1st International WDSA / CCWI 2018 Joint Conference, Kingston, Ontario, Canada – July 23-25, 2018

Improving Contamination Detectability in Water Distribution Systems using Active Fault Detection

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ABSTRACT

Contamination event detection in Water Distribution Systems (WDS) is an important part of the overall procedures followed by operators to ensure the delivery of safe drinking water to consumers.

In practice, detection methodologies may use a small number of sensors, which may be placed optimally throughout the network, to monitor water quality. Typically, due to their high costs, only a small number of these sensors are available within each WDS, and as a result, a part of the network is not monitored by sensors.

In this paper, we propose a novel methodology for detecting contamination events by increasing the area monitored by these water quality sensors. Specifically, the proposed methodology can be used in emergency cases when information is available about a possible contamination event in the system, to actively manipulate WDS actuators, by closing and opening valves, and alter the flow directions within the network.

This is based on the concept of Active Fault Detection, in which the control input of a system is modified with the aim to improve detectability of a fault.

This active detection scheme, drives flows from specific parts of the network in pre-determent paths, to allow the sensors to monitor the quality of water from previously unobserved parts of the network. As a result, the monitoring coverage of the sensors is increased and some contamination events occurring within those areas can be detected. Moreover, the methodology facilitates the isolation of the contamination propagation path and its possible source. We demonstrate how such goals can be achieved on two simple example networks, discuss the benefits of the results and open the discussion for further work in this area.

Keywords: Water Distribution Systems, Active Fault Detection, Contamination Detectability

1 Introduction

Water Distribution Systems (WDS) are complex, life-essential structures that provide quality water to consumers with required amounts, hence making their proper operation a top priority for any system operator. One of the most popular techniques used to ensure the quality of the provided water for the consumers along the distribution network is water quality monitoring in selected points using fixed sensors (Ostfeld et al., 2008) (Krause, Leskovec, Guestrin, VanBriesen, & Faloutsos, 2008). Such sensors are built on top of the existing system elements providing continuous monitoring of the water flow through them and alert any discrepancy from the required values either by remote data transfer or manual measuring. Any deviation from the required quality is considered as a fault and needs to be quickly detected and treated to prevent extensive damage to consumers and high rehabilitation costs.

The selected points for sensor location are determined, in most cases, using an optimal analysis of the WDS topology and hydraulics to achieve, mainly, three goals: (1) maximal coverage of the network, (2) early detection of fault events and (3) information on the event source — all with a minimal number of sensors. The result of such analysis is a set of sensor at specified locations. This kind of layout is regarded in this paper as a Passive Fault Detection (PFD) scheme since it is based on the existing topology and hydraulics of the network without any manipulations on them. The system topology and hydraulics are regarded as given data and the layout solution is applied on it.

In contrast to the scheme described above, an Active Fault Detection (AFD) scheme performs changes on network topology and hydraulics usnig actuators (i.e. valves, pumps) to improve the performance of fault detection in the network (Niemann, 2006) (Simandl & Puncochar, 2009 in regard to the three main goals described above. Such manipulation may include changes in pumping schedules or tank operations, reconfiguration of the system elements such as pipes, valves or diameters, adding or removing of system elements or any other change to the topology or the hydraulics of the network. The concept of AFD has been studied during the last decade mainly in the field of electrical engineering (S L Campbell, Horton, & Nikoukhah, 2002; Stephen L Campbell & Nikoukhah, 2015). The basic methodology uses an active input into the network called the auxiliary signal — a set of known, pre-determent input procedures in known times to improve the detection ability of a sensor (Stephen L Campbell & Nikoukhah, 2015). The time after the signal is generated is a test period after which the sensor determines whether the system has failed. Detections made during the test period are focused in terms of the failure origin.

The auxiliary signal can be actively generated in various forms – depending on the type of system. In WDS such signal may include quality variations in selected points (i.e. booster chlorination), DATA transformation between network elements (i.e. Internet of Things – IoT), pressure variations, change in pump schedule or, the one used in this work, actively scheduling of valve operation to create specific, different flow paths.

To demonstrate the approach described above, a simple eight (8) nodes network is presented (Figure 1). The flows are constant in direction and the water travel time between nodes i and j is $\tau_{ij}=1$. A quality sensor is located at node S.

Figure 1(a) demonstrates the PFD given layout of the network. The set of nodes that is covered by the sensor S are nodes {1,2} and the links connecting them (highlighted in red). In this layout, any contamination originating from other nodes will not be detected by the sensor.

Figure 1(b) demonstrates how with the same topological layout, by actively closing the link between node 2 and S, an AFD approach improves fault detectability by increasing the set of covered nodes to {1,2,3,4,5,6} and the associated links (highlighted in red).

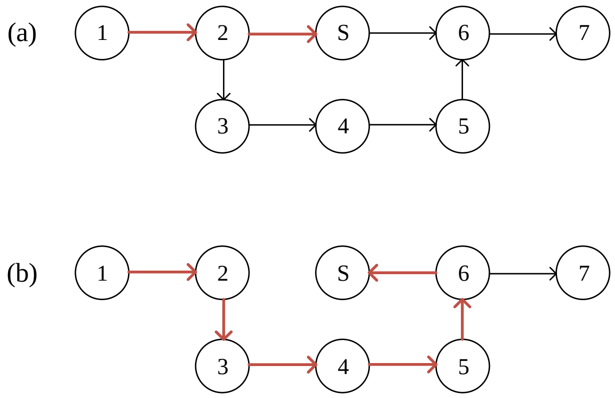


Figure 1. Passive Vs. Active Fault Detection schemes

2 Problem Formulation

A Water Distribution Network (WDN) described by a graph $\mathrm{G} = \{\mathrm{N}, \mathrm{L}\}$ is given, where the nodes N represent junctions of pipes and water demand locations and the links L represent pipes and pumps. In this network there exists a subset of nodes, indicated by N_s , where stationary water contamination sensors are installed. Each node *i* in N is associated with a water demand at the node location, indicated by $d_i(k) \in \mathbb{R}$.

For this initial work it is assumed that there is a time period *T* for which water demands are constant, thus $d_i(k) = d_i, k \in T$. This is a typical case of night flow conditions. The status of the pumps is also assumed known and constant. Thus, for a given network configuration and for the time period *T*, the water flows q_i in all pipes $j \in \mathrm{L}$ are constant. We assume all pipes in L have valves installed that can remotely and instantly be closed or opened. The status of each pipe *j*, i.e. the status of the valve on each pipe, is indicated by $u_j(k) \in \{0,1\}$ where $u_j(k) = 0$ if the valve is closed at the discrete time step *k* and $u_j(k) = 1$ otherwise. By changing the valve settings, the incidence matrix of graph G is modified.

This work aims to develop an algorithm that maximizes the monitored area of the network using the installed contaminant sensors, by changing the status of pipe valves, while satisfying mass balance equations of the network, i.e. all consumer demands are satisfied considering some minimum pressure requirements. Specifically, the algorithm should take advantage of the spatio-temporal relationships in the network and ensure that water that passes from an unmonitored node *i* at a time step *k*, will eventually pass through a sensor node at a later time step *k* + *Tr*, where *Tr* is the water travel time from the unmonitored node to the sensor node. At time step *k* + *Tr* the aforementioned node *i* becomes a monitored node. In other words, for a node to be monitored there should exist a directed path from that node to a sensor node, for a period of time *t* that is equal or longer than the water travel time *Tr* from that node to the sensor, *i.e.* $t \geq Tr$. The output of the algorithm, will be a binary matrix $U(k) \in \{0,1\}^{n_l \times m}$, where n_l is the number of links and *m* is the number of time segments that are needed for the algorithm to monitor the whole network. This represents the status schedule of pipe valves in the network.

In the event of contamination detection, the algorithm should be able to localize the contamination source. This can be achieved by back-tracking the contaminant through the path that brought it to the sensor node. Using the detection time *Td* and the travel time of the contaminant through the path, the contaminated source can be located. This implies that the path should not have multiple source nodes. If at the time of detection, the path has multiple source nodes, the algorithm should be able to distinguish the contaminated nodes by generating network configurations that have isolated paths from the possible contaminated nodes to the sensor nodes.

In this work, an algorithm that generates the described above paths is described. The algorithm generates the paths by starting from the source node and following all connected links until reaching a water source node. If more than one connected link is available, the algorithm closes the valves on the maximal number of links to leave only the minimal number of links required for water balance conditions in all nodes of the network, while ensuring that no other flow sources available on the path except the water source thus ensuring the origin of any water flow in the specific path. This condition is crucial for isolation of the infection source. In each step where a valve has been determined closed, the algorithm solves the new network with the closed valve to ensure all demands are satisfied and stores that operation in the output matrix. Each junction where valves had been stored as closed in the output matrix, is a candidate junction for re-visiting in a different path.

3 Example Application #1

To demonstrate the potential of the above described methodology it is demonstrated on NET1 WDS (Rossman, 2008). The network has one sensor located at node #32 (Fig. 2). It can be observed from the flow links direction, that the coverage area of the sensor does not include nodes #13 and 23, nor pipes #12, 133 and 32. Any contamination sourcing in the above nodes or pipes will not be discovered by the sensor layout for this network. The algorithm steps, as used in this example, are given in Table 1 and explained below.

Table 1. Algorithm steps for Net1 example network

Step #	Current Node	Link	Next Node	Closing Link	Path #	Comments
0	32	31	31	122	**1**	
1	31	121	21			
2	21	111	11	21		
3	11	10	10			Cannot close link 11
4	10	9	9			Finish path
0	32	31	31	122	**2**	
1	31	121	21			
2	21	21	22	111		
3	22	112	12	22		
4	12	11	11			Cannot close link 12 or 110
5	11	10	10			
6	10	9	9			Finish path
0	32	122	22	31	**3**	
1	22	22	23	112, 21		
2	23	113	13			
3	13	12	12			Cannot close link 110
4	12	11	11			
5	11	10	10			Cannot close link 111
6	10	9	9			Finish path

The “Step” column in Table 1 counts the number of steps to generate each distinguished path from the sensor to the source while “Current Node” “Link” and “Next Node” describe the algorithm propagation trough the network elements. The “Closing Link” column stores the link identifying number of which the algorithm had to close in each path to ensure single source flow of the path described in the “Path” column. Where "Cannot close link #" is mentioned in the step “Comments” it means the closing of the specific pipe will cause the new network hydraulic simulation to fail in water balance condition.

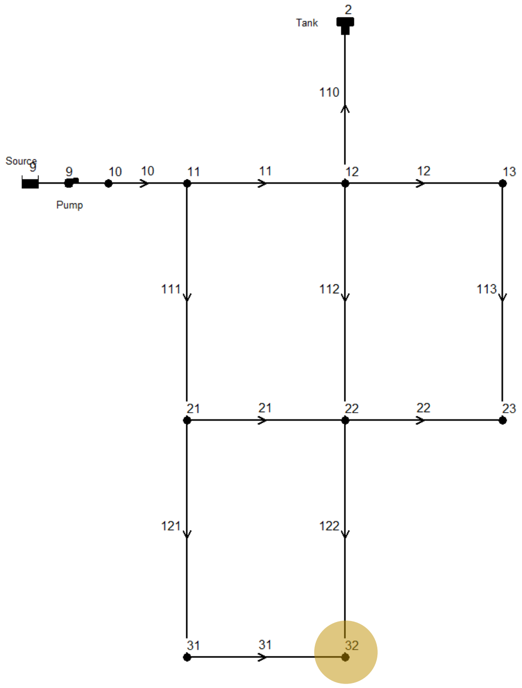


Figure 2. Net1 WDS simulation with sensor location in node #32 (highlighted)

Figure 3 shows the resulting paths from the algorithm application on Net1. It can be observed that the resulting 3 paths cover all nodes and links in the network with only one sensor installed. Although in the problem simulation it was assumed all pipes have valves, the result for Net1 can be achieved with only 6 valves located on links #122, 21, 111, 22, 31 and 112. This list of valve locations is a direct result from the algorithm simulation (Table 1, column Closing Link). The isolated part of the network in each path is the flow links connecting the water source to the sensor location.

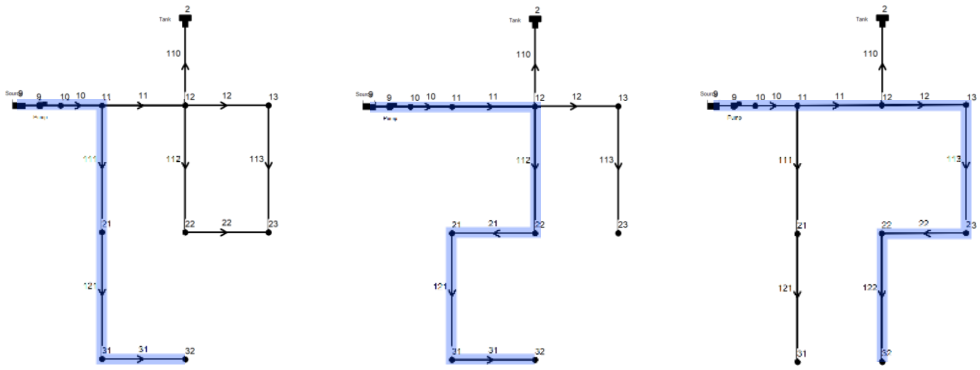

Path 1 **Path 2** **Path 3**

Figure 3. The resulting 3 paths on Net1 example. Flow path is marked in blue

4 Example Application #2

The same concept is demonstrated on the Hanoi WDS (Fujiwara & Khang, 1990) with minor modification to the original WDS: (1) the branch parts were removed and (2) the reservoir head has been increased to 10,000 feet (to overcome any hydraulic constraints in all flow paths) (Fig 4.). The first modification was made because branched parts cannot be completely covered by any sensor located other than the end node of the branch (in constant flow condition) The second modification was to ensure no negative pressures throughout the algorithm simulation. The modified Hanoi network was tested with a single sensor location at node #30. Again, it can be seen from the flow scheme that the entire part to the right to links #28, 16, 17, 18 and 19 is not covered by the sensor located at node #30 (no flow from these nodes to the sensor location). The same algorithm steps have been applied as described in Table 2.

Table 2. Algorithm steps for modified Hanoi example network

Step #	Current Node	Link	Next Node	Closing Link	Path #	Comments
0	30	31	29	32	1	
1	29	30	28			
2	28	29	23			
3	23	23	20	24		
4	20	20	3			
5	3	2	2	19		Cannot close link 3
6	2	1	1			Finish path
0	30	32	31	31	2	
1	31	33	32			
2	32	34	25			
3	25	25	24	26		
4	24	24	23			
5	23	23	20			Cannot close link 29
6	20	20	3			
7	3	2	2	19		Cannot close link 3
8	2	1	1			Finish path
0	30	32	31	31	3	
1	31	33	32			
2	32	34	25			
3	25	26	26	25		
4	26	27	27			
5	27	28	16			
6	16	16	17	15		
7	17	17	18			
8	18	18	19			
9	19	19	3			
10	3	2	2			Cannot close link 3 or 20
11	2	1	1			Finish path

0	30	32	31	31	**4**	
1	31	33	32			
2	32	34	25			
3	25	26	26	25		
4	26	27	27			
5	27	28	16			
6	16	15	15	16		
7	15	14	14			
…	…	…	…			
15	4	3	3			
16	3	2	2			Cannot close link 19 or 20
17	2	1	1			Finish path

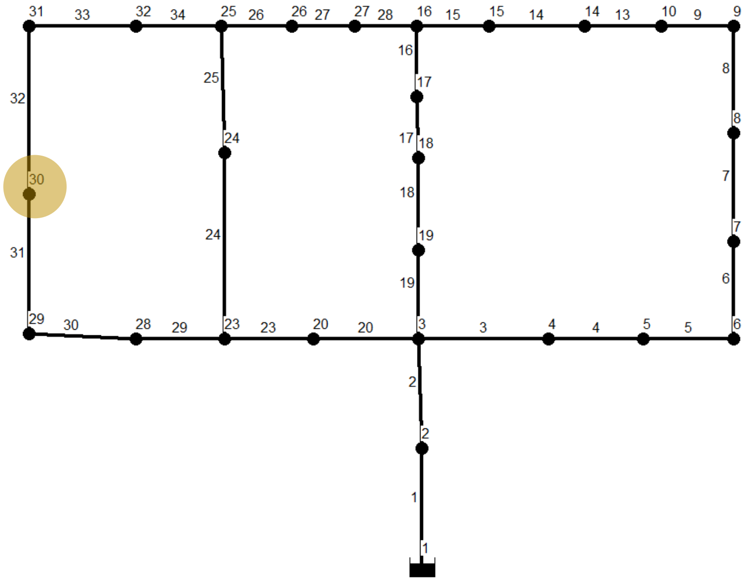
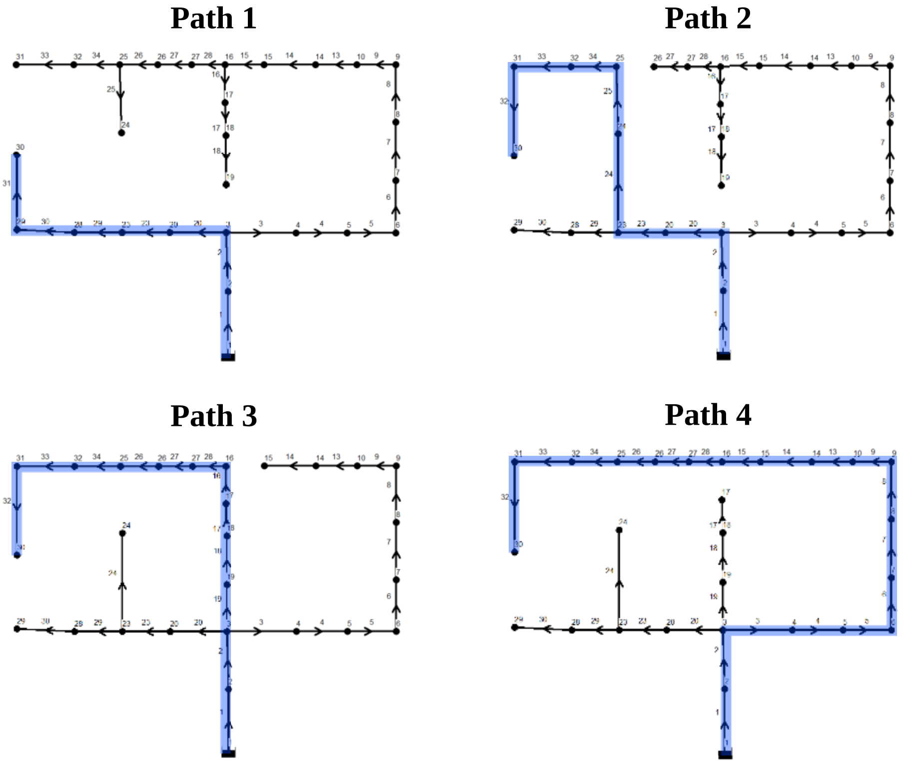


Figure 4. Modified Hanoi WDS simulation with sensor location in node #30 (highlighted)

The algorithm produced four distinct steps on the example network, covering all nodes and links in the network using only one stationary sensor. In this example, 8 valves are required to ensure the resulting 4 paths located on links #32, 24, 19, 31, 26, 25, 15 and 16 (fig. 5).



Path 1

Path 2

Path 3

Path 4

Figure 5. The resulting 4 paths on the modified Hanoi example. Flow path is marked in blue.

5 Discussion

The results from both examples show that following two goals determined in the problem formulation of this paper are achieved by the suggested algorithm:

(1) In terms of increased coverage– both examples show how parts of the network not originally covered before the application of the algorithm were monitored with no sensors added. This result is beneficial in terms of improving the performance a single sensor without any added cost.

(2) In terms of infection source isolation – the generated paths from both examples have a unique flow path from source to sensor, a fact that reduces the candidate part of the network from which a detected infection may have originated.

Although the heuristic algorithm described in this paper shows promising results on the example networks, there are many challenges to be addressed before the successful systematic application of AFD concepts on WDS to improve contamination diagnosis. Specifically, the creation of flow paths from many areas of the network to sensors may not be feasible in different networks. An investigation of the feasibility of AFD algorithms on different topologies, flow conditions and sensor configurations is required.

Furthermore, even when a solution is feasible, the optimality of this solution in terms of detection time and contamination isolability must be guaranteed. Other considerations may be to minimize the control actions taken, thus minimizing intervention on network operation, as well as considering the cost of applying such control actions. The cost can be translated into economic cost of closing/opening valves, or into consumers affected by the contamination that would otherwise not be affected.

Finally, the algorithm should be automated and be able to calculate a solution even if multiple sensors exist in the network. Its operational schedule may include intermittent valve operation to increase performance.

6 Conclusions

This paper demonstrates the possibility of increasing the effectiveness of stationary water quality sensors in WDS using AFD concepts. Although the field of applications of such concepts in WDS is weakly studied, this work shows great potential in pursuing such methodologies. The problem is formulated by defining the goals and constraints for the application of this concept in WDS and a heuristic algorithm is proposed which complies with these goals and constraints in the two examples presented. Both presented examples show encouraging results, a fact strengthening the potential of the described methodology. Further work is encouraged as most of the challenges of using AFD concepts in WDS is not addressed in this paper.

7 References

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