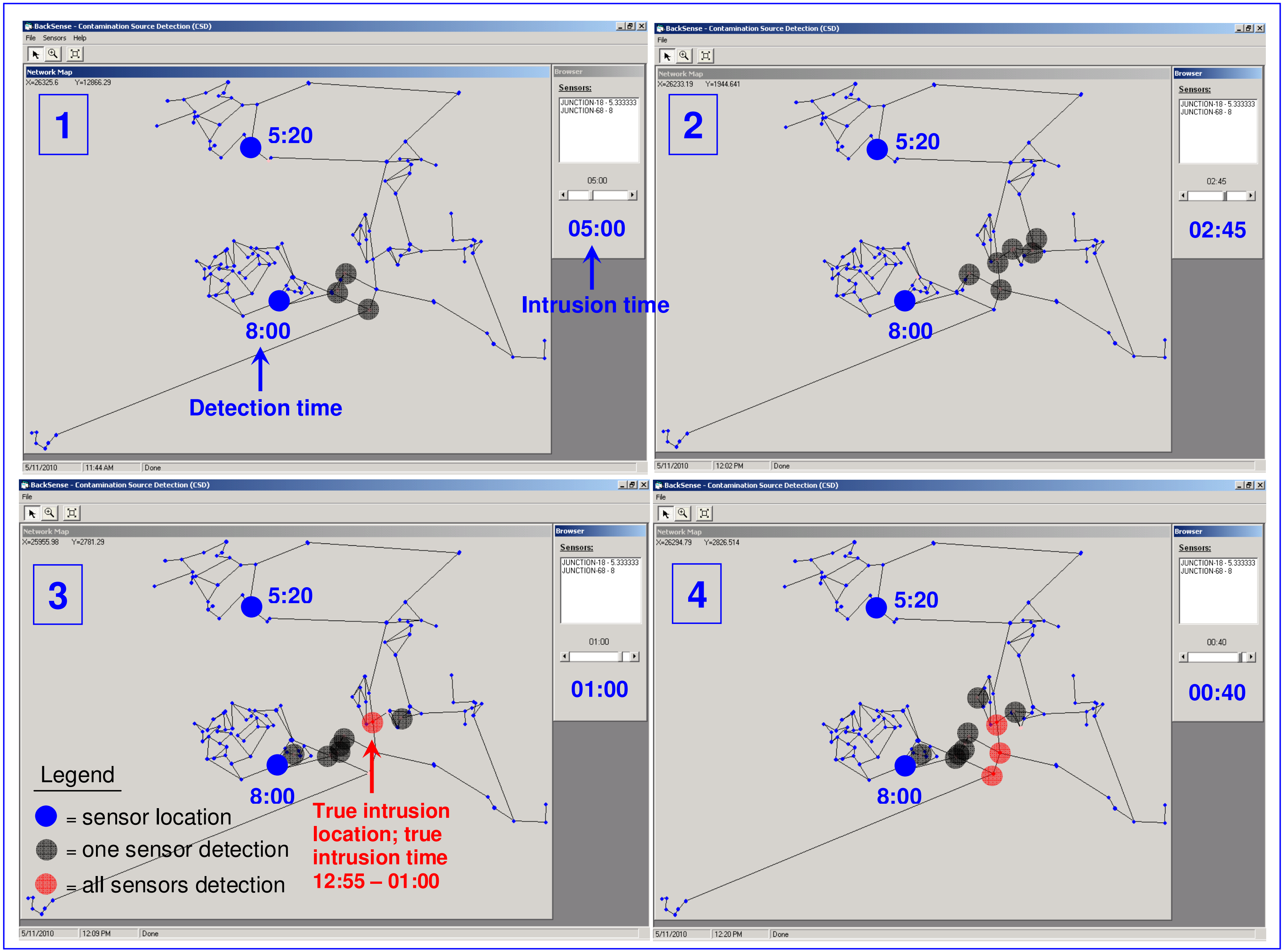

Fig. 3: Snapshots of hydraulics reverse simulation results for possible intrusion locations and times