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MODELING ENERGY LOSSES IN THE HYDRAULIC SYSTEM OF VOMBVERKET WATER TREATMENT PLANT

Modellering av energiförluster i Vombverkets hydrauliska system

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Abstract

Vombverket, one of the major water treatment plants in south Sweden, originally built in the 1950's, was significantly expanded in the 1990's. Because of this expansion, the water flow path was prolonged. The plant was not optimized for the new process design with regard to the hydraulic conditions, but substantial pressure losses were introduced through the addition of bends, valves, and other hydraulic components. In order to increase the capacity of the system, pumping has been considered; however, an alternative to this measure is to eliminate some of the added energy losses. The locations and properties of these losses should be established by performing a detailed analysis of the hydraulic system for a range of different flow conditions. The present study started with a literature review on energy losses in hydraulic systems, followed by a thorough investigation of the existing system based on available drawings and other material. The hydraulic system was schematized to yield a simplified conceptual model, which included components with significant influence on the losses of the system. Measurements of the pressure and flow rate were carried out at selected points in the hydraulic system in order to quantify the losses. A hydraulic model was developed, and available measurements were used for calibration and verification. Different modifications to the hydraulic system were simulated for a range of operational conditions. In the model simulations, the plant was divided into three sections comprising the filter buildings 1, 2 and 3, each encompassing a series of hydraulic components. Two types of modifications to the system were shown to be favorable; (1) remove the two weirs and the Venturi meters in filtration building 1 and 2 and one gate valve in building 1; and (2) directly connect the hydraulic system in filtration building 1 and 2 to the downstream reservoir, thus shortening the water flow path and reducing energy losses.

Key words – Hydraulic system, energy losses, capacity, components, Venturi meter, pipe flow, loop, nodes

Sammanfattning

Vombverket, ett av de betydande vattenreningsverken i södra Sverige, byggdes ursprungligen på 1950-talet, men en omfattande expansion genomfördes under 1990-talet. Denna expansion förlängde flödesvägen för vattnet genom verket. Det nya verket var inte optimerat vad gäller de hydrauliska förhållandena och betydande tryckförluster uppstod i systemet genom att en rad olika hydrauliska komponenter såsom rörkrökar och ventiler introducerades. För att öka kapaciteten i verket överväger man pumpning, men en alternativ metod är att på olika sätt reducera de hydrauliska förlusterna. Vad gäller den senare metoden måste sådana förluster lokaliseras och kvantifieras genom en detaljerad analys av det hydrauliska systemet för en rad olika flödessituationer. Föreliggande studie startade med en litteraturgenomgång beträffande energiförluster i hydrauliska system, följt av en detaljerad analys av det existerande systemet baserat på tillgängliga ritningar och annat material. Äldre ritningsmaterial specialstuderades för att identifiera de förändringar som genomfördes i samband med expansionen av verket. Det hydrauliska systemet schematiserades så att en förenklad modell erhölls, inkluderande alla komponenter som signifikant bidrager till energiförlusterna i systemet. Mätningar genomfördes av tryck och flöden i valda punkter i systemet som ett underlag för att kvantifiera förlusterna. Datorprogrammet Pipe Flow Expert användes för att utveckla en detaljerad hydraulisk modell och tillgängliga mätningar utnyttjades för kalibrering samt verifiering av modellen. Efter denna validering undersöktes effekten av olika modifieringar av systemet för olika flödesförhållanden. I modellen delades verket in i tre olika sektioner vilka omfattade filterbyggnad 1, 2 och 3 tillsammans med en rad olika hydrauliska komponenter. Två typer av modifieringar av systemet visade sig vara effektiva vid modellsimuleringarna, nämligen: (1) avlägsnande av två överfall och en Venturimeter i filterbyggnad 1 och 2, samt en slussventil i filterbyggnad 1; och (2) direkt anslutning av ledningarna från filterbyggnad 1 och 2 till nedströms reservoar, innebärande en reducering av flödesvägen och sammanhängande energiförluster.

Figure 1. *Overview of Vombverket water treatment plant with the different filter blocks (FB).*

1 Introduction

Sydvatten AB is a municipally owned company producing and supplying drinking water to about 900,000 inhabitants in south Sweden through two water treatment plants (WTP), Ringsjöverket and Vombverket. The company was founded by five municipalities in Skåne and serves today 16 municipalities in the region. Sydvatten produces approximately 2.3 m^3/s of drinking water. Vombverket commenced production in 1948 and produces drinking water using an artificial groundwater recharge process (see Figure 1). This water flows through strainers before reaching the 58 infiltration ponds. Here the water is infiltrated to recharge the natural aquifer, then pumped up for treatment through 114 wells. Vombverket provides drinking water to the municipalities Burlöv, Malmo, Staffanstorp, Svedala, Vellinge, and certain parts of Lund and Eslöv.

Prolonging the water flow path in connection with the expansion of Vombverket in the 1990's led to increased energy losses in the hydraulic system, hence a significant drop in the plant discharge capacity. Installing pumps to boost the pressure could be an option to recover the capacity; however, this would imply continuous operational and maintenance costs at the plant leading to an increasing cost for the consumers. As an alternative to pumping, a solution might be found that relies on a reduction of the energy losses in the system. Thus, a detailed study of the hydraulic system losses would provide for a more sustainable solution, involving specific system modifications with minimal and acceptable economic implications.

The main objective of the study was to investigate the hydraulic system of the WTP with the purpose of reducing energy losses that occurred after the plant expansion.

The project involved two sub-objectives:

1. To create a model of the hydraulic system between the mixing chamber and the facility for chloramine dosing.
2. To investigate different cost-effective measures to modify the hydraulic system, hence reducing energy losses.

2 Basic pipe flow theory

Flow in pipes is classified as being laminar or turbulent, although there also exists a small region of transition between these two types of flow. The ratio of inertia forces to viscous forces, known as the non-dimensional Reynolds number (Re), determines the type of flow prevailing. The flow is laminar or turbulent when this ratio is less than 2000 or greater than 4000, respectively, with the intermediate interval corresponding to transitional flow. The value Re = 2000 is normally taken as the threshold value between laminar and turbulent flow (Cengel and Cimbala, 2006a). The transition from laminar to turbulent flow depends on the pipe geometry, surface roughness, flow velocity, temperature, and fluid type and properties. Turbulent flow is the most common flow regime and it is classified as being smooth or rough, depending on the relative pipe surface roughness and Re number.

2.1 Governing equations

The fundamental principles of fluid flow are the conservation laws, which include conservation of mass, energy, and linear momentum. The traditional conservation laws are written in either integral or differential form (Vennard and Street, 1982).

The conservation of mass, also known as the continuity equation, is the most basic of the principles and it requires that mass is neither created nor destroyed in a specified finite control volume. This implies that the rate of change of fluid mass in a control volume must equal the fluid mass transport through the boundaries of the volume, which in the one-dimensional case for incompressible flow simply yields,

$$Q = AV \quad (1)$$

where Q = volumetric discharge through the pipe section, A = cross-sectional area of the pipe and, V = mean velocity of the fluid in the pipe.

The conservation of energy or Bernoulli's equation, states that, for a unit mass of a fluid, total energy is expressed as a sum of kinetic, potential and pressure energy/work,

$$\frac{V_1^2}{2g} + \frac{P_1}{\gamma} + Z_1 = \frac{V_2^2}{2g} + \frac{P_2}{\gamma} + Z_2 + \sum h_l - h_m\,(pump) + h_t\,(turbine) \quad (2)$$

where, P = pressure, γ = weight density of the fluid, and $\sum h_l$ is the sum of both friction and minor losses in the system. Other terms are $\frac{V_1^2}{2g}$ the velocity head, $\frac{P_1}{\gamma}$ the pressure head, $\frac{P_1}{\gamma} + Z_1$ the piezo-metric head, Z_1 the elevation head, and $\frac{V_1^2}{2g} + \frac{P_1}{\gamma} + Z_1$ the total head in section 1 of the pipe (Cengel and Cimbala, 2006b).

2.2 Pipe friction losses

The viscous shear stresses in the fluid (water) and turbulence occurring along the internal pipe wall due to the material roughness create a resistance to fluid flow through pipes known as pipe friction and is measured in meters of fluid, hence the name head loss due to pipe friction. The head losses in a pipe are generally a result of fluid viscosity, internal pipe diameter, internal pipe wall roughness, pipe length, and the velocity (Crane, 1988).

The most accurate way to calculate pipe friction losses is by using *the Darcy – Weisbach formula,*

$$h_l = f\frac{L}{D}\frac{V^2}{2g} \quad (3)$$

where f = pipe friction factor, which is a function of the Reynolds number and the relative roughness *(e/D)*, L = pipe length, D = pipe internal diameter, e = equivalent roughness, V = fluid velocity, and g = acceleration due to gravity (Sleigh and Goodwill, 2009). The f-value can be obtained from the Moody diagram (Figure 2), if the values of Re and *(e/D)* are known depending on the flow regime.

The friction factor, f, can also be obtained through using empirical expressions such as the *Colebrook-White equation:*

$$\frac{1}{\sqrt{f}} = 1.14 - 2\log\left(\frac{e}{D} + \frac{9.35}{\mathrm{Re}\sqrt{f}}\right) \quad (4)$$

Pipe friction may be influenced by changes in e with time, which affects f; these changes may occur because of dirt accumulation in the pipes, corrosion and pipe aging, among other things (Larock et al, 2000). The fric-

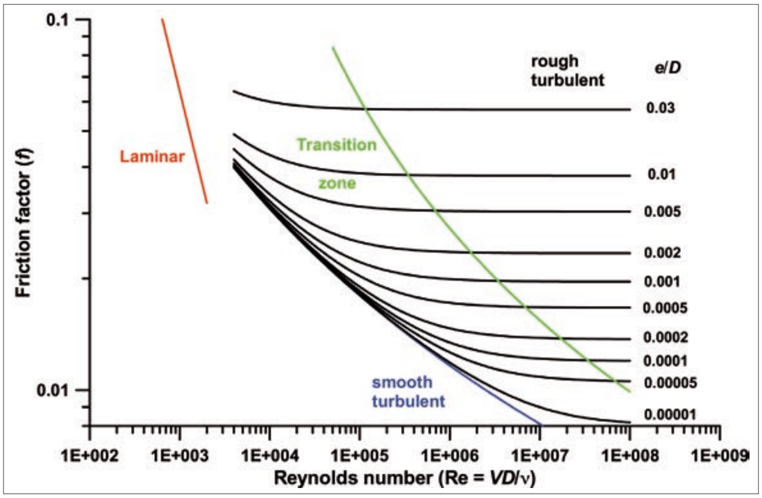

Figure 2. *The Moody diagram.*

tion factor is smallest in smooth pipes and increases with increasing roughness for a specific Re number.

2.3 Local losses

Local (or minor) losses occur at specific points in a pipe system, mainly due to geometric changes in the flow cross section or different hydraulic components, and are calculated using the general expression,

$$h_l = K_l \frac{V^2}{2g} \tag{5}$$

where K_l = coefficient that depends on the nature of the loss in the pipe system. Most commercial pipe fittings manufacturers provide the K_l value for their components that they obtain through experiments. These losses are typically a result of local disruptions to the flow in the pipe system resulting from the hydraulic components introduced in the system (Vennard and Street, 1982). Such components include:

1. Pipe entrance and exit losses from a tank/reservoir
2. Sudden expansions and contractions
3. Gradual expansions and contractions
4. Flow obstruction components such as valves; open or partially closed
5. Pipe fittings such as bends; 90°–45° elbows and tees among others
6. Flow meters, Venturi meters
7. Filtration systems, sand filters (rapid or slow)

Consider an abrupt obstruction in a pipe section (see Figure 3), where energy is dissipated as a result of flow conditions typical for minor losses. As the velocity of the water particles in the pipe increases, the pressure decreases and vice versa.

Vennard and Street (1982) depict a situation where energy is dissipated creating a minor loss in pipe flow primarily due to the eddies formed as the fluid decelerates just after the constriction (see Figure 3). Between Sections 1 and 2 the flow is accelerating, typically with little loss of energy, whereas between Sections 2 and 3 deceleration occurs with eddy generation and significant energy losses. Between Sections 3 and 4 is the flow established again and the locally generated eddies disappear.

2.4 Analyzing pipe networks

Pipe networks are classified into *branched* and *looped networks,* shown in Figures 4a and 4b, respectively. The number of continuity and energy equations that you can formulate, in order to determine unknown flows and pressures, will be directly proportional to basic relationships between the number of pipes, nodes (junctions), and loops that occur in both types of networks. These relationships are denoted as NP = number of pipes, NJ = number of junctions, and NL = number of loops in the network for which individual equations are written down. A node is a single point at which two or more pipes meet. A node may not specifically be a point of any energy loss but rather a joint for pipes. In branched networks, NL is zero since there are no complete loops and the number of pipes is always one less than the number of nodes or junctions in the system. Reservoirs are not considered as nodes so when they appear in a system then NP = NJ.

In a looped system, typically one continuity equation

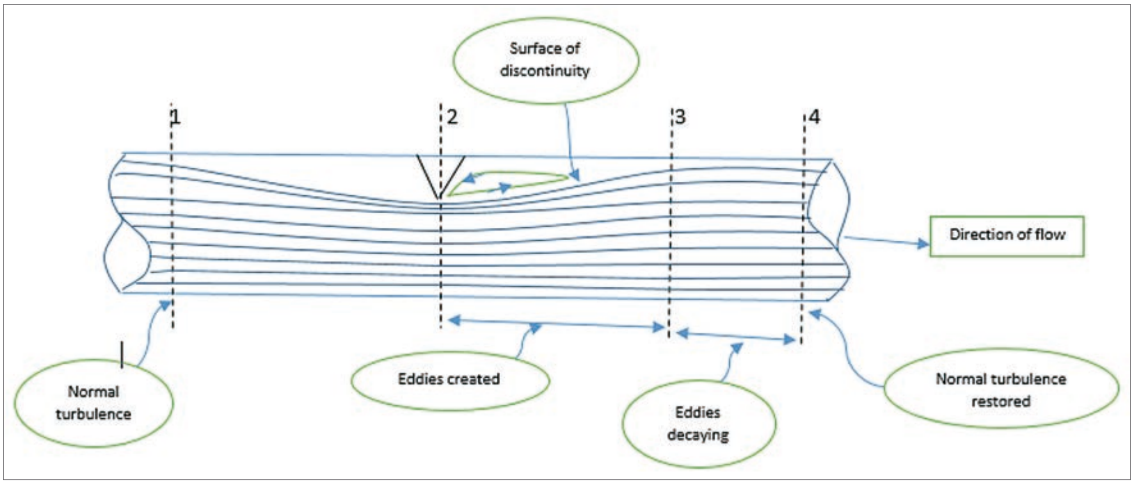

Figure 3. *Analysis of minor losses in pipelines.*

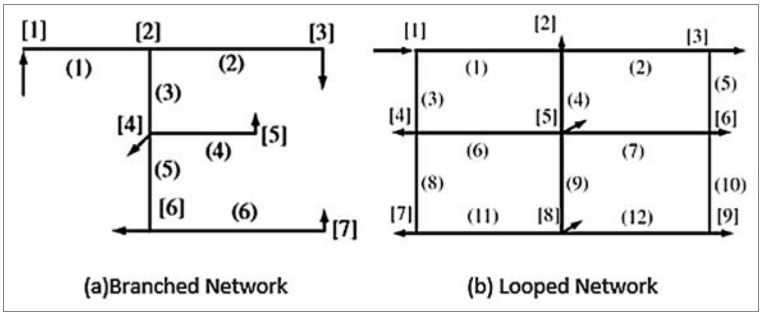

Figure 4. *Illustration of a branched and looped pipe network with the numbers in square brackets representing the node number and those in round brackets the pipe number.*

is obtained in each junction and one energy equation for each loop. The coupled system of equations needs to be solved using numerical techniques. For a looped network the number of loops (NL) is calculated from:

$$NL = NP - NJ \tag{6}$$

Larock et al. (2000) noted that for networks with two or more supply sources (e.g., reservoirs) Eq. (6) applies, and when the system is composed of one supply source, then another equation is required where the single source is considered as a node and introduced through a negative demand:

$$NL = NP - (NJ - 1) = NP - NJ + 1 \tag{7}$$

3 Study site – Vombverket

The Vombverket WTP has two main intake points from Lake Vombsjön, with an approximate discharge of 1 m^3/s that is passed through micro sieves before reaching the 58 infiltration ponds. The water is then infiltrated to recharge a natural aquifer from which it is pumped up, using 114 wells, to the treatment plant (Figure 5 shows the layout of the whole system at the plant). The water goes through several stages of treatment in the plant, but this study focuses on the section between the mixing chamber and the chloramine dosing chamber as illustrated in Figure 6.

3.1 Hydraulic system schematization

The hydraulic system of Vombverket WTP was schematized taking into consideration all the elements that cause significant resistance to the flow in the system. The schematized layout was divided into three sections, denoted as filter block/building 1, 2, and 3 (FB1, FB2 and FB3). The system starts in the mixer that is represented as a tank. Pipe elevation, reservoir water level, and surface pressure were the initial boundary conditions. The mixer is open to the atmosphere hence the surface gauge pressure is zero (relative to the atmospheric pressure). What components to include and exclude in the system depend on the modeler's experience with the system, general engineering judgement, and information from the literature. The junctions/nodes are not true physical elements but mark points where two or more pipes or valves are connected. The nodes are connected by links representing the pipelines.

The studied hydraulic system consists of reservoirs/tanks, short length pipes, rapid sand filters, bends, tees, gradual and sudden contraction and enlargement fittings, flow meters, flow control valves, Venturi-meters, and hydraulic structures such as weirs. The different components in the system of significance are discussed briefly below.

Reservoirs/tanks: There are five reservoirs within the studied section (see Figure 6). These include the mixing chamber, Chloramine dosing facility, two weir basins

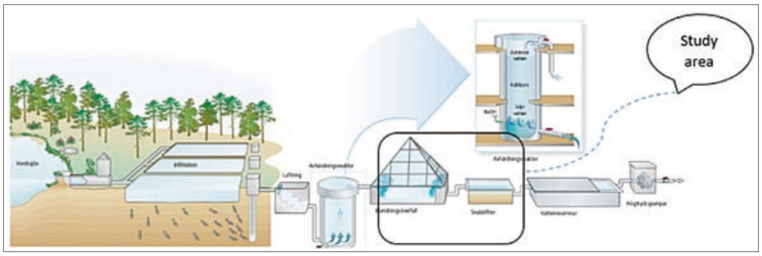

Figure 5. *State-of-the-art drinking water treatment process and system layout of Vombverket water treatment plant.*

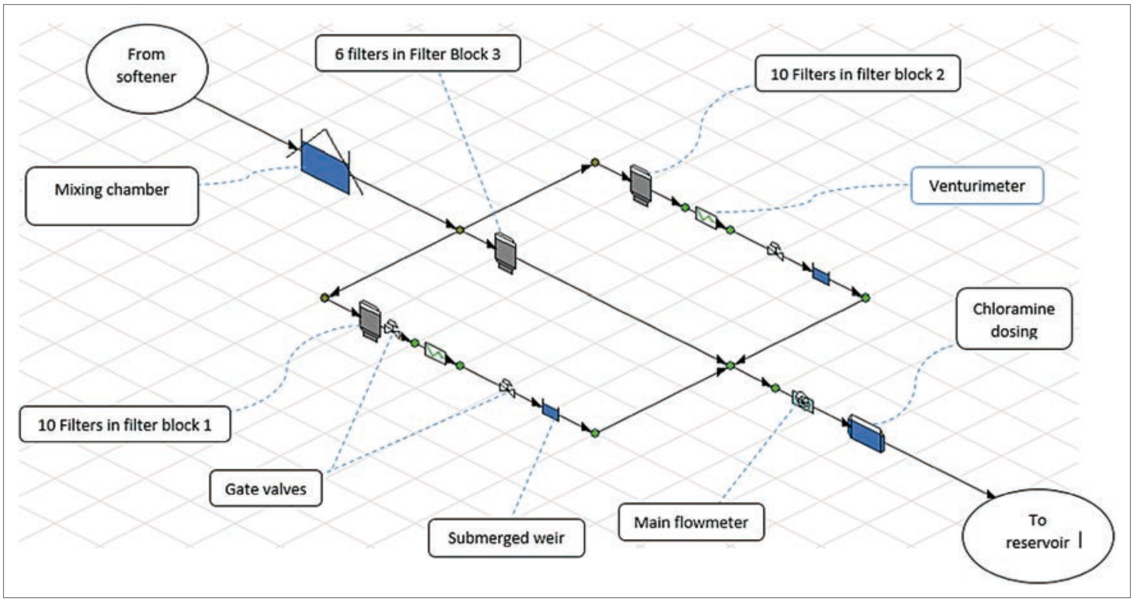

Figure 6. *Schematization of the hydraulic system at Vombverket showing major parts.*

located at filter buildings 1 and 2 respectively, and the safety basin located in filter building 3 that works as an escape route for water in case the flow at the intake exceeds the capacity of the filters (not shown in the schematization). In this case, the water will rise and flow over a high wall into a 1600 mm pipe connected to the disinfection basin, hence bypassing the filtration process. The model simulation ends in the disinfection basin.

Control valves: The valves in the treatment plant are automated, hence fitted with actuators for accurate and easy control. All these valves are connected to the central control system. The flow in the system is regulated by the percentage of valve opening depending on the demand. The pressure and flow measurements used to model the system were obtained when the valves were both fully and partially opened. The types of valves present in the WTP are gate valves and butterfly valves.

Flow meters: These meters are of electromagnetic type causing minimal energy losses in the system. Flow meters are found in all the three filter buildings and they are used for flow measurement in the system.

Venturi meters: The Venturi meters are devices also used for flow measurement in hydraulic systems. For the case of Vombverket, there are two Venturi meters installed in the system. They are short, compressed devices appearing in both filter buildings 1 and 2.

Rapid sand filters: There are 26 rapid sand filters in the Vombverket hydraulic system. Filter buildings 1 and 2 have 10 filters each, with 24 m^2 of surface area per filter. Filter building 3, which is the newest of all the buildings and a result of the expansion that lead to the energy loss problems, has 6 filters with 40 m^2 each, almost twice the size of the filters in buildings 1 and 2. The filter sand was replaced 1999 in filter blocks 1 and 2 as well as in filter block 3. The filters are flushed automatically at specified set periods.

Bends: Energy losses in bends comprise of the loss caused by curvature hence change in flow direction, length-induced loss, and loss due to downstream tangent properties. The velocity profile changes and the maximum velocity shifts to some point between the pipe wall and the centerline (Keulegan and Beij 1937; Crane 1988). Caution must be taken when choosing the bend shape to minimize the losses, which is related to the *r/D* ratio hence determining the loss coefficient in Eq. 5.

Tees: The flow path is of importance; the flow can be either converging or diverging. The flow is further classified as being branched or a through-flow and depending on the type, the head loss can be estimated. Other fittings considered as bespoke fittings include sudden and gradual contractions as well as enlargement fittings. The loss coefficients of those components can be calculated through the input of the pipe diameter at both sections of the pipeline together with the length, if applicable.

Weir: Weirs are hydraulic structures used for flow control and measurements. There are two weirs in the study section of the plant, one in each of the houses belonging to filter building 1 and 2.

Some of the components in the system could not be modeled in a straightforward manner. Thus, they had to be represented/modeled as bespoke components available in the model. For example, the rapid sand filters – in filter building 1 and 2.

The components discussed above appearing in the system cause losses that have led to a marked reduction in the system capacity. For example, the Venturi meters contribute significantly to the losses; however, they are no longer used since there are automated flow meters connected to the central control system. The weirs at the plant are submerged, hence no longer fulfilling their original purpose, but rather acting as secondary reservoirs in the hydraulic system creating losses where most of the velocity head disappears. The overall lengthening of the flow path also exposes the water to higher energy losses due to the increased distance travelled to reach the main reservoir.

3.2 Field measurements

Data from several different types of measurements were employed to set boundary conditions, to calibrate and verify the model, and to optimize the system. The first step was to ensure that the model reproduced the observed data at the plant. Data for the plant running at full capacity with all the valves open 100% was obtained from the system archive and compared to the model results using proper boundary and initial conditions. These data mainly encompassed flow rates. With these system results reproduced, other data sets were obtained for further calibration and verification of the model.

Using measurement gauges, the relative gauge pressure was obtained at specific locations in the system and at specific times in all the three filter buildings of the plant. For filter buildings 1 and 2, the pressure at points near the flow meters from each filter was measured, recording gauge pressure and time. The measurement time was later used to obtain the specific flow at that time through the filter or the node using data from the central control system. The same was done in filter building 3, but at slightly different locations such as at the flow meter after filters 21 and 26 (see figure 12), at the 1200 mm tee exiting filter building 3, and at the main flow meter.

There were pressure gauge connection points in the filter buildings at specific locations. These points were used to obtain results and to perform analysis, both regarding the model and the measurements. Figure 7 shows the inside layout of the pipe network in filter building 2. There were pressure points before each individual control valve at every filter in the building as shown in Figure 7.

4 Results

Measurements were performed at the Venturi meter in filter building 1 where there are two pressure gauge connection points, one immediately upstream the device and the other below the downstream weir basin. The weir at this point is submerged; hence this gauge will measure the static pressure representative of the pressure level after the Venturi meter. Values of the head loss versus the flow rate at this location were obtained for the period 10/1/2015 at 00:00 to 10/14/2015 at 00:00 eve-

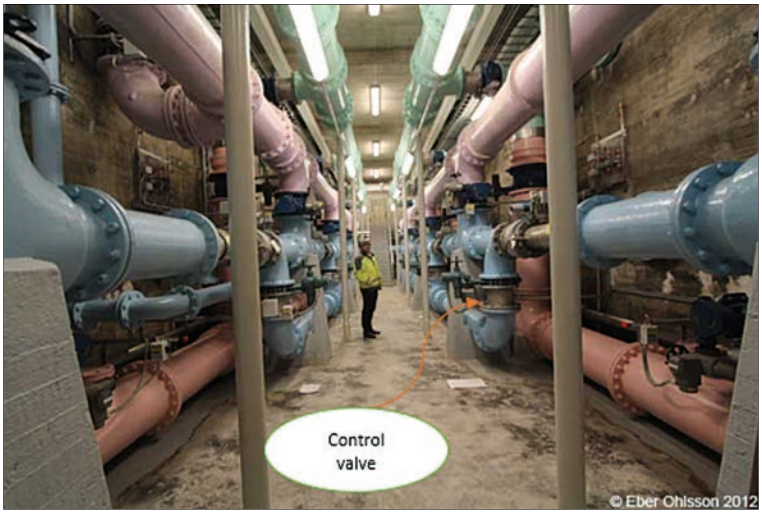

Figure 7. *Inside view of one of the filter buildings, where blue pipes carry filtered water, orange pipes are for drainage, the green upper most pipes are feeding the filters with raw water, and the pink pipes are for backwashing the filters.*

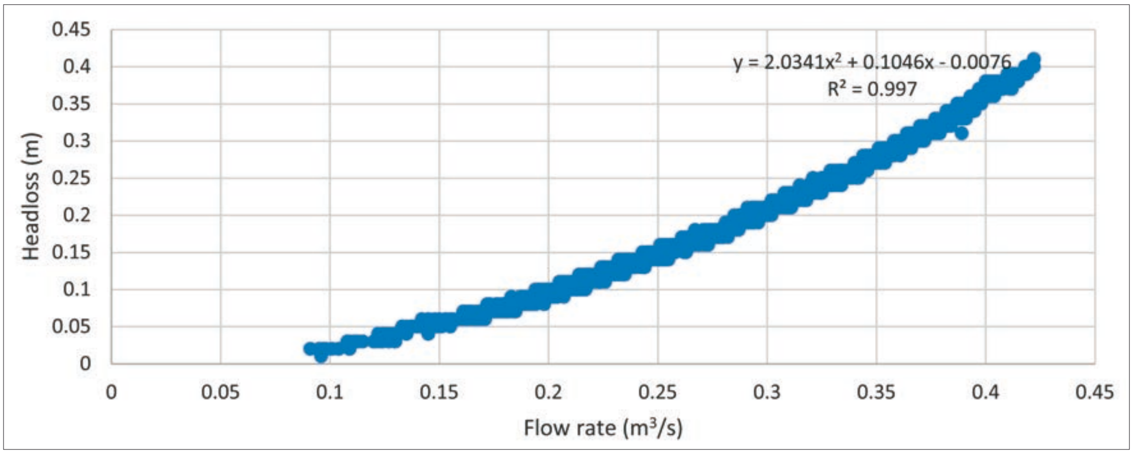

Figure 8. *Measured head loss versus flow rate across the Venturi-meter in block 1 taken from 10/1/2015 at 00:00 to 10/14/2015 at 00:00 every 6 minutes together with a fitted second-order polynomial.*

ry 6 minute. This provided a good data set for determining the head loss over the Venturi meter that is one of the major losses in the system. Furthermore, the data constituted a basis for describing this loss in the model when simulating the flow in the system. The measured values are plotted in Figure 8 with the head loss as a function of the flow. The model software allows for the addition of hydraulic components where a second-order polynomial is employed to describe the curve loss. The polynomial curve of this data is also given in Figure 8 indicating good agreement between data and the empirical equation. From this equation, three points are obtained and entered into the model to define the curve described by the equation; from this, the head losses can be calculated through the Venturi meter as a function of the flow rate. It should be noted from Eq. 5 that the head loss should be directly related to the flow rate, but the model employs a complete second-order polynomial to describe the losses from a general hydraulic component.

Regarding the filters, two measurements of head loss versus flow rate were initially obtained. It was assumed that all the filters are operating at similar conditions and properties. Thus, the curve loss in Figure 9 was employed in the model to see if it would reproduce the observed data when all valves are fully open; however, this was not the case. Filter building 1 agreed with these data, but filter building 2 was in disagreement and more data had to be obtained to calibrate filter building 2 (see Figure 10).

The corresponding flow rates through each filter in the system were recorded at the time when the pressure

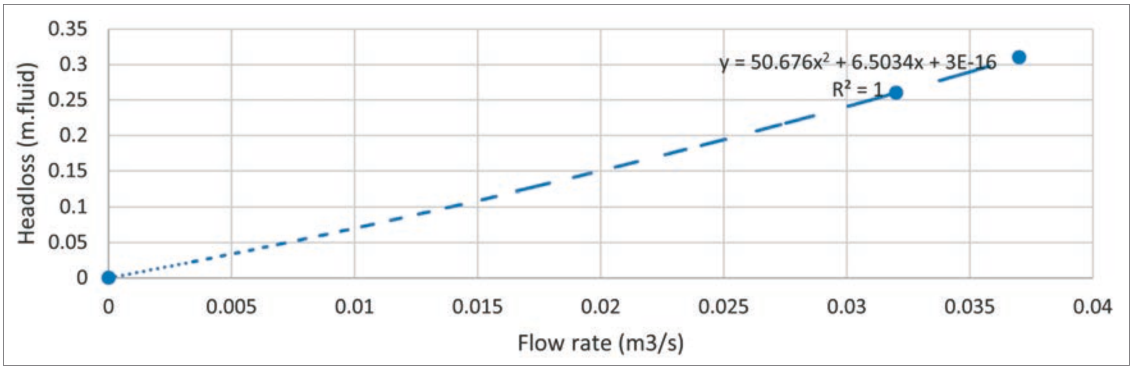

Figure 9. *Initial data used for all the sand filters, with head loss versus flow rate from two filters in the system. It was assumed that all filters have the same properties under similar conditions.*

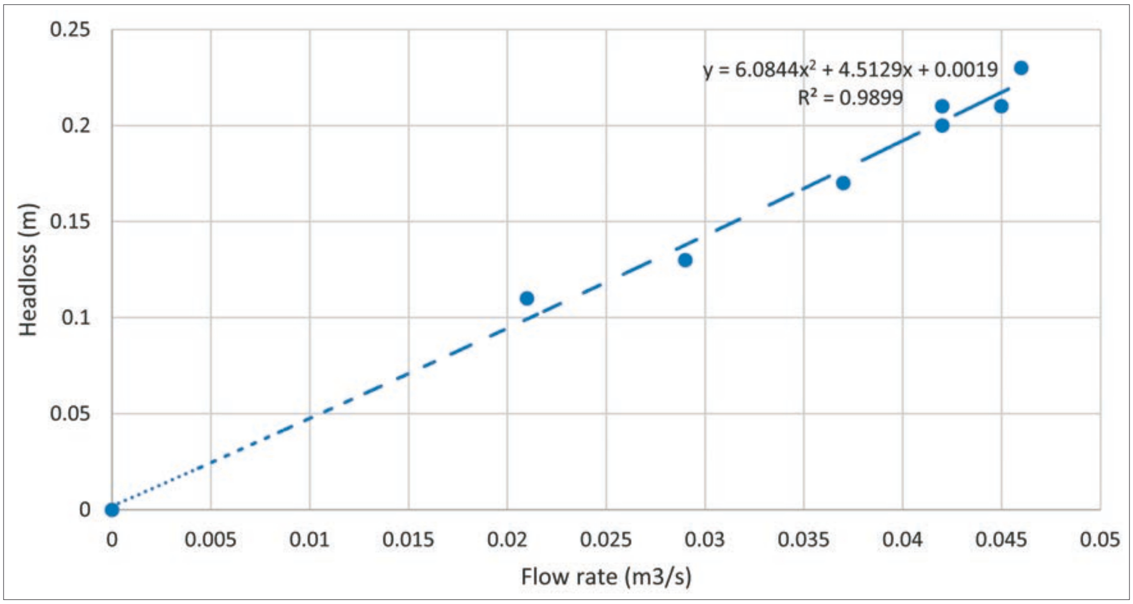

Figure 10. *Data set used to calibrate FB2 to reproduce the observed system results.*

readings were carried out, and the result is shown in Table 1 and 3. These data were analyzed and compared to the calculated values by the model; thus, verification of the model performance was possible.

The data in Table 1 is the observed data for pressure, taken when the plant was run with all valves in filter building 2 fully open. The corresponding flow rates at the time when the measurements were taken were ob-

Table 1. *Measured pressures and flow rates at each filter (11 to 20) in filter block 2 at a specific time of day used for model verification.*

FILTER BUILDING 2	Pressure measured next to the flow meter at each filter (m)	Time	Pressure drop between the filter and the Venturi meter (m)	Flow rate (l/s)
Filter 11	3.37	10:35	0.41	55
Filter 12	3.35	8:38	0.43	46
Filter 13	3.37	8:50	0.41	45
Filter 14	3.36	8:59	0.42	43
Filter 15	3.37	9:06	0.41	42
Filter 16	3.59	10:44	0.19	44
Filter 17	3.53	9:24	0.25	46
Filter 18	3.5	9:35	0.28	48
Filter 19	3.42	9:45	0.36	48
Filter 20	3.43	9:57	0.35	58
Height difference between pressure gauges			*0.844 m*	
Pressure before Venturi meter			*3.78 m*	*9:55am*
Pressure corrected for height difference			*2.936 m*	
		Conditions		
All valves in FB2 were fully open			*100% open*	

Table 2. *Flow rate (1/5) measured at specific times when pressure readings were taken in FB2.*

Time	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24	F25	F26
8:38	**32**	**32**	**32**	**32**	**32**	**32**	**32**	**32**	**29**	**32**	**55**	**47**	**45**	**42**	**42**	**43**	**46**	**49**	**48**	**56**	**80**	**78**	**80**	**80**	**79**	**79**
8:50	**33**	**33**	**33**	**32**	**32**	**33**	**33**	**32**	**32**	**32**	**55**	**46**	**45**	**42**	**42**	**44**	**46**	**49**	**48**	**56**	**81**	**81**	**81**	**81**	**81**	**80**
8:59	28	0	30	30	30	30	30	29	36	29	55	47	45	43	42	44	46	49	49	56	69	71	69	71	70	71
9:06	28	0	27	28	30	30	29	30	33	28	55	47	45	43	42	44	46	49	48	56	73	75	74	74	75	76
9:24	**29**	**29**	**30**	**30**	**29**	**29**	**29**	**29**	**28**	**29**	**55**	**46**	**45**	**43**	**42**	**44**	**46**	**49**	**48**	**56**	**73**	**75**	**73**	**74**	**74**	**73**
9:35	**32**	**33**	**31**	**33**	**33**	**33**	**32**	**33**	**26**	**33**	**54**	**46**	**44**	**42**	**41**	**43**	**46**	**48**	**48**	**56**	**81**	**83**	**83**	**81**	**82**	**82**
9:45	**32**	**33**	**33**	**32**	**33**	**32**	**32**	**32**	**32**	**32**	**54**	**46**	**45**	**42**	**41**	**43**	**46**	**48**	**48**	**56**	**80**	**80**	**81**	**82**	**81**	**81**
9:55	32	32	32	32	32	32	32	31	32	32	61	0	53	50	48	45	48	50	50	58	79	79	78	78	79	80
9:57	32	32	32	32	32	32	32	31	31	31	61	0	54	50	48	46	48	50	50	59	76	77	77	76	76	76
10:35	**28**	**28**	**28**	**28**	**29**	**28**	**28**	**28**	**28**	**28**	**55**	**51**	**44**	**42**	**41**	**43**	**45**	**48**	**47**	**55**	**24**	**72**	**72**	**69**	**69**	**69**
10:44	30	31	31	30	30	30	31	31	27	30	55	51	45	42	41	43	46	48	48	55	0	76	77	79	77	77

Table 3. *Measured values from Vombverket in filter block 3 used for model verification.*

FILTER BUILDING 3	Pressure gauge reading at point next to the flow meter at each filter (m)	Elevation from set level (m)
Filter 21	4.5	0.065
Filter 26	4.6	0.090
Large tee junction (1200 mm)	4.7	0.075
Point at the main flow meter	3.26	1.20

tained simultaneously. Table 1 is the raw data that were picked randomly by the authors and an expanded version is shown in table 2.

Table 2 shows the flow rates through the filters in the entire plant at the time each individual measurement in Table 1 was obtained, also showing what was happening in the other filters in the plant. As seen in Table 2, some filters had zero flow rate meaning that at the time the specific filter was backwashing, which creates a transient pressure that tends to affect the modeling results.

The values in red (Table 2) represent the cases when there was no filter backwashing at the time of the pressure reading. This partial data set was used for verification of the model, where specific sensitive locations for the pressure were chosen for filter building 3. These locations included the large tee junction, where the water from filter buildings 1, 2, and 3 meets in the 1200 mm inner diameter pipe (see Table 3).

A data set was obtained from the system archive that was representative of the highest discharge recorded in recent years and the purpose was to reproduce the design flow rate for the system when all the valves are fully open in the entire plant. The flow data from the18th of June 2014 at 21:00 was used, see Table 4.

Table 4. *Data set for the highest discharge recorded in recent years from the 18th of June 2014 at 21:00 (from control system archives).*

Filter block 1 (l/s)		Filter block 2 (l/s)		Filter block 3 (l/s)	
F1	54	F11	52	F21	130
F2	41	F12	49	F22	128
F3	44	F13	47	F23	129
F4	37	F14	40	F24	129
F5	36	F15	40	F25	129
F6	36	F16	43	F26	130
F7	38	F17	47		Average 129
F8	40	F18	48		
F9	34 – 39	F19	48		
F10	49	F20	55		

4.1 Modeling of the hydraulic system

Modeling pipe systems is performed using basic hydraulic principles, that is, the conservation of mass (Eq. 1) and the conservation of energy (Eq. 2). It is assumed that, all the physical system features such as pipe diameters, length, roughness, and individual vital component locations are known and the only variables to determine are the discharge in the pipe elements and pressure at all nodes in the network. During pipe network analysis, it is vital to start by identifying the most important features of the system and to ensure that they are sufficiently detailed and well defined. Schematization is the first step in the analysis of a large pipe system, because it helps to specify the most important aspects and components to consider during the analysis. During schematization (1) not all connections are represented as distinct nodes and junctions, but some can be combined – see Figure 6; (2) only the major and most vital parts of the distribution system are considered and presented; and (3) only major components with a significant impact on the system should be included. The hydraulic system at Vombverket was modeled using the software Pipe Flow Expert, and a detailed model as shown in Figures 12 and 13 was developed. Here, a brief summary is given of the capability of the model to simulate hydraulic systems together with the solution scheme employed.

4.2 Pipe Flow Expert model

4.2.1 Model structure

In the Pipe Flow Expert software, pipe hydraulic systems can vary from a single pipe, conveying water from one point to another, to large complex water distribution networks with hundreds or thousands of pipes. The network may include pipelines of varying sizes and material, reservoirs, looped-systems, valves, pumps, flow meters, heat exchangers, filtration devices, and many other components, as well as changes in elevation from point-to-point, that affect the flow in hydraulic systems.

The modeler can draw and make use of horizontal, vertical, or slanting lines representative of pipes that join different nodes in the system. The physical input data and boundary conditions to the model include but are not limited to:

1. The pipe internal diameters, roughness, and length
2. Inflow and outflow at each node
3. The individual node elevations
4. If reservoirs/tanks are present then, the liquid level, surface pressure, and elevation must be included.
5. Pump performance data

This input data can be modified at any stage in the design process. On completion of the hydraulic system layout and design, the flow rates and pressures are calculated and a system analysis may be performed, allowing for estimates of energy losses in the system.

4.2.2 Solution method

After the introduction of computers in the 1960s, the Hardy-Cross method had become the basis for most of the numerical solution techniques (Vennard & Street, 1982). However, this method had issues with convergence, especially for large systems consisting of many components such as pumps, pressure relief valves (PRV), and back pressure valves (BPV) as well as a large number of pipes in the network. Thus, alternative numerical techniques evolved, which led to Newton's method. This method has proved to be much more efficient and appropriate for solving nonlinear system of equations and it is nowadays typically used in computer software (Larock et al., 2000). The pipe friction loss is calculated using the Darcy-Weisbach equation (Eq. 3) with the friction factors determined from the Colebrook-White formula (Eq. 4).

The linear theory method is used to attain an initial approximate solution. Iterative approaches are then employed to adjust the flow rates until an approximate pressure balance is reached. This approximate solution is then converged to a more accurate solution through the use of more sophisticated matrices and iterative algorithms. Due to the complexity of pipe system designs, Pipe Flow Expert uses the Newton method to solve for the flow rates and pressures from the nonlinear system of equations produced (Pipe Flow Expert, 2016).

4.3 Model simulations

4.3.1 Model formulation

Modeling and simulation is a discipline of creating a certain degree of understanding of how different parts of the system interact to produce a certain result. A model is an illustrative simplification of an actual system with respect to time and space with an intention to provide understanding of the actual system. Simulation, however, refers to the computerized version of the model run over time and space to analyze the consequent interactions. These are iterative in nature. Therefore, a model is developed, simulated, analyzed, revised and continuously iterated until the desired understanding of the system is achieved.

The length, diameter, and roughness of the pipes based on available information were the initial input to the simulations. The node elevations giving the starting and ending elevations of the pipes were also specified in the model. Depending on the pipe properties and fitting/component characteristics, the friction coefficients were calculated. Reservoirs are nodes that represent an infinite external source or sink of water. The sand filters were modeled as bespoke components. For a bespoke component, the model gives an option to specify the energy losses. This can be as a fixed loss, curve loss, or through a coefficient. For this part of the system the curve loss option was used since it agrees best with the observations.

The sand filters in filter buildings 1 and 2 could not be modeled as open surface reservoirs, but bespoke components were used since the software describes a reservoir as an infinite source, which would create a break in the system. An infinite source implies that the inflow is not equal to the outflow and the software considers the open surface reservoir as a large lake. Therefore, a second-order curve loss was used that relates the head loss to a specific flow rate. The effect of a weir was modeled by including entrance and exit losses at the node representing the weir position, see Figure 13.

Three value points of head loss versus flow rate were obtained and fed to the model. A second-order polynomial was generated to describe this relationship, see Figure 9. The filters in the buildings were initially assumed to have the same properties; hence this curve loss was used in all the 26 filters (Ssenozi, 2016).

For filter building 3, the individual surface areas of the six sand filters are approximately twice that of those in building 1 and 2. Therefore, this was considered while generating the second-order polynomial for these filters. The maximum allowed flow from each of these filters is 129 l/s. All the elements contributing to the pressure drop in the system were represented (see Figure 6). The Venturi meters were also modeled as a component described by a curve loss, obtained using three points generated from the curve equation in Figure 8.

4.3.2 Sensitivity analysis

This process involved identification of those parameters in the system that the model was most sensitive to (Da Silva *et al.*, 2015). The degree of sensitivity, that is, the impact caused to the system when that specific parameter value varied, was determined. Evaluation was made from the way in which adjusting the parameter value(s) affected the model output, in order to identify parameters that might be readily modified to improve the performance and characteristics of the model. The objective factors included flow rate and head losses, which in this case are the quantities that were used to select better over poorer solutions.

The parameters that were evaluated included node elevation, water level, frictional value of elements, characteristics of bespoke components (curve loss), pipe inner diameter, pipe length, and pipe roughness. The variables whose sensitivity are being determined are the dependent variables, for example, pressure and flow rate. The variables whose change or adjustment will improve the performance and characteristics of the model are the independent variables.

Some of these parameters have fixed values for this project and their adjustment are not required, for example the pipe diameter and length. The bespoke components' characteristics (curve losses) implied the highest degree of sensitivity and were given more attention during the calibration. The friction coefficients for the fittings in the system appeared to be a sensitive parameter for the model results, but the challenge was that, most of the fittings are standard fittings obtained from the model database (manufacturer catalogues) and there is no option to change their values. The friction coefficients of the bespoke fitting were calculated using pipe diameter and lengths, which are fixed as per the plant specifications; hence, these could not be altered (Ssenozi, 2016).

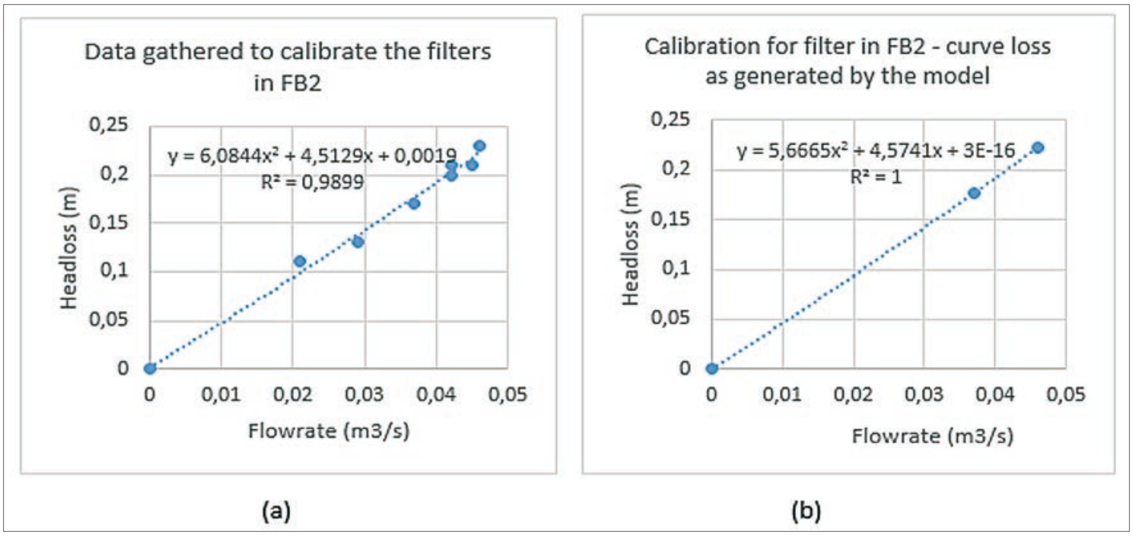

Figure 11. *(a) Raw data used for sand filters in FB2 and (b) model input dataset from the curve equation in (a) for the sand filters in FB2 for calibration.*

Table 5. *Comparison between calibrated model flow rates and measured flow rates in FB2.*

Filter (FB1)	Measured (l/s)	**Calc. (l/s)**	Filter (FB2)	Measured (l/s)	**Calc. (l/s)**	Filter (FB3)	Measured (l/s)	**Calc. (l/s)**
F1	54	**42.0**	F11	52	**48.3**	F21	130	**129**
F2	41	**40.6**	F12	49	**46.7**	F22	128	**129**
F3	44	**39.8**	F13	47	**46.3**	F23	129	**129**
F4	37	**40.5**	F14	40	**46.5**	F24	129	**129**
F5	36	**41.7**	F15	40	**47.7**	F25	129	**129**
F6	36	**42.2**	F16	43	**46.7**	F26	130	**129**
F7	38	**41.0**	F17	47	**45.5**			
F8	40	**40.3**	F18	48	**45.2**			
F9	39	**41.2**	F19	48	**45.7**			
F10	49	**42.5**	F20	55	**47.2**			
TOTAL	414	**411.9**		469	**466**		775	**774**

Note that in this study, the parameters to which the model was considered to be significantly sensitive were those giving an average percentage variation greater than 5% with respect to flow rate.

4.3.3 Calibration

The curve equation in Figure 11a, was used to generate the three points to be fed to the model as shown in Figure 11b.

This data set in Figure 11b led to good agreement between the model results and the measurements. In order to obtain the highest level of accuracy, the average percentage of variation for the measured and modeled flow rate and pressure were set independently. For pressure, a stricter criterion (Table 6) was used. Some of the measured values, especially in F1, F10, F11 and F20, are a bit higher than the calculated ones. This is proof that the degree of clogging varies from filter to filter, and it is not constant, as was assumed in the modeling process. The other factor could be the pressure drop at the 1200mm tee junction.

As observed in Table 5, the total calculated and measured flow rates are in strong agreement, but some of the individual flow rates from specific filters show differ-

Table 6. *Comparison between calculated and measured pressure for data employed in model verification.*

Filter	Time	Measured Results (m)	Model Results (m)	Variation %	Remarks
F12	8:38 am	4.194	4.198	0.095	A
F13	8:50 am	4.214	4.224	0.237	A
F14	8:59 am	4.204	4.186	0.428	A
F15	9:06 am	4.214	4.208	0.142	A
F17	9:24 am	4.374	4.222	3.475	D
F18	9:35 am	4.344	4.226	2.716	C
F19	9:45 am	4.264	4.207	1.337	B
F20	9:57 am	4.274	4.164	2.574	C
F11	10:35 am	4.214	4.088	2.990	C
F16	10:44 am	4.434	4.189	5.525	D
Venturi	9:55 am	3.780	4.061	7.434	D

A – variation < 1% = strong agreement, B – variation between 1–2% = Agreement, C – variation between 2–3% = Fair Agreement, D – variation >3% = Disagreement

Filter No.	Time	Measured Results	Model Results	Variation %	Remarks
F26	13:50 pm	5.70	5.707	0.123	A
Big-Tee junction	14:06 pm	5.65	5.598	0.920	A
F21	14:18 pm	5.35	5.655	5.7	D
Main flow meter	14:49 pm	5.76	6.928	20.3	D

ences. The deviation in percentage between measured and calculated flows was determined. Anything below 15% are judged to be in strong agreement, above 30% in disagreement, and intermediate values in fair agreement. All the results are in strong agreement, besides the result in F1 that gives a value of 28%. This is near disagreement and it could be a result of several factors during measurement such as human error, filter backwashing, pressure drop at the 1200mm tee junction, and filter clogging.

4.3.4 Verification

The 15 data sets summed up in table 6 from Tables 2 and 3, obtained on April 13, 2016 between 8:00 and 15:00, were used to verify the model. This involved running the model for each data set for the specific time. Table 6 illustrates the agreement between the calculated and measured pressures in the plant.

4.4 Measures to reduce energy losses

The measures investigated to reduce energy losses in the hydraulic system involved (1) removing hydraulic components responsible for the main losses and replacing them with more advanced components having low loss characteristics; and (2) changing the hydraulic system layout. The latter measure would involve changes in the flow path length, hence reduction in the energy losses (Ssenozi, 2016). Figure 12 displays some of the individual components facing removal in the modification process and the color pattern illustrates the water flow velocity for the hydraulic system in filter building 3, as described in section 7.1.

Filter block 1 and 2 have similar layout with only small differences in components and their properties. Figure 13 shows a detailed layout of the hydraulic system in FB1.

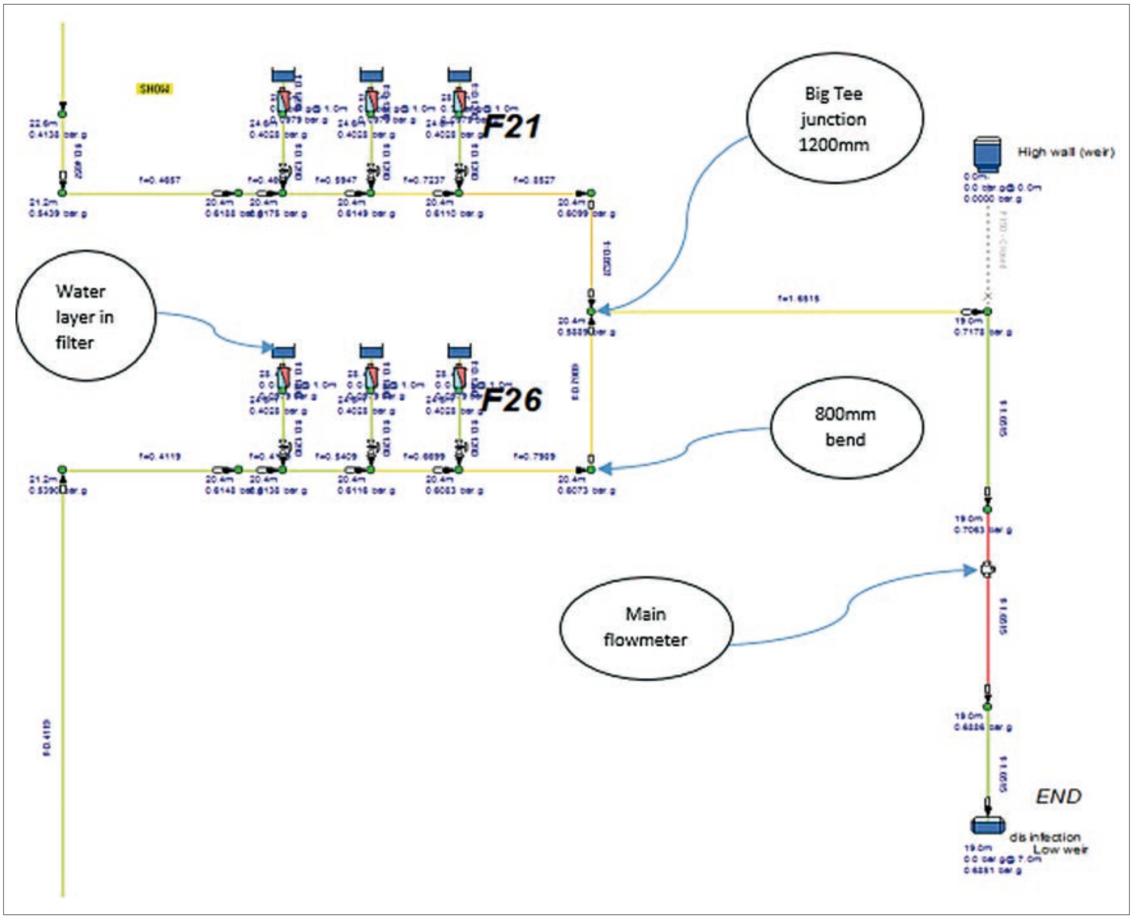

Figure 12. *Detailed model layout of the filters and components in filter block 3.*

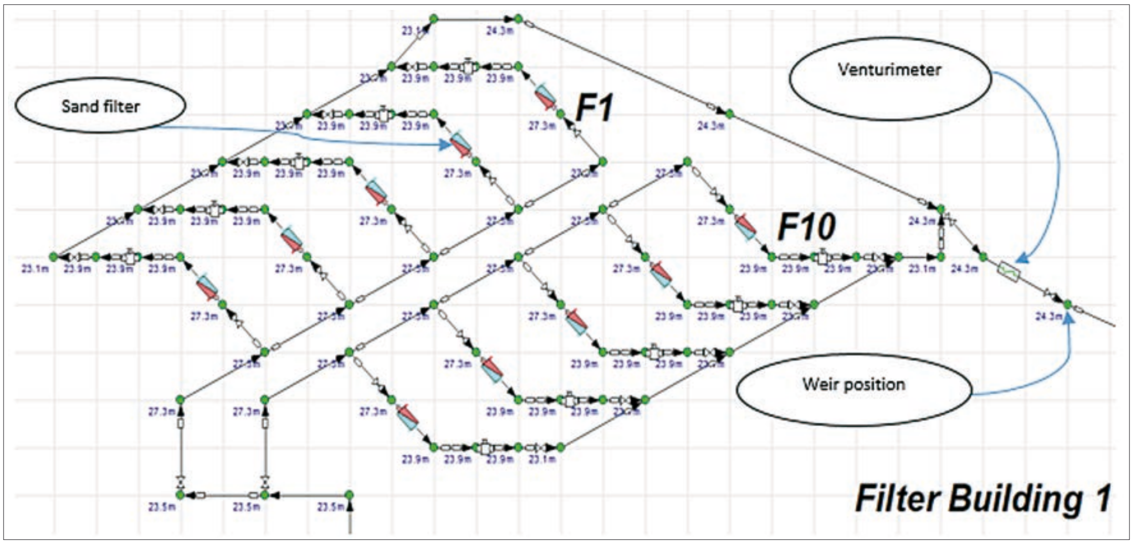

Figure 13. *Detail of hydraulic system in FB1 with general layout and components.*

4.4.1 Removal of hydraulic components

The identification of the major components that significantly contribute to the system pressure losses was the first task. In general, higher water velocities imply higher energy losses. Colors are used in Figure 14 to represent different velocities in the system, where a velocity above 2.1 m/s is shown with red, 1.7–2.1 m/s with orange, 1.2–1.7 m/s with yellow, 0.7–1.2 m/s with light green and <0.7 with green. It is noted that in all parts of the system where the velocity is above 1.2 m/s, the energy loss may be sufficiently high to warrant a check if a specific component contributes significantly to the total losses (Pipe Flow Expert, 2016).

The components investigated in this study included:

1. The Venturi meters in both filter FB1 (Figure 13) and FB2.
2. The gate valve placed before the Venturi meter in FB1 (Figure 13).
3. The double bends in filter block 1 that lead to a change in elevation from 23.15 m to 24.327 m (Figure 13).
4. The hydraulic structures/weirs at the end of filter buildings 1 and 2. At present, these are not working as intended and have become obsolete. They are completely submerged, acting as inline tanks in the system; thus, marked losses are introduced in the system, for example, exit and entrance losses (Figure 13).
5. The mixing chamber placed where water joins the pipe system. There is suction of air into the system and the air has nowhere to escape but takes the same pathway as the water to the sand filters. This generates a lot of resistance in the system due to the air locks and air pockets created in the pipeline (see Figure 6).
6. The 1200 mm, 90-degree convergent tee-junction in filter building 3. This is a point where water from filter block 1 and 2 meet, converging through the tee and leaving through the branch, causing energy loss (Figure 12).
7. The two 800 mm, 90-degree bends in block 3 leading the water to the 90-degree tee-junction (see Figure 12).
8. The constriction from 1600 mm to 900 mm at the main flow meter towards the disinfection basin in block 3. This is where the highest pressure drop occurs in the system (Figure 12).

Table 7. *Investigation of the impact of each action made to the system in terms of flow increment and pressure.*

Components to be removed	Flow from FB1 (l/s)	Flow from FB2 (l/s)	Pressure before the disinfection basin	Total discharge (l/s)	Flow increment (l/s)
Both Venturi meters	457.7	539.4	0.6891	1771.1	120.0
Valve before Venturi-meter in FB1	412	466	0.6886	1651.6	0.1
Venturi and valve in FB1	459.5	539.2	0.6891	1772.7	121.2
Venturi, valve and weir	474.4	556.8	0.6893	1805.2	153.7

Table 8. *Simulation results for modification of the hydraulic system in Vombverket.*

Action	Discharge FB1 (l/s)	Discharge FB2 (l/s)	Flow increment (l/s)
Direct connection of FB 1 and 2 to the reservoir with Venturi meter and gate valve removed	837.6	843	803.1

It was not possible to model some of these components, for example the turbulence and the air pockets in the pipeline next to the mixing chamber.

4.4.2 Simulation of system layout modifications

The most plausible modification to be made to the hydraulic system involves the shortening of the flow path, which would take the system back to the original built design. The elongated flow path that exposes the water to an array of accumulated resistances would be bypassed, boosting the system capacity. The two 800-mm bends, the constriction from 1600 mm to 900 mm at the main flow meter, and the 1200 mm tee-junction in filter building 3, could be bypassed (Ssenozi, 2016). Also, there is a plan to install a device for treatment with ultra-violet light after the main reservoir, which would function well with this modification. Simulation results when FB1 and FB2 are connected directly to the reservoir with the Venturi-meters and the gate valve before the Venturi meter in FB1 removed are shown in Table 8.

Another aspect of the hydraulic system that was investigated was the pressure at the exit nodes of FB1 and FB2 when connected directly to the reservoir with respect to specified discharge demands.

5 Conclusions

The expansion of the hydraulic system at Vombverket in the 1990's led to a reduction in the plant performance in terms of capacity and pressure. A thorough investigation of the possible sources, locations, and properties of the energy losses was performed in this study. Based on this investigation, the model Pipe Flow Expert was implemented followed by calibration and verification. The model revealed the parts of the system where high velocities occurred together with significant energy losses.

A sensitivity analysis was carried out to facilitate the calibration process, where the most prominent parameters to which the model is sensitive were identified. A clear picture of which parameters/variables were affecting and not affecting model simulations was obtained, making it possible to know which variables to adjust.

Calibration helped to improve the performance and general behavior of the model, especially the part in filter block 2 that initially was in disagreement with observations. Subsequently, a good fit was obtained between calculations and measurements, resulting in satisfactory predictions of node pressures and discharges in all sections of the system. Additional data sets were used to determine how reliable the model calibration was through independent verification simulations for the system; these simulations also produced a good match between the observed and modeled results.

Simulation for different scenarios of possible measures, which would improve the system performance in terms of reducing energy losses and increase flows were evaluated and determined on an individual and combined basis.

This study resulted in recommendations categorized as one and two, leaving the final decision to the stakeholders to choose the most appropriate and suitable solution depending on the allowable budgeting and regional future anticipated expansion plans.

For an optimized result, category one (described in Table 7) which involves removing the weirs in both FB1 and FB2, Venturimeters and one of the gate valves in

Table 9. *Simulation results for pressure at exit points in FB1 and FB2 for specific flow rates.*

Flow (l/s)	With all components		Without Venturi &valve		No Venturi, valve &weir	
	FB1(bar.g)	FB2 (bar.g)	FB1 (bar.g)	FB2 (bar.g)	FB1 (bar.g)	FB2 (bar.g)
400	0.3990	0.4690	0.4359	0.5049	0.3023	0.4425
500	0.3291	0.4129	0.3854	0.4677	0.2552	0.4060
600	0.2492	0.3488	0.3260	0.4234	0.1999	0.3624

The unit bar. g, is the relative pressure.

FB1, should be adapted. This implies a significant increase in the flow rate to the design value of 500 l/s from each house. Table 9 also shows the impact of this action on the exit pressure for specific set flows from filter blocks 1 and 2.

For a maximized result, with flow control valves installed to ensure that the maximum allowable flow rate of 500–600 l/s from each filter building is not exceeded for quality purposes, category two would be appropriate, described in Table 8. This will give the plant an overall new layout.

Optimization in this respect means that the system is modified to an extent so that sufficient discharge is attained with consideration to the costs incurred, where as maximization is when all that matters is the discharge independently of the cost (Ssenozi, 2016).

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References

Cengel, Y.A., and Cimbala, J.M. (2006a) Fluid Mechanics: Fundamentals and Applications Chapter 8: Flow in pipes. ISBN: 0-07-247236-7. Published by: McGraw-Hill. Available at: https://www.uio.no/studier/emner/matnat/math/MEK4450/h11/undervisningsmateriale/modul-5/Pipeflow_intro.pdf. Retrieved on: 1/2/2016

Cengel, Y.A., and Cimbala, J.M. (2006b) Fluid Mechanics: Fundamentals and Applications Chapter 5. ISBN: 0-07-247236-7. Published by: McGraw-Hill. Available at: https://www.uio.no/studier/emner/matnat/math/MEK4450/h11/undervisningsmateriale/modul-5/Pipeflow_intro.pdf. Retrieved on: 1/2/2016.

Crane Co, (1988) Flow of fluids through valves, fittings and pipe. Crane Engineering Department. Technical Paper No. 410. Available online at: http://uolab.groups.et.byu.net/files/pipefitt/hints/1988Crane.pdf Accessed on: 4/11/2016

Da Silva, M.G., de Oliveira de Aguiar Netto, A., de Jesus Neves, R.J., do Vasco, A.N., Almeida, C. and Faccioli, G.G. (2015) Sensitivity Analysis and Calibration of Hydrological Modeling of the Watershed Northeast Brazil. Journal of Environmental Protection, 6, 837–850. http://dx.doi.org/10.4236/jep.2015.68076

Keulegan, G.B and Beij, K.H. (1937) Pressure losses for fluid flow in curved pipes. Research paper RP965 (volume 18) U.S Department of Commerce and National Bureau of Standards. Available at: http://nvlpubs.nist.gov/nistpubs/jres/18/jresv18n1p89_A1b.pdf, retrieved on 1/4/2016.

Larock, B.E., Jeppson, R.W., and Watters, G.Z. (2000) Hydraulics of Pipeline Systems. CRC Press, ISBN: 0-8493-1806-8.

Pipe Flow Expert (2016) User Guide. Available in: Pipe Flow Expert v7.30 Model Software "Documentation".

Sleigh, A. and Goodwill, I. (2009) CIVE2400- Fluid Mechanics: Fluid flow in pipes. University of Leeds. Available at: https://sipil2010.files.wordpress.com/2011/08/pipe-flow-5.pdf. Retrieved on: 4/4/2016

Ssenozi, I, (2016) Energy losses in hydraulic systems of water treatment plants: An application to Vombverket in south Sweden. ISSN: 1101-9824. Available at: http://lup.lub.lu.se/student-papers/record/8889353

Vennard, J.K. and Street, R.L. (1982) Elementary Fluid Mechanics (Sixth Edition), John Wiley, ISBN 047104427X.