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Flushing planner: a tool for planning and optimization of unidirectional flushing

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Abstract

Unidirectional flushing is a technique for periodic cleaning of water supply pipes to remove deposits and may also be an important response to contamination of drinking water networks. For unidirectional flushing the defined flushing path is fed by clean water at an entrance point. The development of an efficient flushing strategy is not straight forward. The objective is to minimize the effort of operating staff. The flushing plan consists of a well-defined series of flushing actions in which the current flushing path is always connected to previously cleaned sections. The paper describes the software tool referred to as Flushing Planner.

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Keywords: Unidirectional Flushing; flushing path, flushing plan, graph decomposition

1. Introduction

Unidirectional flushing (UDF) campaigns for cleaning of pipes to remove sediment are implemented by many water supply utilities on a regular basis (Korth et al., 2011). The sediments consist of corrosion by-products or particles that enter the system at the treatment plant (Korth et al., 2008). In order to prevent discoloration of the drinking water by resuspension the sediments have to be removed from time to time. Another important application for UDF concerns the cleaning of the pipe system as a response to deliberate or accidental contamination. In this case the primary goal is to minimize the impact of the contamination on public health by

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public notification and isolation of contaminant in the pipe system that has been affected. The cleaning of the affected pipes is essential before recommissioning of the supply.

The security of public water supply has been a big concern since the events of September, 11, 2001. An extensive research effort has been undertaken for the development of optimal sensor networks and contaminant warning systems including software solutions for detection and source identification. However, there is little literature on planning of optimized unidirectional flushing campaigns. Baranowski and LeBoeuf (2008) and later Haxton and Uber (2010) used Genetic Algorithms for minimizing the impact of contamination events by selection of most appropriate nodes for flushing. However, the approach assumes that each node is a possible hydrant location for flushing by alteration of the demand and doesn't take into account the actual location of hydrants and valves. Poulin et al. (2010) describe different flushing methods as well as an algorithm for selection of flushing path that steps forward loop by loop. The algorithm is similar to the one proposed in this paper. However, the method described here is not restricted to flushing of subnetworks that have been isolated due to a contamination event.

In general, Periodical Unidirectional Flushing (P-UDF) has to be distinguished from flushing as a response to a contamination event. Response Unidirectional Flushing (R-UDF) is targeted at minimizing the impact of the contamination on public health and must be implemented with strict time constraints. In contrast, P-UDF is part of the regular maintenance of the system and consists of a planned and well-arranged sequence of single flushings. For both applications the flushing plan addresses a preselected subsection of the total water supply system that is denoted here as the flushing area. In the case of a flushing as a response to contamination the flushing area is determined by the contaminated subsection of the network whereas for routine flushing the identification of the flushing area is based on the network characteristics like network topology and the decomposition of the pipe system into transport, main distribution, secondary distribution and house connection pipes. For each flushing action one or more flushing hydrants, the flushing path (series of pipes) and an arbitrary number of isolation valves have to be defined. The optimal flushing plan consists of a structured sequence of actions for the cleaning of the pipes of the flushing. The optimal flushing plan should minimize the effort for valve manipulations, which are required for the temporal isolation of the flushing path, while guaranteeing an appropriate flow velocity in the flushing path and maintaining a sufficient supply pressure in the rest of the system (at least for P-UDF). The minimization of the effort is crucial for minimizing the exposure time of the population and to quickly resume the supply. Under normal conditions minimizing the effort is a matter of economic efficiency and minimization of cost. The method described in the following is more related to P-UDF and does not consider simultaneous flushing using different hydrants at the same time or flushing without valve manipulations. These methods can be necessary in case of contamination with highly toxic material in order to prevent the population from getting into contact with the substances.

The paper is organized as follows. After a brief description of the design criteria of the flushing program, modifications of network topology are discussed that are necessary to integrate the valves and hydrants into the network graph. The valves and hydrants are normally assigned to pipes and are not normally included in the network graph as additional nodes and links. Here, valves and hydrants and additional nodes are included to form a "full graph". This "full graph" including valves and hydrants and links and nodes is then decomposed into different connectivity components which are the basis for the further steps of the identification of the flush plan. In the first step, the pipes of the graph theoretical forest that cannot be flushed due to absence of hydrants at extremities are identified and added to the non-flushable subgraph. In the next step the remaining graph is further subdivided into flushing areas. For that purpose, the pipes that meet some user defined criteria like maximal flushable diameter or minimum flow velocity that prevents sedimentation are additionally excluded from the graph. The flushing areas are then the maximal connected components that result from connectivity analysis of the reduced graph.

In the next step, the flushing areas are further decomposed into flushing paths. A flushing path consists of a series of pipes that are, besides the entrance point at the beginning of the path, isolated during flushing. Different user-defined criteria like the above mentioned optimal path length or the maximal allowable difference in pipe diameter/flushing velocity of pipes are considered as constraints. For the identification of flushing paths a greedy algorithm has been implemented that is similar to the approach presented by Poulin et al. (2010) and proceeds loop by loop through the subgraph of the flushing area. Eventually, the final flush plan contains the ordered sequence of flushing paths including valve operations.

The algorithms used for the Flushing Planner are all based on topological decomposition methods of the network graph and different graph search techniques. Some of the algorithms also use modified topologies. As an example, the segment graph can be identified that consists of one node for each segment, the original valves as well as links between valve nodes and segment nodes. The segments are the maximal connected subgraphs that are generated by removing all the valves from the original graph.

2. Design Criteria

For efficient and reliable cleaning of pipes through UDF different criteria have to be considered as constraints that are described in the following table-

Table 1: General criteria for optimal unidirectional flushing

criteria	feasible range	significance
Length of flushing path	400 m – 800 m	Upper threshold: Limitation of headloss along the flushing path for guaranteeing sufficient flow velocities. Lower threshold: operational efficiency, Reducing risk of re-suspension in upstream pipes that do not belong to the flushing area by inappropriate high flow velocities.
Min. flow velocity during flushing <i>min v_s</i>	0,9 - 1,8 m/s (Poulin et al., 2010)	The minimum flow velocity that is necessary for completely cleaning of the pipe wall by conventional flushing. Is limited by the hydraulic capabilities of the flushing hydrant as well as the hydraulics of the upstream network.
Max. flow velocity of an average demand day under normal conditions: <i>max v</i>	0,3 m/s	Determines if flushing of a pipe is necessary. If <i>min v</i> is exceeded on a regular basis -> no sedimentation in the pipe.
Accessibility of flushing hydrants	sufficient	Hydrants must be reachable by car and the disposal of flushing water (commonly into the sewer system) must be possible without any negative impact.

Basically, criteria for routine flushing and flushing for decontamination after a contamination event can differ. One example is that during routine flushing the supply of the population must be guaranteed without any interruption. In contrast, it is assumed that for decontamination the flushing area has been isolated from the rest of the system and the population is prevented from taking water from the system. In this case the criterion of maintaining full supply during the flushing is not considered.

3. Software module Flushing Planner

3.1. Overview of methodology

The software module of the Flushing Planner (referred to as “FlushPlan”) includes different functionality that is listed here and described in more detail in the following subsections:

- Preparation of full graph topology including valves and hydrants as links and nodes
- Identification of flushable/non-flushable pipes
- Identification of flushing areas based on calculated flow velocities

- Calculation of segment graph
- Calculation of minimum flushing paths (hydrant to hydrant)
- Calculation of optimal flushing paths and the flushing plan

3.2. Preparation of full graph topology

The data required for the module flush plan are usually taken from a hydraulic simulation model or, in exceptional cases, from a Geographic Information System (GIS) that include in addition to common network data such as pipes, valves, pumps and nodes also the information about the exact location of valves and hydrants. In general, this cannot be taken for granted since different simulation and/or GIS packages use different data models. For example, the well-known open source program EPANET (Rosmann, 2000) that has been developed by the US Environmental Protection Agency (EPA) does not provide efficient data structures for simple isolating valves and hydrants. Isolating valves can be modeled possibly just as links (type valve) and hydrants as nodes. However, this leads to problems since consideration of these extra links and nodes increases the size of the model significantly (see e.g. Walski et al., 2006). For each isolating valve two extra nodes would be introduced, for each hydrant one additional node. In general, the size of the model is of great importance for the handling (clarity, storage, data management, efficiency of model database and GUI, ...) and in particular for the calculation time that is needed for hydraulic simulations.

Most of the available commercial hydraulic simulation software packages as well as GIS systems therefore chose a different data structure for representation of isolating valves and hydrants. These features are modelled as so called point objects on pipes. That means that isolating valves and hydrants are properties of the related pipe link. There is a 1 to n relationship between pipe and isolating valves. That means that a pipe can include n different valves. The same applies to hydrants. For each isolating valve/hydrant there is a unique mapping to a pipe. On the other hand a pipe can have an arbitrary number of isolating valves/hydrants. For the exact allocation of the real world object the position of the isolating valve/hydrant (e.g. distance to first node of pipe) is stored. Of course, other attribute data for the valves and hydrants like type of valve, state, fire fighting flow, etc. can be stored with the object.

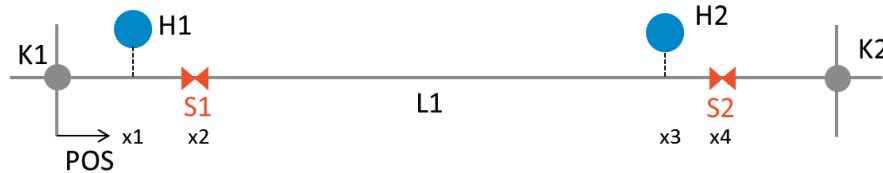


Fig. 1: Modell A: Modelling of isolating valves (S1, S2) and hydrants (H1, H2) as point objects on pipe

Fig. 1 shows an example of a pipe (L1) with initial upstream node K1 and downstream end node K2 and includes two isolating valves (S1, S2) and two hydrants (H1, H2). The related data model is shown in the following table.

Table 1: Data model A for example pipe with point objects on link

LINK ID	FROM	TO	TYPE	VALVE ID	PIPE	POS
L1	K1	K2	PIPE	S1	L1	X2
				S2	L1	X4
NODE ID			TYPE	HYDR. ID	PIPE	POS
K1			JUNCTION	H1	L1	X1
K2			JUNCTION	H2	L1	X3

In this case, the data objects “valve” and “hydrant” do not represent nodes and links in the sense of a node link graph model rather than being just objects that are assigned to the shown simple pipe.

Representing these objects as links in EPANET requires that each valve is a separate link and each hydrant is a separate node (Fig. 2).



Fig. 2: Modell B: Full system with valves and hydrants integrated as links and nodes

In this case, the extra tables for valves and hydrants are not needed anymore. The objects H1, H2, S1, S2 are included in the nodes and links table and distinguished by the “type” attribute. The data tables for the system shown in Fig. 2 are presented in Table 2.

Table 2: Data model B for full network graph where hydrants and valves are represented as nodes and links

LINK ID	FROM	TO	TYPE	NODE ID	TYPE
L1	K1	H1	PIPE	K1	JUNCTION
L2	H1	K2	PIPE	H1	HYDRANT
S1	K2	K3	VALVE	K2	JUNCTION
L3	K3	H2	PIPE	K3	JUNCTION
L4	H2	K4	PIPE	H2	HYDRANT
S2	K4	K5	VALVE	K4	JUNCTION
L5	K5	K6	PIPE	K5	JUNCTION
				K6	JUNCTION

As it can be seen from Fig. 2 and Table 2 the full system graph is built from the original one by subdividing the single pipe L1 into shorter segments L1 to L5. The division points are the locations of valves and hydrants. The hydraulic simulation of the full system graph is less efficient because for each additional node (one for each hydrant and two for each valve) there is a new row and column in the system of equations. Since the calculation time increases in polynomial fashion with the number of nodes it is not recommended to use the data model of Table 2 in general.

For hydraulic calculations based on the model of Fig. 1 closed valve states are considered by removing the pipe. If at least one valve is closed the pipe is removed from the network graph for calculation. For the system apart from that pipe there is no difference which of the valves is closed under the assumption that there is no additional consumption within the pipe. In a similar way the hydrants are modelled. Under normal conditions the hydrant is closed and has no impact on the network hydraulics. For fire flow calculations the hydrant can be temporarily replaced by an extra node, or even simpler, the fire flow can be taken from the node with closest distance to the hydrant.

The new module FlushPlan assumes that model A used and the data are delivered in a form similar to Table 1. Since for the calculation of flushing paths, the full system graph is required, then the first step of the method

consists of the temporal mapping of model A to model B. For that purpose, firstly, the dedicated valves/hydrants of each pipe are determined and ordered according to their distance to the first node of the link. It is assumed that for the geographical representation for each pipe a polyline is given representing their exact location in the x-y-plane of the model area. With this information an orthogonal projection of the point objects representing valves and hydrants can be calculated and the polyline is split on the projection points. Consequently, a pipe with m point objects is subdivided into $m+1$ sections being the polylines of the pipes of the full network graph. For definition of the new pipes two cases are distinguished:

1.) The separating point object is of type hydrant: A new node is created that represents the hydrant. The two pipe sections that result from the split by the hydrant get connected to the new node of type hydrant (H1, H2 in Fig. 2).

2.) The separating point object is of type valve: In this case two new nodes are generated that serve as initial and end node, respectively, of the new pipes at the split point. The two nodes are connected by a link of type valve (new nodes K1 and K2 for valve S1 and K4 and K5 for valve S2 in Fig. 2). Nodes K1, K2 and K3, K4, get the same coordinates in order to visualize the valve as a single point object as in the original system. The resulting network graph is called full graph G_F and will be used as basis for the development of the algorithms of FlushPlan.

Before the explanation of these algorithms a few topological properties of G_F in comparison to the original network graph G are briefly described.

- Number of nodes: $n_{G_v} = n_G + n_H + 2 n_S$ (1)
where:

n_{G_v} : total number of nodes of G_v

n_G : number of nodes of G

n_H : number of hydrants

n_S : number of gate valves

- Number of links: $m_{G_v} = m_G + n_H + 2 n_S$ (2)
with

m_{G_v} : total number of links in G_v

m_G : number of links in G

- Number of connectivity components: $n_{C,G} = n_{C,G_v}$ (3)
- Number of loops (L: Loops) of G and G_v are identical: $n_{L,G} = n_{L,G_v}$

Proof:

$$n_{L,G} = m_G - n_G + n_{C,G}; \quad (4)$$

$$n_{L,G_v} = m_{G_v} - n_{G_v} + n_{C,G_v}; \quad (5)$$

$$(1), (2) \text{ and } (3) \text{ in } (4): n_{L,G_v} = m_G + n_H + 2 n_S - (n_G + n_H + 2 n_S) + n_{C,G} = m_G - n_G + n_{C,G} = n_{L,G}$$

The mapping of G to G_F is a so called homeomorphism. That means that the main topological properties of G are also valid for G_F .

3.3. Identification of flushable/non-flushable pipes

Flushing of pipes is possible only if there is a hydrant at the downstream end of the pipe. In general water supply systems are composed of looped parts and branched trees at the outer parts. Whereas in the looped part the water can reach the flushing hydrant by at least two distinct paths and unidirectional flushing can be guaranteed only by temporary closure of valves, in the branched subgraph the flow direction is predefined by the network topology. From a graph theoretical point of view, the water flows from the root of a tree to its leaves. The root node is the connection to the looped subgraph (e.g. T-cross) and the leaves are usually the customer connections. For every pipe of the branched subnetwork the direction of flow is known "a priori" – independent from the complexity of the tree. The closure of a valve in a tree would immediately result in disconnected network parts that cannot be supplied anymore. The meaning of the term "downstream" in the tree is identical with "at a larger distance from

the root node”. This implies that a tree can be completely flushed only if there is a hydrant at any leaf (end node). In other words, every node of degree one has to be a hydrant.

Since for real systems it cannot be guaranteed that any end node is a hydrant, a module has been implemented that calculates the flushable subnetwork based on the information about the full graph G_F . The algorithm is based on the topological decomposition of the network graph (Deuerlein, 2008) into different connectivity components.

In the first, step the maximal connected components of the graph G_V are identified. For considering different input locations source nodes such as reservoirs and tanks or pumping stations are connected with a virtual ground node by virtual links. Under regular conditions, the resulting graph should consist of one component only ($C_{G_V,main}$), otherwise there would exist disconnected parts without supply ($C_{G_V,l} \dots C_{G_V,nc}$).

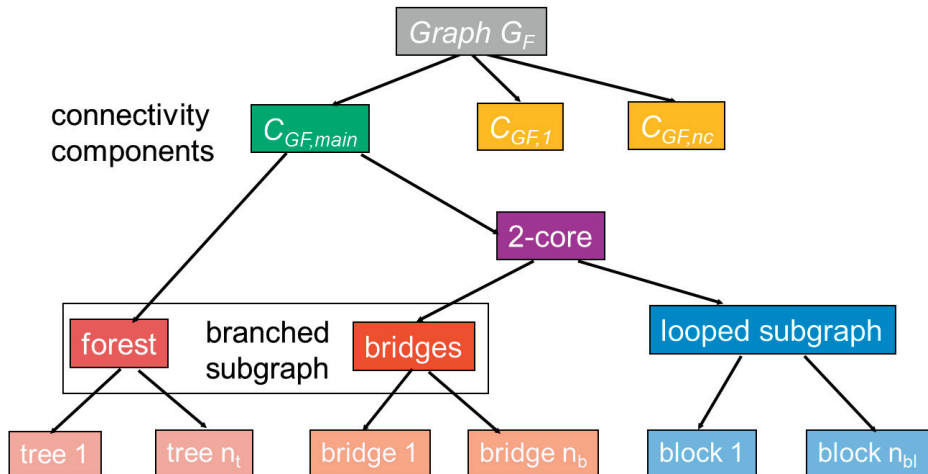


Fig. 3: Schematic presentation of graph decomposition

Each component is further subdivided into branched and looped subgraphs. The looped subgraph consists of distinct looped blocks that are interconnected by bridge components. Each node of a looped block can be supplied by at least two pipes. The components of the branched subgraph are the trees of the forest and the bridge components. Bridge components have two nodes in common with the looped subgraph whereas trees and looped blocks (or bridge components) intersect at exactly one node, the so called root node. The set union of bridges and looped blocks is called 2-core of the graph.

At this stage the calculation of the non-flushable Graph G_{NS} considers topological criteria only. For simplification, it is assumed that each pipe that is upstream of a hydrant can be flushed with sufficient flow velocity. The hydraulic verification of this assumption is not the focus of this paper. For the identification of G_{NS} , first the forest of network graph is considered. The graph decomposition algorithm has already built an ancestor and successor list for each pipe of the branched subgraph. Therefore the identification of non-flushable pipes is straight forward. The algorithm proceeds from leaves to the root of the trees and marks all pipes until a hydrant or the root node is reached. After termination of the algorithm the marked links and their initial node and last node comprise the graph of the non-flushable subnetwork G_{NS} . The intersection of G_{NS} and G_S is the set of hydrant nodes that are located in graph theoretical trees.

3.4. Identification of flushing areas based on calculated flow velocities

The most important criterion for appearance of encrustations on the inside walls of the pipes is the flow velocity in the pipe. The maximum flow velocity during an average demand day $\max v_{d,A}$ is chosen as a reference value. It can be calculated for instance by use of a hydraulic simulation model. The threshold value for the minimum

velocity v_m above which no sedimentation is expected can differ from network to network and should be defined in accordance with discussions with the staff of the utility. Realistic values range from 0.3 m/s to 0.5 m/s. For the identification of the flushing areas the pipes are subdivided into two sets:

- 1.) pipes with: $\max v_{d,A} < v_m$: -> have to be flushed
- 2.) pipes with: $\max v_{d,A} \geq v_m$: -> no sedimentation is expected. Therefore there is no need for flushing.

Other criteria such as the pipe diameter can be considered as well for the identification of flushing areas. Above a certain diameter of pipe, these pipes cannot be cleaned with conventional techniques like unidirectional flushing since the required flow velocities in those pipes cannot be reached by opening hydrants or the discharge could exceed the capacity of the sewer system (to take the flushed water). Depending on the size of the calculated flushing areas they can be further subdivided into separate units that refer to the total pipe length that can be cleaned for example in one day.

3.5. Calculation of the Segment Graph

An important tool for analysing network connectivity is the so called segment graph. Different definitions for segments can be used with respect to the network elements that separate the segments. These separating elements can consist of valves as well as hydrants. In this context a segment consists of the maximal connected subgraph that includes none of the separating elements. For example, the segments that result from the decomposition of the total network graph into subgraphs without valves are the smallest units that can be separated and shut down in case of a pipe burst within the segment.

For the calculation of segments, first, the separating elements are removed from the system graph. A connectivity analysis that calculates the maximal connected components of the resulting graph delivers the segments. In the case of a contamination event, the determination of the minimal contaminated subgraph that can be isolated from the rest of the system is important. With the segments also the valves that have to be closed are identified.

For analysing the connectivity of the segments, the so called segment graph can be used. In the segment graph each segment is represented by just one node – independent from the actual number of nodes and pipes that are in the original segment. In contrast to the graph that is used for identification of segments, the segment graph includes also the separating elements such as isolation valves. Their end nodes are connected by virtual links with the segment node.

3.6. Identification of flushing paths and calculation of optimal flush plan

The calculation of flushing paths is carried out for the predefined flushing areas separately. For that purpose in the first step, the inflow nodes of the flushing area have to be identified. An input node is characterized by the fact that the degree of the node in the flushing area subgraph is smaller than the degree in the full graph and that the flow of the connected links that are not part of the flushing area is towards the node. Then, the graph of the flushing area is modified by connecting the input nodes and a virtual ground node by virtual links. The modification of the graph simplifies the application of general concepts of graph theory. In this case, the Block Graph Tree (BGT) of the modified graph is calculated and the algorithm succeeds from the root of the BGT to the leaves. If the flushing area itself consists of a more complicated topology with several two-connected blocks and bridge components the order of flushing actions is determined by block graph tree that is calculated by the graph decomposition algorithm.

In order to guarantee that the flushing is achieved with clean water, the direction must be from root to the leaves. The flushing actions in bridge components are uniquely defined by the input node and the flushing hydrant of the flushing path. The flow direction is given by the topology of the network graph. Within looped blocks the situation is different. The separation of the flushing path with a uniquely defined influx to the flushing path requires valve manipulations. In this case, the description of the flushing action consists of the pipes of the flushing path, the input node, the flushing hydrant and a set of valve manipulations. In the following the calculation of flushing path within the looped subgraphs is described in more detail.

For prioritization of flushing actions it is assumed that a steady-state calculation for an average demand loading case has been carried out in advance. The algorithm progresses from the pipes having higher flows to those with lower flows. A loop oriented method has been chosen. The loops with highest flow rates are cleaned first followed by the connected loops. For implementation, a priority queue for nodes with degree > 2 (branching nodes) is used. The priority is the input flow to the adjacent loops for each branching node. After flushing of one loop is completed the flushing plan succeeds with the loop of highest input flow in the queue. With this method it is guaranteed that the next flushing path is always supplied with clean water from previously flushed pipes.

Tree subgraphs connected to the loop are cleaned after flushing of the entire loop has been completed. For flushing of trees, no valves have to be shut since the flow direction is already uniquely defined by the topology of the network graph. By definition of the flushable subgraph G_S it is guaranteed that each leaf node of the trees is a hydrant. The method is demonstrated for a section of a real water distribution network (Fig. 4). The inflow node of the flushing area is in the centre at the top which is supplied with clean water. The flushing area consists of several loops with connected tree structures. The first flushing action is shown in Fig. 4 a). The pipes of the flushing path FP 1 are drawn in a dark blue colour. In order to prevent multiple inflows to the fire hydrant the valves that are marked with red colour have to be closed. After cleaning of FP 1 the method progresses to FP 2 (Fig. 4 b)) which is part of the same loop as FP 1. The yellow valves remain closed from flushing of FP 1. In addition the green valve has to be opened and the two new red valves have to be closed for isolation of FP 2. Flushing of FP 3 (Fig. 4 c)) completes cleaning of the first loop. After that the connected trees can be cleaned. In Fig. 4 d) the first flushing action of the second loop is shown. Please note that all valves of Loop 1 are opened enabling that the maximum amount of water that is hydraulically feasible to be able to reach the input node of the flushing path FP 4.

For the separation of the flushing paths within a loop different criteria can be defined by the end user. For example, the preferable flushing path length can be chosen. In addition the modeller can decide if diameter changes within the flushing path are allowed. All the different criteria follow the same objective: to guarantee a sufficient flow velocity (and therefore sufficiently high wall shear stresses) for resuspension of incrustations. An additional measure could consist of flushing with the opening of more than one hydrant. However, this is not considered in the automatic flushing path identification with the tool Flushing Planner.

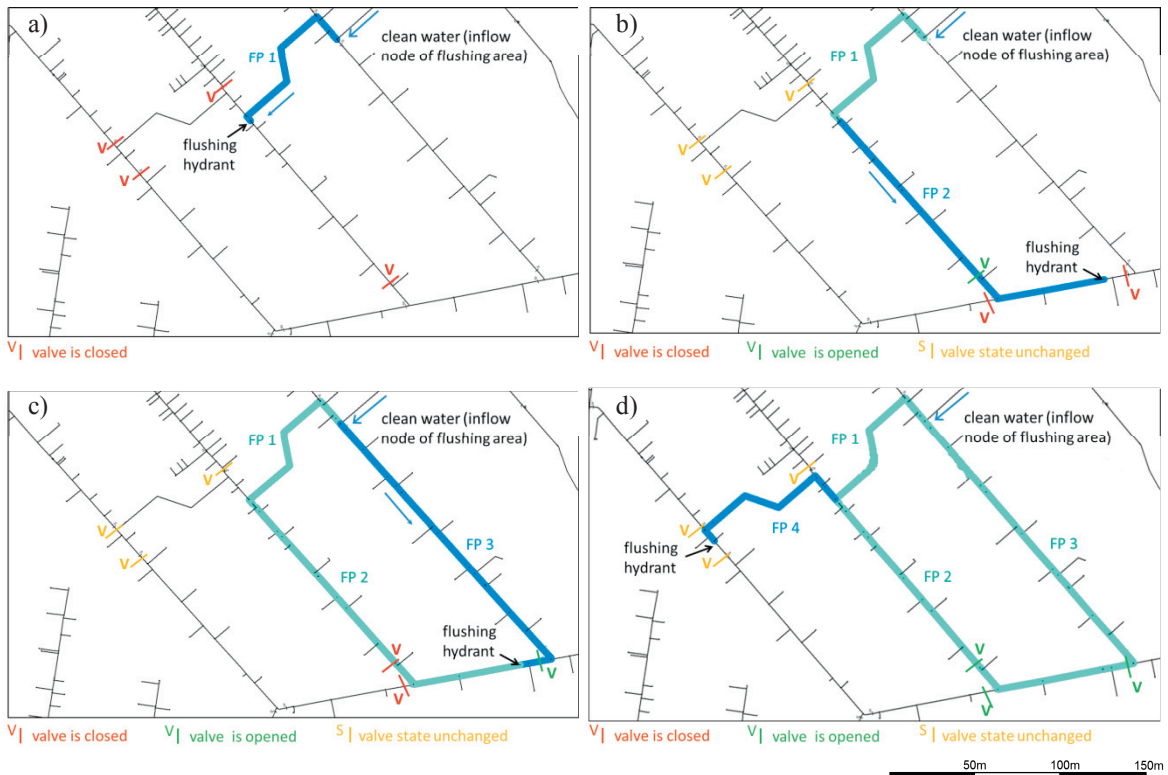


Fig. 4: Unidirectional flushing example

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