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Improved Real-Time Monitoring and Control of Water Supply Networks by Use of Graph Decomposition

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Abstract

In this paper, the concept of graph decomposition is used for simplification and enhancement of solution algorithms for different problems related to water supply network security and management. Three examples including sensor placement, source identification and decision support for response actions are presented. The decomposition concept can be used as general framework for adaptive modeling. Based on one comprehensive all pipe model of the entire supply system, the most appropriate level of accuracy can be chosen. Unlike conventional network aggregations and simplification algorithms, the proposed model simplifications do not have the problem of losing the original information. The method is suited for being used within a real-time environment where calculation time is one of the most important requirements for practical applicability.

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Keywords: Real-Time Monitoring; Graph Decomposition; Network Simplification; Inverse Problems; Adaptivity

1. Introduction

Increasing availability of all pipe hydraulic simulation models and of remotely transmitted measurement data has opened up new possibilities for applications in hydraulic engineering. However, the new availability of data has also led to increasing complexity in hydraulic system analysis of water distribution networks. Especially in the case where the software runs in an online environment, short calculation times are crucial for the applicability of the model and related algorithms. One example gaining popularity is the use of hydraulic online simulation providing results for

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network hydraulics and water quality almost in real-time. By drawing a comprehensive picture of the current state of the system the straightforward simulation improves monitoring of the real physical system in near real-time. Other questions that arise in the context of optimal control, energy efficiency, response and others often require the solution of mathematical optimization problems that are based on the hydraulic simulation. These problems being inverse in nature and often ill-posed are much more difficult to tackle than the straight forward simulation and often not solvable in polynomial time (NP hard). Often a large number of simulations are needed. In order to make algorithms for solution of inverse problems available in a real-time environment it is very important to work with the most appropriate level of detail of the underlying simulation model.

In this paper, the concept of decomposition of the network graph [1] is used as a basis for the solution of inverse real-time problems. Graph decomposition always inherently involves different simplifications that can effect a dramatic reduction of the size of the problem to be solved. A general overview of the decomposition concept is followed by some application examples related to water supply network security and monitoring including sensor placement, source identification and contamination response. It will be shown that the basic concept is not limited to the examples and can be applied to other nonlinear network problems as well. Basically, the method consists of the decomposition of the whole problem into one or more simplified global problems and subordinated local problems. Subject to the required level of detail the solution of the global problem may be sufficient or can be further improved by a more detailed study of the local solutions.

Another advantage of the concept is that it is well suited for the use of parallelization techniques. The decomposition, when applied to a model that runs on a computer with multiple cores or in the cloud, enables the local solutions to be calculated at the same time and integrated afterwards to the global solution. The connectivity of the whole system is maintained by rigorous transition conditions. The paper is closed with a short discussion of the best-suited level of detail of hydraulic models with respect to different problems.

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2. Basic concept

A common water supply network (WSN) graph is composed of different connectivity components that can be distinguished with respect to their topological properties. Normally, WSNs consist of a looped main distribution system where any pair of nodes can be connected by redundant paths, and a branched secondary supply system that connects the customer connections with the core that is composed of looped blocks being interconnected by bridges. Loops in the system increase reliability of supply because, even in some cases of pipe failures, the water can still reach every demand node. Nevertheless, the additional pipes result in increased initial investment cost and reduced network observability due to alternative flow paths. In large supply systems, there can be also a superior transport system that connects the water source with the distribution network or different subzones among them. The large diameter pipes of the superior transport system mostly have no redundant pipes because the increase in cost would be too heavy. In summary, WSNs are combined systems including looped and branched subgraphs. In the following, a concept for decomposition of a general supply network graph will be outlined before demonstrating its application to the solution of few selected problems in the water supply network security context.

Fig. 1 shows the result of the decomposition of the network graph of the Wolf-Cordera-Ranch benchmark example [2]. On the left side the entire system is presented whereas the box on the right shows the framed section in higher resolution. Looped parts of the system (each node can be reached by at least two alternative paths) are drawn in blue color, whereas the bridge pipes that connect the looped subsystems are indicated with red color. The union of looped blocks with bridge components is called core. The brown lines show the forest of the network graph that consists of distinct trees. The trees are connected with the core at the root nodes (cyan).

For each block also its so called supergraph is identified. The supergraph is a topological minor of the original graph and consists of supernodes and superlinks. The supernodes have degree > 2 in the block subgraph. The superlinks consist of a series of links of the original graph and span from one supernode to another. In Fig. 1, bigger circles distinguish the supernodes from the interior nodes. The union of superlinks and trees connected at the interior nodes will be called a cluster.

It is important to note that the calculated connectivity components are not limited to static examinations. In fact, the decomposition algorithms are very fast and can be used also for showing the current state of the system reflecting changes in connectivity due to system operations such as valve closures, shutdowns of pump etc. Embedded in an online environment, the decomposition algorithm delivers the current state of network connectivity in real-time.

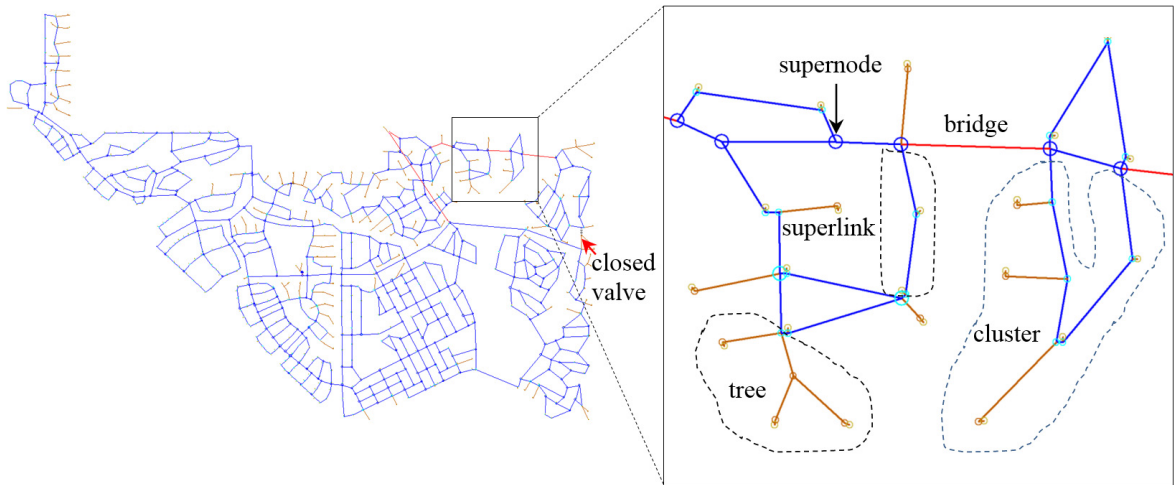


Fig. 1. Graph decomposition of the Wolf-Cordera Ranch benchmark network. Applications

2.1. Sensor Placement

The design of an optimal sensor layout is one of the key problems to be solved before implementing an online monitoring system. Different strategies are used including expert opinion, ranking methods and mathematical optimization [3]. The latter involves the consideration of a number of objective functions such as minimizing time to detection and maximum coverage with minimum costs. For estimation of the impact of contamination scenarios the optimization software is linked with hydraulic and water quality simulation (see, for example, the open source software TEVA-SPOT [4]). For the estimation of contamination impact, a huge number of scenarios has to be simulated taking into account different source locations, duration and daytimes at which the contamination starts. Simulation models of real supply systems can consist of hundreds of thousands nodes and pipes. Theoretically, every node is a potential contamination source, thus, leading to an incredible large number of scenarios that have to be simulated. Although running times for extended period simulations are nowadays comparably short for single extended period simulation runs, they are still far too long for calculating the impact for every node of the system. Therefore, often simplified networks where parts of the network are aggregated are used with the consequence that the results delivered by the modified models are not sufficient in terms of accuracy.

Using the graph decomposition concept can dramatically reduce the number of scenarios that have to be simulated, without losing accuracy. Two examples are outlined in the following:

- 1.) Preselecting of possible sensor locations (as support tool for expert opinion strategy): end nodes of a bridge are particularly suitable for installation of sensors due to their topological properties: For example, the right end node of the bridge in Fig. 1 is the entrance of all the water to the downstream block. If a sensor is placed here it can be guaranteed – assuming that the sensor is able to detect a contamination – that as long as the sensor shows negative alarm state the water entering the zone is not contaminated.

- 2.) Mathematical optimization focusing on the supergraph: As explained above the supergraph as topological minor of the original graph consists of supernodes (degree > 2 in the core subgraph) and superlinks (series of pipes without bifurcation). The time consuming process of impact calculation can be decomposed into local and global steps. Within

the local step only the disjoint clusters are considered consisting of superlinks combined with adjacent trees (see Fig. 1). For every node of the cluster the contamination transport is calculated only until the contamination reaches one of the two supernodes. The concentration and time of arrival at the supernodes are transferred as input for the contamination scenarios considered within the global step. The local calculation is carried out for all clusters adding new contamination scenarios at the supernodes. Redundant scenarios characterized by similar start times of the contamination can then be removed from the list of scenarios at the supernodes. The global time consuming step is solved for the supergraph only. That means that the number of nodes to be considered is reduced to the number of supernodes. Fig. 2 shows the reduction from 160 (nodes in total) to 20 (supernodes) for a selected part of the example network in Fig. 1.

A further enhancement can be reached by extra consideration of forest nodes. Assuming contamination scenarios with only small input flows, the flow direction in a tree is from the root to the leaves. Consequently, a contamination starting at a tree node remains locally constrained to the downstream nodes in the tree and does not influence the contamination scenario at the supernode. All contamination scenarios at tree nodes can be treated separately or totally neglected due to their relatively small impact.

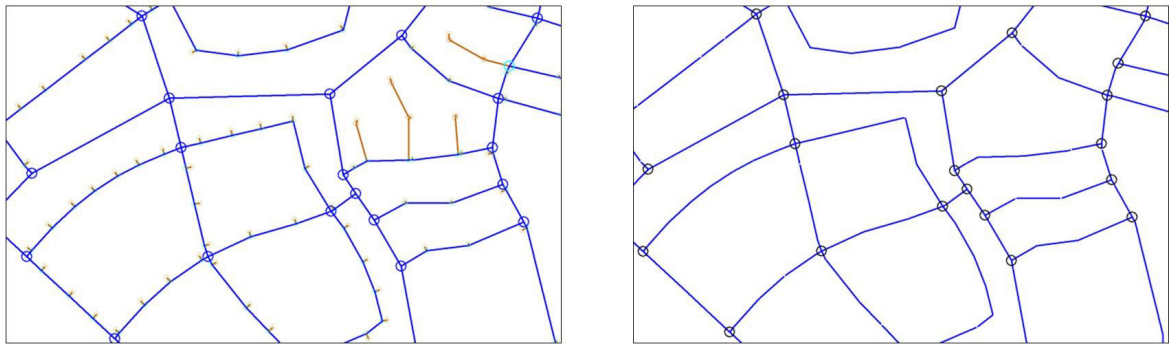


Fig. 2. Reduction of number of nodes (contamination scenarios) for selected box from 160 to 20.

In conclusion, all different contamination scenarios where the source is within the superlink, are distinguished only marginally by the local impact. Therefore the study of contamination scenarios can be subdivided into local and global steps. In the local step the worst case scenario for the superlink can be studied independently from the rest of the system. In the global step only the supergraph is considered, thus, reducing the number of possible source candidates for the impact calculations dramatically (normally by a factor of 10 to 20). In the majority of cases it should be sufficient to simulate contamination scenarios focused exclusively on the supernodes.

2.2. Source Identification

For a given sensor network with positive and negative sensor alarms the identification of the source of contamination is a well-studied and often described problem that is related to online use of the CWS. The objective is to determine the contamination source location as exact as possible almost in real-time. The decomposition concept can be used for analyzing the current state of the system and for the enhancement of the calculation. The strongest simplification of the network graph is the so called block graph tree (bgt). In the bgt the looped blocks are replaced by representative block nodes that are linked with the cut nodes of the blocks connecting them to other blocks or bridges. For illustration, Fig. 3 shows the bgt of the network section in the right box of Fig. 1. Given a set of positive and negative sensor alarms at a certain time, the solution of the source identification problem can be subdivided into several steps. In the first step the block graph tree of the network is analyzed in order to separate the affected subsystems from the rest of the system. The bgt has the nice property that, first, the direction of flow for all branches is known a priori without hydraulic calculation and second that each node has a unique ancestor.

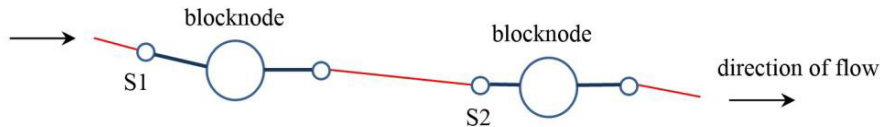


Fig. 3. Reduction of number of nodes (contamination scenarios) for selected box from 160 to 20.

The block graph tree is subdivided by sensor locations. Assuming perfect sensors and that the sensor network design follows the experts opinion to place sensors at the end of bridge pipes as explained in the last section (S1 and S2 in Fig. 3), the subtree that consists of all links between sensor nodes with negative alarms is safe. In contrast, downstream nodes of positive sensor alarms cannot explain the alarm. Therefore they are also excluded from the next search step. The source candidate region consists of the set of upstream (ancestor) nodes and pipes of sensors with positive alarms that have biggest distance from the root of the bgt minus the set of upstream nodes and links of sensors with negative alarms that have a downstream sensor with positive alarm. The negative alarm sensors without any positive alarm sensor downstream are excluded from the SI-algorithm. The different combinations of sensor alarms for the system of Fig. 3 and the source locations that can explain the alarms are shown in the following table:

Table 1: Reduction of area of investigation for SI-algorithm based on bgt

Alarm state S1	Alarm state S2	Consequence for SI-calculation
P	P	Source must be upstream S1: Source identification analysis for the subnetwork upstream S1
N	N	No contamination source between S1 and S2 that started prior to flow time from S1 to S2
P	N	Source must be upstream S1: Source identification analysis for the subnetwork upstream S1
N	P	Source must be in between S1 and S2: SI analysis for the subnetwork between S1 and S2

It must be noted that in case of multiple sources the positive alarms only lead to the result that there is one source in the mentioned subarea. However, additional sources in other parts that might appear at the same time cannot be excluded. In the next step a particle backtracking algorithm can be carried out for the candidate subnetworks. It is recommended that the search is executed with focusing on the topological minor. For justification please consider that there is no mixing within a superlink. Nodes with degree > 2 always connect exactly two pipes of the looped subgraph and possibly an arbitrary number of tree links leaving that node. Even if the source is in a connected tree and back-pumping of a considerable amount of contaminated water is assumed, the contamination plume enters the looped system always at the root node of the tree. Therefore it makes no difference for the upstream system if the source is in the tree or at the root node. Consequently, the SI-calculation is carried out only for the core of the network graph neglecting the forest.

2.3. Contamination response

In an extreme case of a severe contamination event, the immediate initiation of effective response actions can be critical for reducing the number of fatalities or people affected by the contaminated water. Therefore, it is very important to have a good estimate of the source location and the area that is already affected or will be further affected during reaction time. The size of the area depends on a number of issues such as the design of the sensor network, network topology and others. The decomposition concept as explained above can help for restricting the area in question based on topological considerations. The advantage is that the topological properties are not sensitive to changes in demand or network operations. The knowledge of pipes that have unique flow direction is as important as the possibility of reducing calculation time by focusing on selected subnetworks that are affected by the contamination.

Another advantage is the direct application of the concept to the identification of gate valves that have to be connected for isolation of the contaminant. Bridge links, if there are any, are well suited because of the possibility of disconnecting the downstream network by closure of only one valve. Forest trees can be neglected if the contamination has not reached the root node yet. Similar considerations for superlinks can help reducing the size of the problem. If the superlink has unique flow direction and the contamination has not reached the upstream node the cluster belonging to the superlink can be neglected.

Of course, the described algorithms can be applied to the all pipes model of the system. However, even if running time is not critical using the decomposition concept not only the solution to the particular problem is delivered but also an improved understanding of the underlying mechanisms and simplified views on the solution are supported. This allows the modeler to spend more time for the analysis of the critical areas of the network where the flow directions may change during the day and the identification of adequate response actions is not straightforward.

3. Summary and Conclusions

The concept of decomposition of a supply network graph and its application to problems related to water network security has been outlined. The concept can be used as general framework for adaptive modeling of water supply networks. It supports the enhanced calculation of particular problems by decomposition into local and global solution steps. In dependence of the required level of accuracy for the solution of the underlying problem, the consideration of the global step might be sufficient. For example, the hydraulic calculation could be carried out for the supergraph neglecting the different flow velocities in the pipes of the superlinks. With additional consideration of the full local steps the simplification does not result in reduced level of accuracy. However, the reduction of time required for the calculation of the exact solution can be still impressive depending on the topological structure of the original system.

As final result it can be concluded that the use of all-pipe models can be reasonable as long as times for data treatment, such as loading the model from storage, graphical user phase interactions and maintenance of the data is acceptable. The time needed for running different algorithms can be dramatically reduced by the decomposition concept. Another important advantage for maintenance of the model is the fact that the database is always the original all-pipe model. The basis is not affected by aggregation and other simplification methods. The all-pipe model normally corresponds almost one-to-one with the GIS as reference system. Therefore all-pipe models can be much easier updated than aggregated ones.

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