On Simplifying the Modelling of Transients in Drinking Water Distribution Systems

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Abstract

Waterhammer analyses are performed frequently if a water distribution network is extended. The criterion for the size of provisions is that under-pressures should not occur due to pump trip. The waterhammer analysis for a large network becomes a tedious job, even if data about the network are available in GIS format. The network has to be simplified to overcome unacceptable computation times.

A method is presented to simplify distribution systems in such a way that the transient pressures are calculated as if the complete system would have been simulated. The method is based on identifying sub-networks and representing these sub-networks with non-return taps and extensions thereof.

The accuracy of several sub-network representations is estimated with a simulation study. Conclusions from this study are as follows. The non-return tap behaves correctly with respect to the average pressure at the sub-network junction. If the sub-network volume is small compared to the main pipeline volume, then the pressure error is less than 5 m in a test system. As the volume ratio between sub-network and main pipelines increases the influence of the storage volume and inertia of the sub-network becomes significant. In these situations the tap should be extended with a single pipe. Large sub-networks are represented efficiently by these combinations of a single pipeline and a tap. The minimum pressure in the simplified system deviates less than ± 1 m from the complete test systems.

Nomenclatura

$V_{m,i}$	=	Volume of main pipe *i*,	[m^3]
$V_{m,j}$	=	Volume of main pipeline network dedicated to sub-network *j*,	[m^3]
$V_{s,j}$	=	Total volume of sub-network *j*,	[m^3]
$q_{i,j}$	=	Steady flow through main pipe *i*, to sub-network *j*,	[m^3/h]
q_i	=	Total steady flow through main pipe *i*,	[m^3/h]
R_j	=	Relative volume of sub-network *j* in the complete system	[-]
$l_{j,i}$	=	Distance from the sub-network junction to tap location *i*	[m]
$q_{j,i}$	=	Flow to tap *i* in sub-network *j*	[m^3/h]
N_j	=	Number of taps in sub-network *j*	[-]

1. Introduction

WL | DELFT HYDRAULICS has consulted many drinking water distribution companies (especially in The Netherlands) on the application of safety provisions such as air vessels and fly wheels in their distribution systems. The waterhammer simulation program WANDA is used to calculate the transient behaviour of a pump trip at maximum capacity.

1.1 History

The most important part of a hydraulic analysis is the modelling of the system. It is not always feasible to model every single pipe in the network for a transient calculation. Consequently the network is simplified in a reasonable manner to a main pipeline system and a set of sub-networks. Reasonable means in this respect that the main pipelines are identified, based on pipe diameters, flows and the network lay-out. Now the distribution system consists of a main pipeline system and a certain amount of taps, representing the flows into the sub-networks.

A tap is a component in WANDA which has been used for many years. A tap behaves like a normal partially opened tap, allowing the specified flow. In a dynamic situation the tap flow decreases as the upstream pressure decreases. Once the upstream pressure equals the downstream pressure the flow becomes 0. When the upstream pressure decreases further two phenomena may take place: a return flow may enter the system or a check valve closes and the flow remains 0 until the upstream pressure again rises above the downstream pressure. For this reason two types of tap exist: a return tap and a non-return tap. It is assumed that the non-return tap models the behaviour in water distribution systems most realistically; one may think of industrial water users having check valves installed next to their flow meter or household washing-machine taps, which are equipped with built-in check valves. Another reason to use non-return taps in waterhammer simulations is the fact that a conservative scenario is calculated if non-return taps are applied. The minimum pressure in the system is lower with non-return taps than with return taps, because of the return flow capacity of the return taps. The tap is specified with the following parameters:

- initial flow
- downstream pressure

The initial flow is normally set to the maximum flow to the corresponding sub-network. The downstream pressure is normally set to the elevation head of the sub-network. In the steady state preceding the pump trip the upstream tap pressure has a certain value higher than the downstream pressure. From the pressure difference across the tap and the initial flow a quadratic resistance coefficient is calculated: $C = \Delta H / Q^2$. This coefficient remains constant during the transient calculation.

1.2 Objectives

The use of non-return taps becomes less realistic as the size of the sub-network increases, because the inertia of the sub-network is not taken into account. The following questions arise from the observations above:

- What is the relation between the minimum pressure at the main pipeline junctions in the complete system and at tap junctions in the simplified system in which sub-networks have been substituted with taps?
- How should the sub-network be modelled or the tap be improved to produce more accurate, less conservative minimum pressures?
- Does a relation exist between the improved tap minimum pressure and the minimum pressure in the sub-network?

Answers to these questions are discussed in this paper. A set of 3 simple test networks has been used to investigate the behaviour of the tap and several improvements.

The three test systems and their simplifications are discussed in chapter 2. Chapter 3 discusses the standard tap behaviour and its limitations. Chapter 4 describes several approaches leading to an improved tap model. Simulation results to compare the different approaches are discussed in chapter 5. Finally the conclusions and recommendations are described in chapter 6.

2. Approach

Three test systems are used in this paper. The test systems are comparable with respect to the pumping station, the maximum capacity and the diameter of the main pipelines. They differ in the lay-out of the sub-networks. Two extreme sub-network lay-outs have been modelled. Test system 1 contains equally distributed water demands in the sub-network. Test system 2 contains water demands only at the end of the sub-network branches, all demands are located at the same distance from the junction. The third test system contains two sub-networks: an equally distributed and a concentrated sub-network. Test system 3 has been built to check interactions between sub-networks.

The pumping station is capable of supplying 1000 m^3/h at 44.5 metres. The specific speed of the pumping station equals 51 $m^{3/4}/s^{1/2}\cdot min$. The polar moment of inertia equals 3 kgm^2. There are no elevation differences present in the network. A check valve with $\xi = 5$ to account for the losses in the pumping station is present downstream of the pump. The delivery head in the sub-networks downstream of the taps is 4 m above the pipe level. The pumping station delivers 1000 m^3/h to the test systems.

The hydraulic schemes consist of two networks: the so-called complete test system and the simplified system; see Figure 1, Figure 7 and Figure 10. The complete test systems contain a full sub-network model with branches and taps at the end of the branches. In the simplified system the complete sub-network model is substituted with a single tap or an improved tap, representing the complete sub-network. Both systems are equipped with virtual pressure sensors to monitor the pressure at the sub-network junction and at the tap in the simplified system. A WANDA control component is used to subtract both pressures in order to monitor the pressure error between the complete and the simplified system directly: $e(t) = H_{real}(t) - H_{simple}(t)$. A positive error means that the pressure in the simplified system is lower than the pressure in the complete system. A positive error is considered better than a negative error, because in that case a conservative minimum pressure estimate is calculated in the simplified system. If the conservative minimum pressure remains above the criterion value (atmospheric pressure usually), then it is guaranteed that the real pressure remains above the criterion value as well.

The behaviour of the standard tap and several improvements as a substitute for a sub-network is investigated in a full pump trip scenario (power failure) in the three test systems. The system behaviour of the tap is presented by means of the time series of the pressure at the tap junction in the main pipeline and the flow from the main pipeline or the flow into the sub-network. The time function of the monitored pressure error is observed in detail and described by means of the following three quantities:

- band width of the error while the primary pressure wave travels through the system,
- the amplitude of secondary pressure waves (due to reflections) and
- the remaining systematic error.

The time frame related to the primary pressure wave is defined as the required travel time to reach the end of the most remote branch of the system. Furthermore the minimum pressures in the complete and simplified systems are tabulated. The behaviour of the standard tap and the improved modelling approaches is compared on these quantities.

3. Standard tap behaviour

3.1 Test systems

The pressure wave speed needs approximately 28 seconds (c = 370 m/s) to reach the sub-network junction; see also Figure 2 through Figure 4 on page 12. In the complete system the under-pressure wave enters the sub-network. The first 3 pipes in the sub-network have been modelled with the same parameters as the main pipeline. For this reason the under-pressure wave continues into the sub-network without any reflection. Thus the flow from the main system must still decrease. After 28 seconds the pressure head in the junction of the complete sub-network remains constant at 15 m for 15 seconds, because small over-pressure reflections compensate the further decrease of the pressure. The consequence of this temporarily almost constant pressure at the junction is the constant flow into the sub-network (only line packing effects are responsible for the slower rate of decrease). The pipe diameter decreases from 600 mm to 400 mm after 3 km in the sub-network (double travel time equals 16 seconds). After 43 seconds the primary under-pressure wave has reflected on this smaller diameter and returned to the junction to draw the junction pressure further downward.

The simplified model shows a slightly different behaviour. The pressure and flow at the junction are in accordance with the complete system in the first 25 seconds, because the under-pressure wave has not reached the junction yet. The under-pressure arriving at the sub-network junction reflects at the resistance in the tap. The resistance allows a fraction of the original discharge, because the downstream pressure is still more than 4 m. This means that an additional under-pressure returns from the tap into the main system, while the complete system is only subject to line packing effects. The pressure at the junction slowly decreases further between 28 and 80 seconds because the tap is still delivering a decreasing amount of water. After 80 seconds the pressure wave has travelled back and forth through the main pipeline and returns at the tap junction as a smaller under-pressure wave, causing the pressure to drop and the tap to close. The tap remains closed during the rest of the simulation. The remaining small over-pressure wave is now travelling between two closed boundaries (check valve and tap) causing small over-pressure shocks at the tap. These over-pressure shocks are compensated by line packing effects.

The pressure error (Figure 4) reflects the described pressure difference at the junction node. It may be concluded that the standard tap describes the basic time-averaged behaviour of the sub-network correctly, although the dynamics related to the storage volume and inertia of the sub-network are ignored. Nevertheless this deficiency does not lead to systematic errors in the pressure at the junction. The imperfections of the tap will be discussed in detail in paragraph 3.2.

Test systems 2 and 3 will not be discussed in detail, because the basic phenomena are comparable with test system 1; see Figure 8 and Figure 11. As opposed to the other test systems test system 3 contains 2 sub-networks demanding only 100 m^3/h each and an infinite pipe demanding the remaining 800 m^3/h. To prevent interaction with cavitation phenomena, cavitation has not been included in this simulation and as a consequence pressures may drop below vapour pressure (app. -10 m). The imperfections of the standard tap are discussed in the next section.

3.2 Imperfections of the standard tap

It has been reasoned above that the standard tap has three basic imperfections leading to inaccurate minimum pressure calculations:

- reflections, generated in the sub-network, are not revealed by the tap,
- the storage volume and inertia are not present in the non-return tap.
- the minimum pressures in the simplified system using non-return taps are not necessarily lower than the minimum pressures in the complete network.

The first and second aspect become more important as the relative volume of the sub-network increases. The effect of a return flow is negligible if the sub-network is small compared to the main pipeline system. On the other hand if the sub-network is very large, the return flow will dominate the system response. The size of a sub-network relative to the main pipeline system can be expressed in terms of a relative volume. The relative volume of a sub-network in a distribution system will be the total sub-network volume divided by a fraction of the total main pipeline volume. Define:

$$V_{m,j} = \sum_i \frac{q_{i,j}}{q_i} \cdot V_{m,i} \quad ,R_j = \frac{V_{s,j}}{V_{m,j}}$$

Using these definitions the following relative volumes are calculated for the test systems:

Test system	relative volume sub-network 1	relative volume sub-network 2
1	0.72	-
2	0.71	-
3	0.16	0.05

The larger the relative volume the more important the modelling of the sub-network becomes. From the table above it is expected that an improved tap, taking into account the storage volume more accurate, will affect test systems 1 and 2 and have less influence on test system 3, because of the values of the relative volumes. It is also assumed that sub-network 1 in test system 3 is more dominant than sub-network 2 in this test system. This assumption is confirmed by the results of the standard tap, because the error that occurred in the first sub-network, is transferred to the second sub-network.

In order to check the importance of the storage volumes, test system 1 has been simulated with several main pipe lengths ranging from 1 km to 20 km (original value is 10 km) with relative volumes of 7.2 down to 0.36.

As expected the error width decreases as the relative volume of the sub-network decreases. The error width does not tend to 0, because the reflections of the primary pressure wave, generated in the sub-network, can not be calculated using the standard tap. It is concluded that an improved tap model should always take reflections into account. The storage volume should be taken into account if the relative volume of the sub-network is more than 0.5. Two extended tap models will be discussed in chapter 4.

4. Extended sub-network representations

The reflection behaviour of a sub-network depends on the travel times in the sub-network. In order to model these reflections, a pipe should be included in the tap model. The extensions discussed in this chapter are limited to those which consist of a single pipeline and one tap, as the objective is a significant simplification of the complete system.

The first extended representation is based on an appropriate choice of the pipe length of a sub-network, which has the same pipe specifications as the first pipe in the sub-network. The second extended representation is slightly more sophisticated and allows diameter variations in the sub-network. Both approaches are discussed in the sections below.

4.1 Centre-point of gravity pipe length

A fraction of the water flows to the end of the sub-network branches, another fraction is demanded in the first pipe of the sub-network. The effect of all demands and distances from the junction can be accounted for by choosing a centre-point of all demands. Define the centre-point of gravity (*cpg*) length of sub-network *j* as follows:

$$l_{cpg,j} = \sum_{i=1}^{N_j} l_{j,i} \cdot q_{j,i} \Bigg/ \sum_{i=1}^{N_j} q_{j,i}$$

Represent the sub-network by a pipe with *cpg*-length and specifications equal to the first pipe in the sub-network. At the end of this pipe the tap allowing the sub-network flow is modelled. In this way the volume and a weighted reflection point of the sub-network are characterised. This approach is simulated in the three test systems in cases testX_2, where ‘X’ refers to the test systems.

4.2 Constant velocity pipe diameter

Waterhammer pressures and reflections are strongly determined by fluid velocities (Joukowsky). In order to model an additional improvement to the *cpg*-length the velocities along the *cpg*-pipeline should equal the actual velocities in the sub-network. Therefore identify the most important path in the sub-network, being the path along which the largest amount of water flows. If several paths (or sub-paths) contain the same flow, one of these paths may be selected arbitrarily. It is not necessary to search a path which is longer than the centre-point of gravity length. The length of this path may be shorter than the centre-point of gravity length. Substitute pipes should be modelled along this sub-network path such that two conditions are fulfilled. First the velocity in the substitute pipes at a distance x from the junction should equal the velocity in the sub-network path at the same distance x from the junction. It should be taken into account that the velocity in the complete sub-network decreases as sub-network taps withdraw water from the sub-network, while all water flows through the substitute pipes to the single substitute tap at *cpg*-distance. Secondly the wall thickness in the substitute pipes should be adjusted such that the wave speed velocity in the substitute pipe equals the corresponding wave speed velocity in the sub-network path. At the end of these substitute pipes the tap is allocated with a downstream head equal to the delivery head of the sub-network and a demand flow equal to the sub-network demand flow. In many situations the water distribution in the sub-network is not known exactly. If the water distribution is not known, velocities in the substitute pipe can not be calculated. In this case the local water distribution should be estimated based on available statistical data and knowledge of the local situation. Then the velocities can be calculated in the substitute pipeline. This approach is simulated in the three test systems in cases testX_3.

5. Testing the extended tap models

The results of both extended sub-network representation models are compared with the behaviour of the complete test systems and the simplified tap test systems. The results are compared on the pressure error characteristics and the minimum pressures.

The time graphs of the pressure error are drawn in Figure 4 to Figure 6 for test system 1, in Figure 8 to Figure 9 for test system 2 and in Figure 11 to Figure 12 for test system 3.

Test 1	Simplification error characteristics			Minimum pressure			
	range [m]	ampl. [m]	dev. [m]	overall location	[m]	main pipeline	[m]
real	-	-	-	(AE)	-2.4	Preal1 (1045)	-1.9
test1_1	[-2.7; 7]	1.5	-0.5	-	-	Psimpl1 (0)	-0.1
test1_2	[-4.3; 3]	1.2	-1.2	-	-	Psimpl1 (149)	-1.1
test1_3	[-2.8;1.6]	1.5	-1.0	-	-	Psimpl1 (896)	-1.5

The complete test 1 system attains its minimum pressure in the sub-network in node AE (see Figure 1). The minimum pressure in the main pipeline is -1.9 m (1.9 m below atmospheric pressure) and is found after approximately 1 km. The simplified models are not able to reproduce the minimum pressure in the system, although the deviation from the minimum pressure decreases from 1.8 m to 0.4 m. The simplification error range decreases from 9.7 m in test1_1 to 4.4 m in test1_3. The systematic error varies between -0.5 m and -1.2 m.

Test 2	Simplification error characteristics			Minimum pressure			
	range [m]	ampl. [m]	dev. [m]	overall location	[m]	main pipeline	[m]
real	-	-	-	Preal1 (3485)	-3.3	Preal1 (3485)	-3.3
test2_1	[-4; 6.7]	2	0.0	-	-	Psimpl1 (303)	-2.0
test2_2	[-7: 13]	3	-2	-	-	Psimpl1(3333)	-5.4
test2_3	[-2; 2]	1.5	0			Psimpl1 (3485)	-2.6

In this test case (tree-structure) the minimum pressure occurs in the main pipeline. Test2_2 shows a systematic deviation from the complete system. The reason is the large diameter of the long centre-point of gravity pipe in the simplified model. Test2_3 remains within a deviation of 2 m and the minimum pressure is overestimated by 0.7 m. The simplification error range decreases from 10.7 m in test2_1 to 4.0 m in test2_3.

Test 2	Simplification error characteristics			Minimum pressure	
	range [m]	ampl. [m]	dev. [m]	main pipeline	[m]
real	-	-	-	Preal1 (2000)	-11.9
				Preal2 (231)	-12.6
				Preal3 (1000)	-16.3
test3_1	[-5; 4]	0.2	0	Psimpl1 (2000)	-11.2
	[-4; 4]	0.2	0	Psimpl2 (462)	-12.1
				Psimpl3 (1000)	-16.3
test3_2	[-4.5; 4]	0.2	0	Psimpl1 (2000)	-11.6
	[-4; 4]	0.2	0	Psimpl2 (846)	-12.1
				Psimpl3 (1000)	-16.3
test3_3	[-3.3;3.2]	0.25	0	Psimpl1 (2000)	-11.3
	[-2.3;2.8]	0.2	0	Psimpl2 (615)	-13.2
				Psimpl3 (1000)	-16.3

Test 3 is the test system with 2 sub-networks. The sub-networks are small expressed in relative volume. Nevertheless the extended sub-network representation shows better results with respect to the pressure error decreasing from 5 m to 3 m.

It is immediately concluded from the tables above that the results improve significantly after application of the extended sub-network representation consisting of a pipe with constant velocity diameter and a single tap. The minimum pressure in the main pipelines deviates less than 1 m if the extended model with constant velocity diameter is applied.

6. Conclusions and recommendations

A simulation study has been performed to estimate the accuracy of several sub-network representations, based on a single non-return tap. Conclusions from this study are as follows:

- The non-return tap behaves correctly to an accuracy of 2 m in the minimum pressure in the main pipeline, although temporary deviations in the pressure at sub-network junctions of 7 m may occur. The accuracy of the non-return tap improves with respect to the minimum pressure in the main pipeline to a level of less than 1 m if the relative volume of the sub-networks is smaller than 0.5. The minimum pressure in the complete systems is lower than in the simplified system.
- Reflections generated in the sub-network can not be accounted for in a standard non-return tap.
- As the volume ratio between sub-network and main pipelines increases the influence of the storage volume and inertia of the sub-network becomes significant as well.
- In these situations the tap should be extended with a single pipe with changing diameter such that the pipe velocity equals the velocity in a selected sub-network pipeline. Large sub-networks are represented efficiently by these combinations of a single pipeline and a tap. The pressure error remains smaller than 3.5 m in the elaborated test systems. The minimum pressure in the main pipeline of the simplified test systems deviates less than 1 m from the minimum pressure in the complete test systems.

The following recommendations are made:

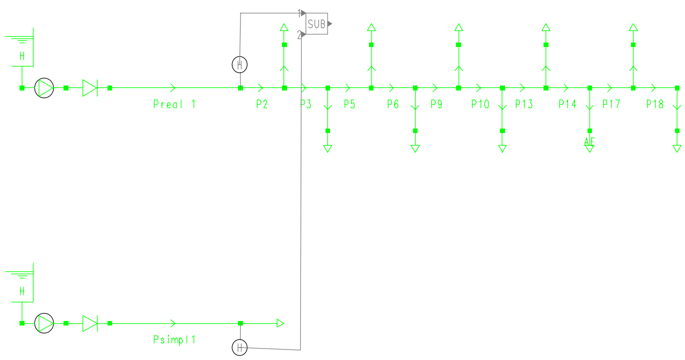
- It is recommended to test the behaviour of the improved tap in looped systems, for many sub-networks have two connecting junctions to the main system.
- A large distribution network with many small sub-networks could be tested with standard taps and extended models.
- The extended tap behaviour with respect to valve closure is an item which has not been discussed in this paper.
- Influence of relative sub-network volume on the minimum pressure accuracy could be estimated in a more general context.

Appendix Figures

Test 1

The simulations in test 1 have been based on a time step of 0.4 seconds. The hydraulic scheme is depicted in the figure below.

Figure 1: Hydraulic scheme Test 1



Pipe specifications

Preal 1, Psimpl1, P2, P3, P5:

L	=	10	km
L	=	1	km for P2, P3, P5
D	=	600	mm
k	=	0.2	mm
e	=	30	mm
E	=	3	GPa
c	=	373	m/s

Other pipes without labels:

L	=	1	km
D	=	200	mm
k	=	0.1	mm
e	=	8	mm
E	=	3	GPa
c	=	357	m/s

P6, P9, P10, P13, P14, P17, P18:

L	=	1	km
D	=	400	mm
k	=	0.2	mm
e	=	20	mm
E	=	3	GPa
c	=	357	m/s

Figure 2: Test 1_1. Real and standard tap flow to junction [m^3/h]

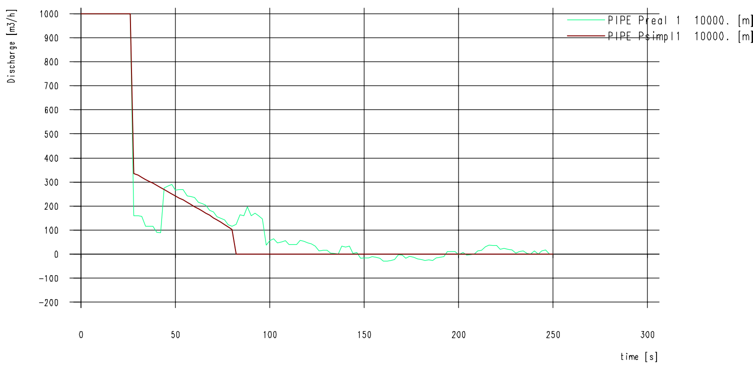


Figure 3: Test 1_1. Real and simplified pressure head at junction [m]

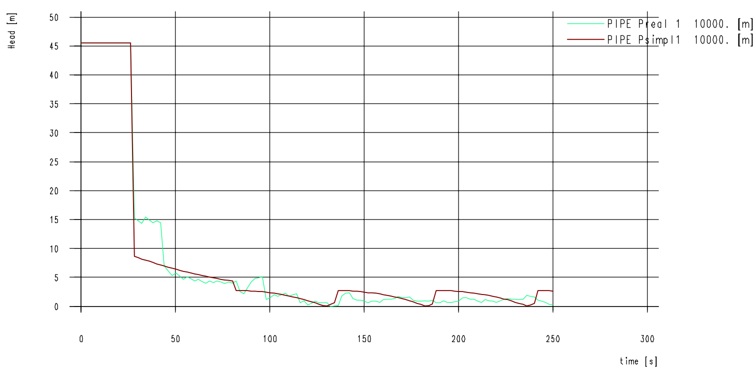


Figure 4: Test 1_1. Head error at junction using standard tap [m]

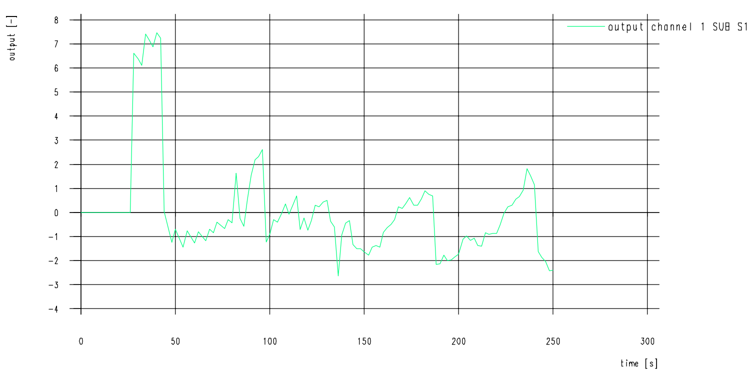


Figure 5: Test 1_2. Head error at junction using *CPG* pipe length and tap [m]

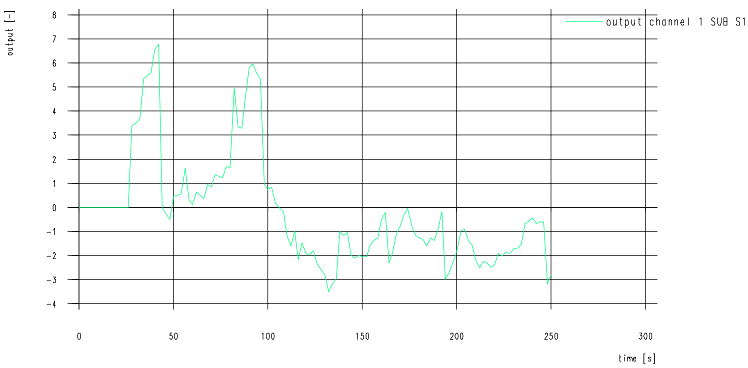
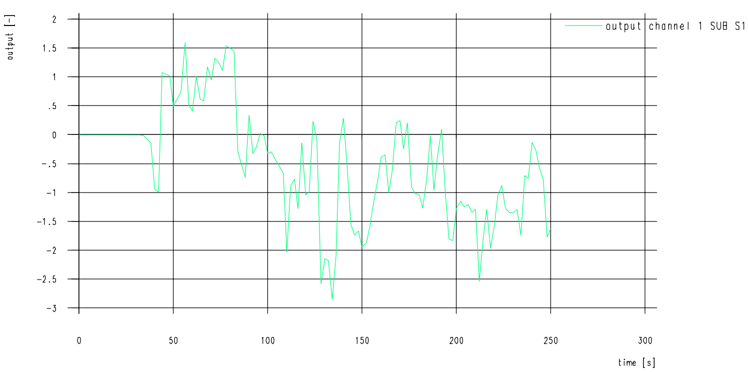


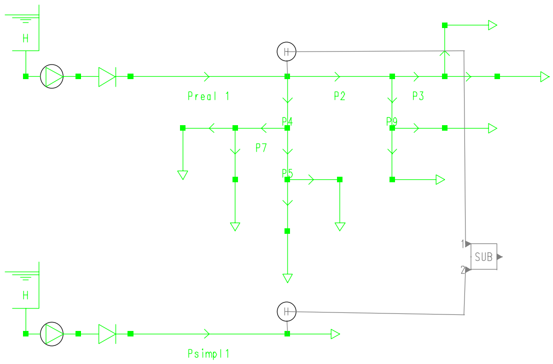
Figure 6: Test 1_3. Head error at junction using constant velocity diameter [m]



Test 2

The simulations in test 2 have been based on a time step of 0.4 seconds. The hydraulic scheme is depicted in the figure below.

Figure 7: Hydraulic scheme Test 2



Pipe specifications

Preal 1, Psimpl:

L	=	5	km
D	=	600	mm
k	=	0.2	mm
e	=	30	mm
E	=	3	GPa
c	=	379	m/s

Other pipes without labels:

L	=	1	km
D	=	200	mm
k	=	0.1	mm
e	=	8	mm
E	=	3	GPa
c	=	357	m/s

P2, P3, P4, P5, P7, P9:

L	=	1	km
D	=	400	mm
k	=	0.2	mm
e	=	20	mm
E	=	3	GPa
c	=	357	m/s

Figure 8: Test 2_1. Head error using standard tap [m]

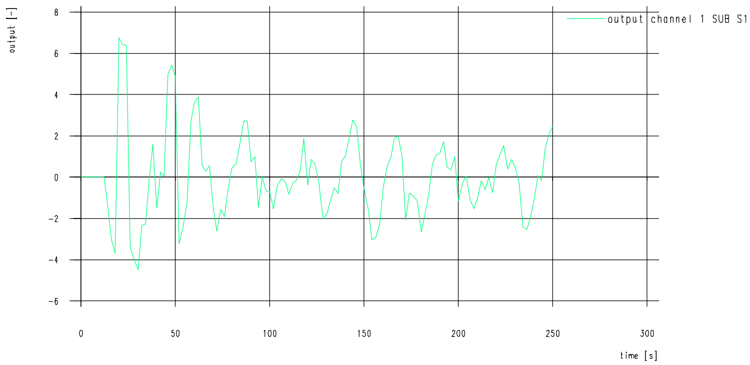
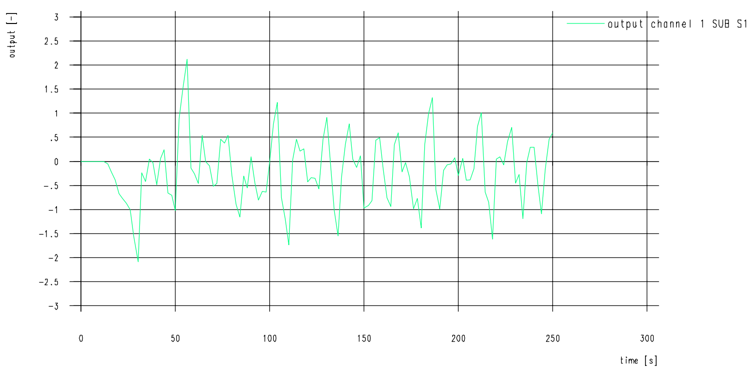


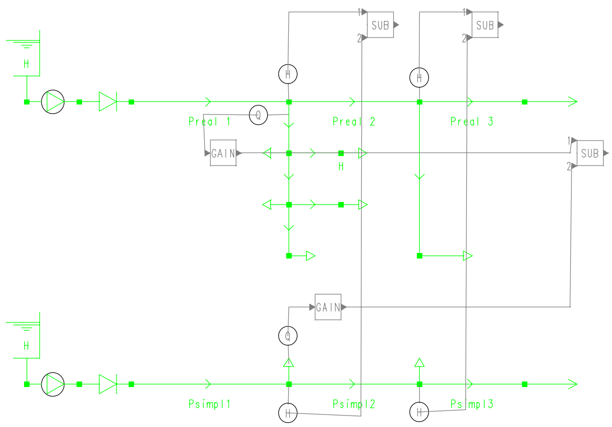
Figure 9: Test 2_3. Head error at junction using constant velocity diameter [m]



Test 3

The simulations in test 3 have been based on a time step of 0.2 seconds. The hydraulic scheme is depicted in the figure below.

Figure 10: Hydraulic scheme Test 3



Pipe specifications

Preal 1, Psimpl1:

L	=	2	km
D	=	500	mm
k	=	0.2	mm
e	=	25	mm
E	=	3	GPa
c	=	370	m/s

Preal 2, Preal 3, Psimpl2, Psimpl3:

L	=	1	km
D	=	400	mm
k	=	0.2	mm
e	=	20	mm
E	=	3	GPa
c	=	385	m/s

Other pipes without labels:

L	=	0.3	km (single pipe in sub-network 2 has length 0.9 km)
D	=	200	mm
k	=	0.1	mm
e	=	8	mm
E	=	3	GPa
c	=	375	m/s

Figure 11: Test 3_1. Head error using standard taps [m]

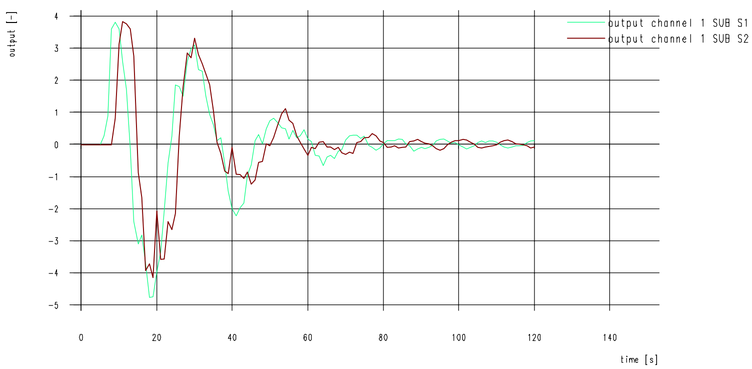


Figure 12: Test 3_3. Head error using constant velocity diameter [m]