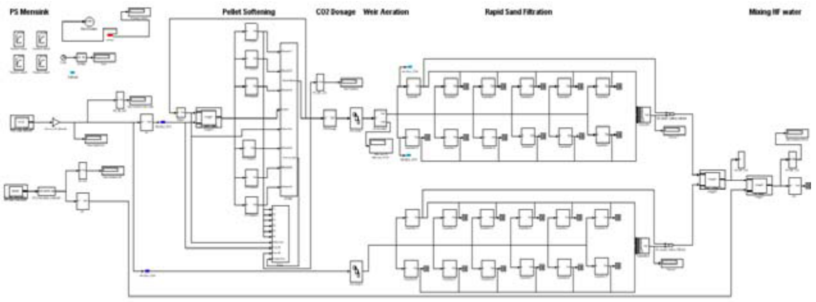
Model Validation and New Water Control Strategies in Drinking Water Treatment Plant Wim Mensink

November 2009

Xiaoyu Yuan



PWN. Puur water en natuur.

Consultancy and Engineering

Gateway to solutions

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Sanitary Engineering Section
Faculty of Civil Engineering and Geosciences

TU Delft

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Master of Science Thesis in Civil Engineering

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Acknowledgements

This final Master thesis you are reading now is the research work performed on Wim Mensink in Heemskerk over the last ten months for the finalization of my master study here in Civil Engineering at Delft University of Technology. This research is conducted by using the Stimela model made for drinking water treatment plant Wim Mensink to validate the model results with the measured results and develop the possible better water control strategies for the current operation. Three companies and institutes are involved into this research, which are drinking water treatment plant PWN, engineering consultancy company DHV and Delft University of Technology. I experienced enthusiasms for my research work and it was my honour to take part in such an integrated project for my final master study here. I am here thankful to everyone who had contributed anything to my thesis work, especially for my daily supervisor Ignaz Worm, a kindly, patient and knowledgeable gentleman who really gives quite a lot of useful and helpful suggestions in my master thesis work. Besides this, I would like to thank my professor Luuk Rietveld and Hans van Dijk. Thanks for all of the necessary tips and sincerely counsels from you. These unconditional supports and trusts in everything were valuable to me during the last ten months' work.
Finally but not the least, I need to say one sincerely word to my parents: "Thank you for your 25 years' arduous work for your son, I have no way to reward this but with brilliant work all my life."

To conclude, I would like to share a short but challenge story of mine with all of you. I am a 'cultural' boy since I was a child because I chose to study piano when I was six years old. I am not good at any sports item because I deeply fell in love with playing piano and music and dreamed to become a pianist at that time. After six months' thesis work, I started to choose long-distance running as my first attempt in my sports area. I insisted on running three times one week and so far I could even run 24 kilo meters outdoor, which was a miracle happening on me and I cannot even imagine that before I did.

Nothing is impossible, challenge all your life and believe yourself!

Xiaoyu Yuan
Delft, November 2009

Abstract

Stimela is an environment for standardized mathematical models of drinking water treatment processes. It can be used to predict the future water treatment situation which may happen or change. In water treatment plant Wim Mensink, the Stimela model train was set up to compare with other alternative water control strategies. Before starting the work of developing new water control strategies with Stimela model, Stimela model for Wim Mensink must be validated so that the model can be seen as a reliable and stable tool for the next work.

Before the validation work, the current water control strategy for the treatment process needs to be investigated clearly to fulfil all the input control information is correct. Besides this, an experiment for obtaining the measured results of pellet diameters over different layers was performed in Wim Mensink. The validation work starts with single pellet softening process for three different reactors over first month from January 20th to February 20th. The fluidized bed height, pressure drop over total height of reactor, pellet diameters and porosities are validated. After that, the validation work is integrated with whole water treatment system to prove the function of pellet softening reactor and the four important water quality parameters over two important locations (after weir aerator location and final RO mixing location). The validated results of softening process are analysed by the relative error way to prove the reliability of the model results compared with measured results.

The final step of the thesis work is developing the new water control strategies to optimize the current control plans of Wim Mensink. Five different water control strategies are put forward. They can be either reached separately according to their own advantages and limitations or fulfil with a step by step order as a whole optimization process. Moreover, the other water control strategies developed by engineering consultancy company DHV are evaluated here with Stimela model so that they can be proved reliable and achievable.

In the future, the application of Stimela model will be spread over all the drinking water treatment plants in the Netherlands and contributes to the central automated control as a drinking water treatment operator training simulator.

Nomenclature

Symbols

t	Temperature	ºC
k_T	Reaction constant	-
S	Specific area of seed crystals	m^2
H_{max}	Maximum hydraulic loss	m
E	Expansion of bed	-
g	Gravity acceleration	m/s^2
p_0	Fixed bed porosity	-
p_e	Fluidized bed porosity	-
v	Velocity	m/s
d	Pellet diameter	m
L_0	Fixed bed height	m
L_e	Expanded bed height	m
Δx_i	Height in model layer i	m
$m_{g,i}$	Mass of grain in layer i	kg
$m_{c,i}$	Mass of calcium carbonate in layer i	kg
p_i	Porosity in layer i	-
A	Surface area of reactor	m^2
ΔP_i	Pressure drop over layer i	Pa
$d_{p,j}$	Pellet diameter in i layer	m
d_0	Initial grain diameter	m
v	Superficial velocity	m/s
v_0	Terminal settling velocity	m/s
n	Experience exponent	-
C_{w2}	Drag coefficient Richardson-Zaki	-
R_{e0}	Terminal settling Reynolds number	-
c_w	Equilibrium concentration of gas in water	g/m^3
k_H	Henry's constant	-
c_g	Concentration of gas in air	g/m^3
P	Partial pressure of gas in gas phase	Pa
V	Total gas volume	m^3
R	Universal gas constant	J/K/mol
MW	Molecular weight of gas	g/mo
W	Total weight of the sand sample	g
W_i	Weight on sieve i	g
S_i	Mesh of sieve i	mm
d_s	Specific diameter	mm
VT	Volume in each layer	m^3
T_{mass}	Total mass of grains in each layer	kg
M_{NaOH}	Molecular weight of NaOH	g/mol

Greek symbols

ν	Kinematic viscosity	m^2/s
ρ_p	Pellet density	kg/m^3
ρ_W	Water density	kg/m^3
ρ_g	Density of grain	kg/m^3
ρ_c	Density of calcium carbonate	kg/m^3
$\rho_{p,i}$	Density of pellet in layer i	kg/m^3
β_1	Constant 1	-

β_2	Constant 2	-
φ_i	Shape factor for fraction between sieve i and sieve i+1	-

Abbreviations

$Flow_{FB1}$	Total flow in filter building 1 m^3/h	m^3/h
$Flow_{FB2}$	Total flow in filter building 2	m^3/h
$Flow_{RO}$	Total RO flow	m^3/h
TH_{out}	Total hardness in filter building 1	mmol/l
TH_{in}	Total hardness in raw water	mmol/l
TH_{RO}	Total hardness in RO permeate	mmol/l
TH_{final}	Total hardness in final clean water reservoir	mmol/l
D_{NaOH}	Set point of NaOH dosing per pellet reactor	l/h
$N_{reactor}$	Number of reactors in operation	-
D_{corr}	Corrected NaOH dosing	l/h
$TH_{cascade}$	Total hardness before cascade	mmol/l
D_{CO2}	Amount of CO_2 dosage	Nm^3/h
M_{NaOH}	Molecular weight of NaOH	g/mol
Ca_{in}	Calcium ion concentration in raw water	mmol/l
Ca_{out}	Calcium ion concentration after pellet reactor	mmol/l

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1. Introduction

1.1 Water supply company PWN

1.1.1 Overview of the water treatment process

The source for drinking water treatment for North Holland is the IJssellake. The water coming from the IJssellake is extracted in two places. In Andijk, water is treated directly to drinking water and another part of the water is pretreated at Waterwinstation Prinses Juliana (WPJ) and then transported to Heemskerk for membrane filtration or UV/H_2O_2 treatment. After UV/H_2O_2 treatment, the water is infiltrated into the dune area and then post treated at Wim Mensink and Bergen. The drinking water treatment plants Wim Mensink, Heemskerk and Bergen form an integrated drinking water treatment system.
The water treated at Wim Mensink and Bergen will be mixed with the part of water treated with membrane filtration from Heemskerk. Figure 1 shows the relations between the different water plants.

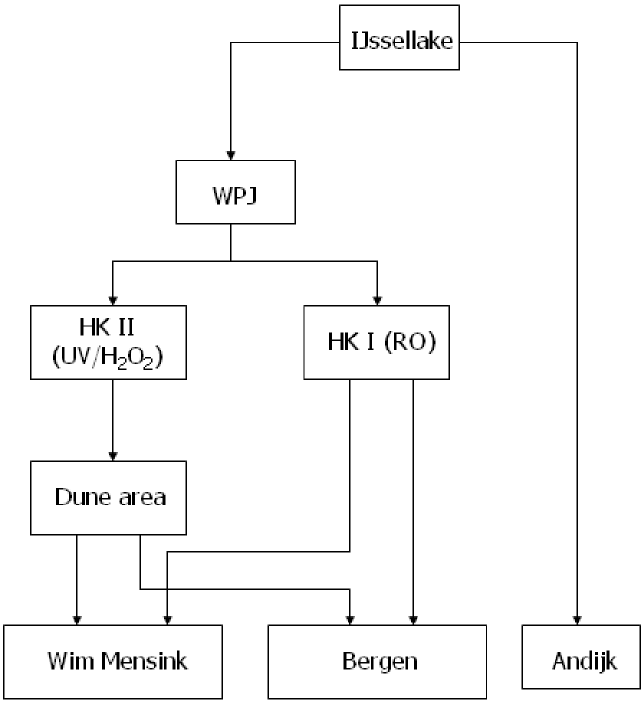


Figure 1: Water treatment scheme of PWN

In the dune area, PWN has permits for the following extractions:
- 16 Mm³/year at IKIEF (surface water infiltration and extraction)
- 25 Mm³/year at ICAS (surface water infiltration and extraction)
- 4.5 Mm³/year at DWAT (deep infiltration and extraction)
- 6 Mm³/year at several places (direct dune water extraction).

However, PWN has set a target to limit the direct dune water extraction to 2 Mm³/year in the nineties to prevent nature damage as a consequence of drought, so the total annual extraction of dune water is 47.5 Mm^3/year.

1.1.2 Heemskerk

In Heemskerk, there are two kinds of water treatment; one is the treatment with UV/H_2O_2, after which the water flows into the dune area, the other is ultrafiltration followed by reverse osmosis. That is mixed with the effluent water from the conventional treatment in Wim Mensink and Bergen. In this research, the UV/H_2O_2 is out of scope so this part of water treatment process will not be discussed. In the RO plant, there are two operation modes. One is winter operation and the other is summer operation. The RO plant produces a fixed flow of 2,040 m^3/h during the eight warmer months and 1,760 m^3/h in winter times. Within one operation mode, the conditions such as flow, pressure are fixed to reach maximum robustness. Figure 2 shows the water process flow in Heemskerk I.

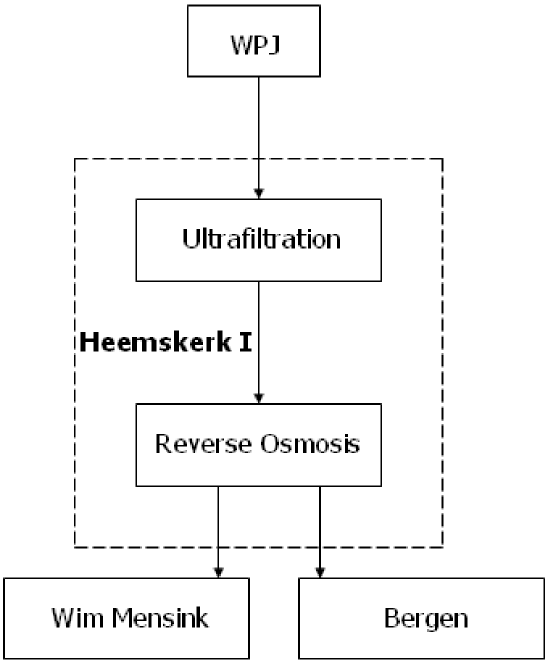


Figure 2: Process scheme of Heemskerk I

1.1.3 Wim Mensink

The water treated at Wim Mensink has a production capacity of 5,850 m^3/h [Martin Klein Arfman, Henk van Duist, 2008] including RO permeate. The extracted dune water is distributed between filter building 1 and filter building 2. The water in filter building 1 is softened with fluidized pellet reactors with bypass and recirculation flow and then flows into cascade and rapid sand filtration units. In the first cascade of the aeration process, CO_2 is dosed to the water to lower the pH and over-saturation. The water in filter building 2 only passes cascade aeration and rapid sand filtration. Both parts of the water are mixed with RO permeate of Heemskerk I using a static mixer. ClO_2 is dosed for safety post disinfection in the mixer and finally the water is stored in reservoirs. After storage water is sent directly to the distribution system. Figure 3 shows the process scheme of the water treatment at Wim Mensink.

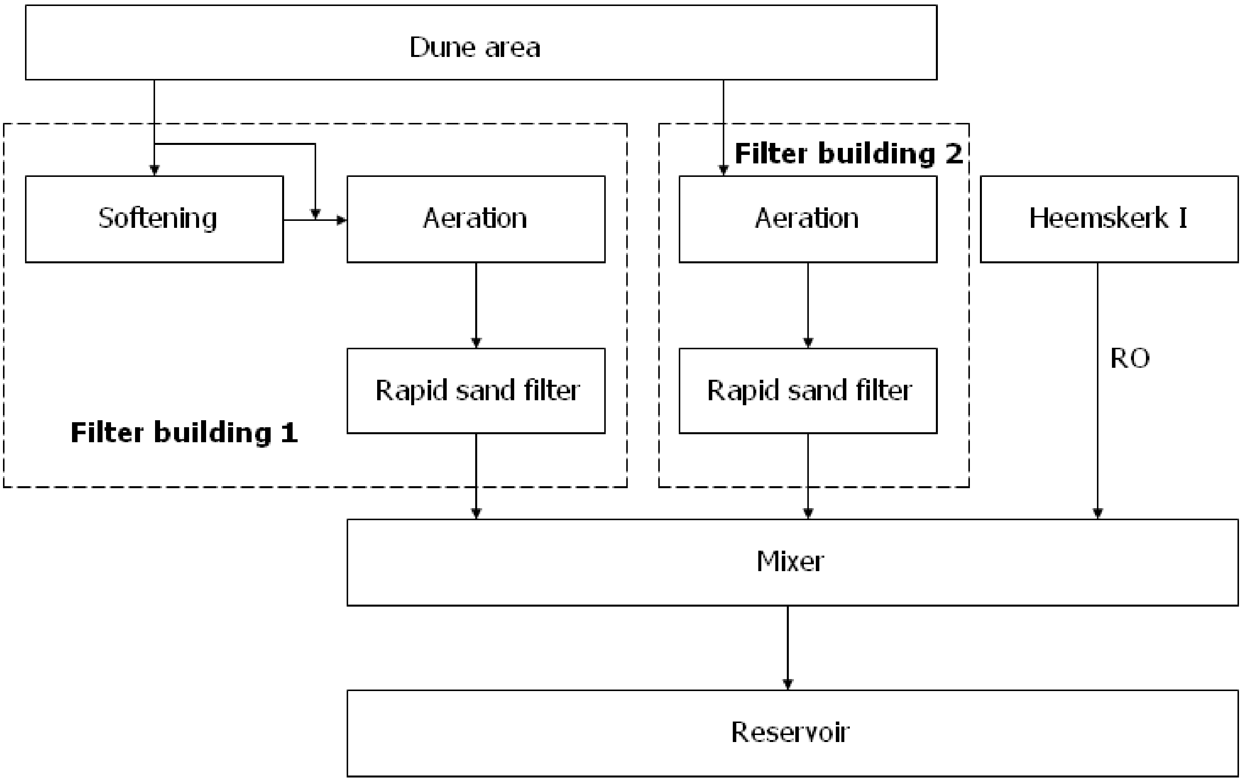


Figure 3: Water process flow in Wim Mensink

The flow ratio between filter building 1 and filter building 2 is 2:1, which means 2/3 of the water flow comes into filter building 1 while 1/3 goes through filter building 2.

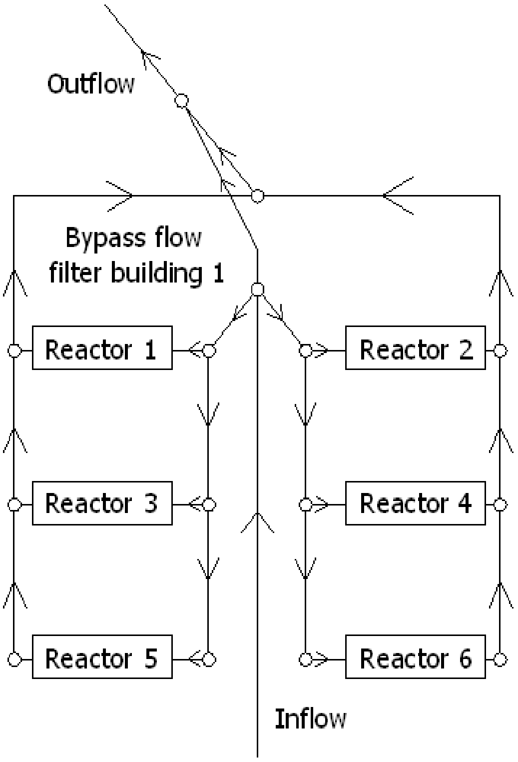
1.1.4 Softening process

There are six softening reactors in Wim Mensink with three reactors in each row at design production capacity for each 500 m^3/h (see Figure 4). In the drinking water production, the desired total hardness in the effluent determines the maximal water production capacity. The hardness of the raw water and the effluent water can be obtained from the online measured results (see Figure 7). The hardness of raw water is 2.42 mmol/l on average and 2.77 mmol/l for the maximal value. In the normal situation, an incoming hardness of 2.60 mmol/l is used as the hardness for raw water. With this value of hardness, five of the six reactors are in operation with a flow of 490 m^3/h to reach a softening depth of 1.3 mmol/l and mix with the average RO permeate 450 m^3/h from Heemskerk I. In this case, the total water capacity for Wim Mensink can reach 4,600 m^3/h with a final hardness 1.5 mmol/l.

There are many details about the chemical dosage, dimensions, process and installation of the reactors. This part of the information is presented in Appendix I of this thesis.

Figure 4: View of the softening reactors in Wim Mensink

There is one bypass pipe connecting between the inlet and outlet of the softening reactors. If less water is treated in the pellet softening reactors than supplied to filter building 1, the rest of the water directly flows to through this bypass pipe. If more water is treated than supplied, water is extracted from the cascade through the same pipe and this flow is called "recirculation flow". Figure 5 and Figure 6 show the softening process with bypass flow and recirculation flow, respectively.



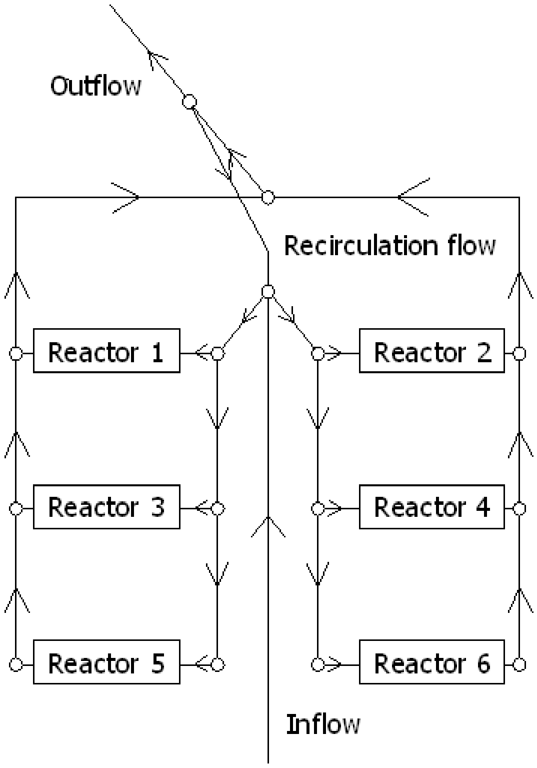


Figure 5: Diagram of softening process for bypass flow filter building 1

Figure 6: Diagram of softening process for recirculation flow

During operation of the softening reactors, reactors are switched on or off depending on the flow supplied to filter building 1 according to the following limits:
Reactors switched on with the following amounts: 450; 666; 1,700; 2,000; 2,666 and 3,100 m^3/h
Reactors switched off with the following amounts: 2,500; 2,300; 1,750; 1,100; 500 and 400 m^3/h

When the flow rate reaches up to the 450 m^3/h, the first reactor switches on. At a lower flow rate, the water will directly flow into the aeration process and is not treated with the softening reactors. With the increase of water flow, the second reactor starts when the flow reaches up to 666 m^3/h. Just before the second reactor switches on, the water flow goes through the bypass flow with a flow rate 666 m^3/h – 500 m^3/h = 166 m^3/h. When the flow rate decreases to 2,500 m^3/h, the recirculation flow is $500 \times 6 - 2{,}500$ m^3/h = 500 m^3/h.
The grain dosing and pellet discharging processes never happen simultaneously because of the fact that they use the same process water system. Pellets discharge always takes the priority over the grain dosing. If 270 kg Ca is removed from a softening reactor, 47 kg river sand will be dosed into the reactor. For the pellet discharging control, reactors will be put in a queue for discharging the pellets when pressure drop over the total height of the reactor exceeds 18 kPa. Every 30 minutes the reactors will be checked to discharge by the order in the queue. The amount of discharged pellets is 50 kg for each reactor. If the pressure over the total height of the reactor is still higher than 18 kPa, then it has to wait for a discharge in next time. The three pellet discharge points at the bottom of the reactors will be opened one by one until the next reactor starts. Figure 8 shows the picture of the pellet discharge points.

Figure 7: Hardness measuring device

Figure 8: Three pellet discharge points at the bottom of reactor

In a normal operational condition, the fixed bed height is 2.0 m and the fluidized height is 3.5 m. After dosing the grain seeds, the pellet distribution for d_{10} is approximately around the diameter of 1.0 mm and the pellet distribution for d_{50} is around 1.3 mm. The uniformity coefficient d_{60}/d_{10} is about 1.2–1.6. The caustic soda is dosed by a dosage pump for every reactor with a minimum of 50 g NaOH/m^3 water flow, in which the concentration of NaOH solution is 25%.

1.1.5 Key performance indicators

The water quality parameters and other performance indicators that are considered to monitor the process performance are given in Table 1:

Table 1: Targeted key performance indicators

Key performance indicators	**Targets**
Total hardness	1.3 mmol/l – 1.7 mmol/l
pH	7.5 – 8.5
RO discharge per year	Minimal
Caustic soda usage per year	Minimal
Carbon dioxide usage per year	Minimal
River sand usage per year	Minimal
Number of switching on and off reactors	Minimal

The operation of Wim Mensink should always obey the performance indicators.

1.2 Problem analysis

Currently, the operation of Wim Mensink is not optimal. Due to the fixed control rules, RO permeate flows back to the dune area and the softening process is not working optimally. There will be 5% water loss of the RO
permeate water to the dune area aquifer. This 5% of discharged RO water needs to be retrieved as much as possible. Therefore, it is decided to implement a simulator (Waterspot) to improve knowledge about the process. The simulator will be used for training operators, for offline and online process optimization and education. As part of the simulator, Stimela models will be used to predict the specific operating situation for the drinking water treatment plant. Besides that, improving the current conditions with better operating tasks or strategies can also be achieved by Stimela modelling.
The drinking water treatment plant Wim Mensink located in North Holland has been simulated with Stimela model. However, the model has not been successfully validated with the historical data and the current water control strategies still need to be developed with the real operating situation so that the model can be used for Wim Mensink as a predictive tool and integrated to central simulator (Waterspot).

1.3 Research objective

The main objective of this research is divided into two parts. The first objective of this research is to setup and validate a water quality model of the drinking water treatment Wim Mensink. The scope of the models is limited to parameters related to the softening process, pH, bicarbonate concentration, flow, bed height, pellet size distribution, dosage of caustic soda, dosage of carbon dioxide and the derived parameters total hardness.

The second objective is to use the model to compare alternative water control strategies for Wim Mensink. The optimal control strategy is defined using the key performance indicators. After mixing with the RO water, total hardness and pH should be within the operational window, while minimizing the RO discharge, the use of caustic soda, sand and carbon dioxide and minimizing the switching frequency of the reactors.

1.4 Research approach

This research started with a literature study of the softening process, Stimela modelling, similar previous work executed in water treatment plant Weesperkaspel, the general understanding of the relevant water treatment plants at PWN and then focusing on the water treatment plant Wim Mensink. To validate the Stimela model, model results were compared with online measurements and laboratory measurements. Graphs were drawn to prove the performance of the model and the limitations of the model were stated before developing the new control strategies. Additional experiment was carried out for measuring different pellets over different layers in the softening reactors to analyse the size distribution of the discharged pellets. On the basis of the operating principles of the pellet softening reactors, necessary water quality to be assured in clean water reservoir and the specific situation in Wim Mensink, the new control strategies for different scenarios were identified and then they were imported to the model for evaluating the results.
The necessary steps for this research are summarized as follows:

1. Literature study and analysis of the Wim Mensink softening process, RO process in Heemskerk.
2. Stimela model analysis for Wim Mensink.
3. Experiment set-up and sieve analysis for pellet distribution over different layers.
4. Model validation based on online measurements and laboratory measurements in Plenty report and actual control strategy in Wim Mensink.
5. Development of new alternative control strategies based on the problem and the optimization plan for Wim Mensink.
6. Evaluation of other alternative control strategies in using the Stimela model.

1.5 Outline of thesis

Within this thesis, Chapter 1 is the overview of the project in which the main purpose is to describe the basic information of PWN, analyze the problem and illustrate the research objective and approach clearly. In the next chapter, the necessary theory basics relating to this thesis work and previous research are presented. Chapter 3 describes the model and shows reader all the relevant information to be used in this thesis work about the model. Chapter 4 illustrates the necessary data acquisition work and the additional pellet size distribution experiment for the model validation work. The model validation work starts at Chapter 5 to validate the effectiveness and availability of the Stimela model. Chapter 6 presents the possible water control strategies and relevant model validated work for other new water control strategies. Finally, the conclusions of this thesis will be drawn and the recommendations for the future work are stated.

2. Theory and literature research

In this chapter, theories of softening, Richardson-Zaki theories, and aeration principles are presented. The softening principles include basic chemical equilibrium equations, the SI principle, the chemical reactions to reduce the hardness by dosing chemicals, crystallization kinetics and the basic hydraulic properties for a fluidized bed. The softening model was calibrated using the Richardson-Zaki method. The aeration principle describes the basic gas-liquid reaction in the cascade process. The relevant previous work about the optimization of the softening process using Stimela models is presented as well.

2.1 Softening principles

2.1.1 Chemical equilibrium in pellet softening reactors

In water, the calcium carbonate is a compound that is difficult to dissolve in water [P.J.de Moel, J.Q.J.C. Verberk, J.C.van Dijk, 2006]:

$Ca^{2+} + CO_3^{2-} \Leftrightarrow CaCO_3$ $\qquad K_s = [Ca^{2+}] \cdot [CO_3^{2-}] = 3.8 \times 10^{-9} = 10^{-8.42}$ (at $T = 25^\circ C$) [Eq. 2.1]

Calcium carbonate will precipitate when pH is larger than 8 which leads to a higher carbonate ions concentration in water. By dosing carbon dioxide or another acid, calcium carbonate will dissolve again and transformed to the form of calcium and bicarbonate ions:

$CaCO_3 + CO_2 + H_2O \Leftrightarrow Ca^{2+} + 2HCO_3^-$ $\qquad$ Where $K_1 = \frac{[Ca^{2+}] \cdot [HCO_3^-]^2}{[CO_2]}$ [Eq. 2.2]

In addition to both basic chemical equilibrium equations existing in water, there are three extra equations always valid in the natural water, which are:

$CO_2 + 2H_2O \Leftrightarrow H_3O^+ + HCO_3^-$ $\qquad$ Where $K_1 = \frac{[H_3O^+] \cdot [HCO_3^-]}{[CO_2]}$ [Eq. 2.3]

$HCO_3^- + H_2O \Leftrightarrow H_3O^+ + CO_3^{2-}$ $\qquad$ Where $K_2 = \frac{[H_3O^+] \cdot [CO_3^{2-}]}{[HCO_3^-]}$ [Eq. 2.4]

$2H_2O \Leftrightarrow H_3O^+ + OH^-$ $\qquad$ Where $K_w = [H_3O^+] \cdot [OH^-]$ [Eq. 2.5]

In the softening process, these five chemical equilibrium equations happen simultaneously in the softening reactors.

2.1.2 Softening with chemical dosing

In practice, three bases are dosed to remove calcium from water, which are soda ash, caustic soda or lime dosing. The choice for dosage depends on the alkalinity of the raw water [J.C.van Dijk, D.A.Wilms, 1991].

$Na_2CO_3 + Ca^{2+} \rightarrow CaCO_3 + 2Na^+$ [Eq. 2.6]

$NaOH + Ca^{2+} + HCO_3^- \rightarrow CaCO_3 + Na^+ + H_2O$ [Eq. 2.7]

$Ca(OH)_2 + Ca^{2+} + 2HCO_3^- \rightarrow 2CaCO_3 + 2H_2O$ [Eq. 2.8]

The caustic soda is applied at Wim Mensink. Based on equation 2.7, removing 1 mmol/l Ca^{2+} causes 1 mmol/l Na^+ in solution and 1 mmol/l HCO_3^- consumption.

2.1.3 Saturation index principle

The saturation index is the degree of precipitating potential for calcium carbonate according:

$$SI = \log \left\{ \frac{(Ca^{2+}) \cdot (CO_3^{2-})}{K_S} \right\} = pH - pH_s \qquad [Eq.\ 2.9]$$

Where the pH_s is the equilibrium pH value of water with the concentration of calcium and carbonate ions, which is

$$pH_s = pK_2 - pK_s - \log ([Ca^{2+}] \cdot [HCO_3^-]) \qquad [Eq.\ 2.10]$$

A negative SI means the water is under saturated so the water will dissolve calcium carbonate. A positive SI indicates that the water is supersaturated and there will be precipitation of calcium carbonate in water. It can be concluded that supersaturation is the chemical driving force for the crystallization reaction.

2.1.4 Crystallization kinetics

In the softening reactor, the crystallization of calcium carbonate will happen on the surface of the pellets. The crystallization can be categorized into two processes, i.e. nucleation and growth [J.C.van Dijk, D.A.Wilms, 1991]. In the nucleation process, the heterogeneous nucleation of calcium carbonate will happen at a lower SI value. The heterogeneous nucleation of calcium carbonate is represented here:

$$-\frac{dCa^{2+}}{dt} = k_T \cdot S \cdot \{(Ca^{2+}) \cdot (CO_3^{2-}) - K_S\} \qquad [Eq.\ 2.11]$$

Where

t = Temperature (ºC)

k_T = Reaction constant (-)

S = Specific area of seed crystals (m^2)

$(Ca^{2+}) \cdot (CO_3^{2-}) - k_S$ = Super saturation or driving force (-)

The precipitation process of calcium carbonate takes place until the saturation index is zero. The crystallization reaction can be described with the following first order kinetic law:

$$\frac{dc}{dt} = -k \cdot c \qquad [Eq.\ 2.12]$$

Where c is the amount of supersaturated calcium carbonate at time t and k is the reaction constant.
When the supersaturation declines, the amount of the supersaturated calcium carbonate is hard to crystallize during the normal detention time, thus the reaction mentioned above can be presented as below:

$$C_t = C_e + (C_0 - C_e)\, e^{-kt} \qquad [Eq.\ 2.13]$$

Where C_t is the concentration of supersaturated calcium carbonate at time t, C_0 is the initial concentration of supersaturated calcium carbonate and C_e is the concentration of supersaturated calcium when reaching the equilibrium.

2.1.5 Hydraulics properties for fluidized bed

The basic hydraulic properties of the fluidised bed are pellet diameter (d), superficial velocity (v), fixed bed height (L_0), fluidised bed height (L), pellet porosity (p), head loss (H), specific surface area (S). The relations between these parameters are:

$$H = 130 \cdot \frac{\nu^{0.8}}{g} \cdot \frac{(1 - p_e)^{1.8}}{p_e^3} \cdot \frac{v^{1.2}}{d^{1.8}} \cdot L_e \qquad [Eq.\ 2.14]$$

$$H_{max} = (1 - p) \cdot L_e \cdot \frac{\rho_p - \rho_w}{\rho_w} \qquad \text{[Eq. 2.15]}$$

$$\frac{p_e^3}{(1 - p_e)^{0.8}} = 130 \cdot \frac{\nu^{0.8}}{g} \cdot \frac{\rho_w}{\rho_p - \rho_w} \cdot \frac{v^{1.2}}{d^{1.8}} \qquad \text{[Eq. 2.16]}$$

$$E = \frac{L_e}{L_0} = \frac{1 - p_0}{1 - p_e} \qquad \text{[Eq. 2.17]}$$

Where
H = Hydraulic loss (mH_2O)
H_{max} = Maximum hydraulic loss (mH_2O)
E = Expansion of bed (-)
ν = Kinematic viscosity (m^2/s)
g = Gravity acceleration (m/s^2)
p_0 = Fixed bed porosity (-)
p_e = Fluidized bed porosity (-)
v = Velocity (m/s)
d = Pellet diameter (m)
L_0 = Fixed bed height (m)
L_e = Expanded bed height (m)
ρ_p = Pellet density (kg/m^3)
ρ_w = Water density (kg/m^3)

According to Equation 2.14 and Equation 2.15, the head loss in fluidized bed will increase for higher velocity until the maximal head loss H_{max} has been reached. A minimum velocity is needed to keep the bed fluidized. The maximum velocity happens by the limitation of sedimentation velocity of pellets.
The height of the fluidized bed will be influenced by the superficial velocity, pellet diameter, fixed bed height, temperature and specific gravity of the pellets.
With the lower temperature in winter, the fluidized bed height is higher than in summer because of the increase of kinematic viscosity of water. A lower temperature slows down the crystallization rate.
Theoretically, dosing of sodium hydroxide will lead the concentration of calcium ions to the equilibrium concentration, an infinite reacting time is needed to achieve this equilibrium concentration and the driving force of the crystallization will decrease to zero. To reach a complete equilibrium, an infinite height of the fluidized bed is needed. Therefore, in practice, a part of the calcium ions will stay in the effluent water. Equation 2.13 presents the concentration of calcium ions as a function of time.
There is an optimal concentration point of calcium ions with the minimum fluidized bed height. To reach a higher depth of softening, the initial super saturation should be higher as well, thus the height of the fluidized bed will be lowered, however, with the further decreasing of the effluent concentration of calcium ions, the increasing rate of the carbonate ions will be far more than the decreasing rate of the calcium ions and the super saturation will decrease again, thus a higher fluidized bed is predominant again with lower concentration of calcium ions in the effluent water.

2.2 Model theory of softening process

The Stimela model for softening is developed by Kim van Schagen [Kim van Schagen, 2008]. The model divides the upflow reactor into different layers over the height and each layer consists of the volume of grains, volume of calcium carbonate and the volume determined by the porosity. A higher layer has a larger porosity and less mass of grains and calcium carbonate of water. The specific graph of the model can be seen in Figure 9 [Kim van Schagen, 2008]:

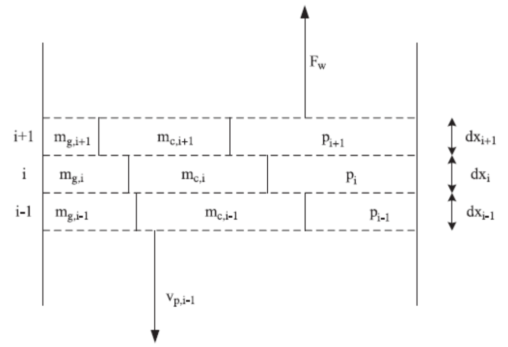


Figure 9: Modelled layers in the reactor [Kim van Schagen, 2008]

The height of each layer is given by the Equation 2.18

$$\Delta x_i = (\frac{m_{g,i}}{\rho_g} + \frac{m_{c,i}}{\rho_c}) \cdot (1 - p_i)^{-1} \cdot A^{-1} \qquad \text{[Eq. 2.18]}$$

Where

Δx_i = height in layer i (m)

$m_{g,i}$ = mass of grain in layer i (kg)

$m_{c,i}$ = mass of calcium carbonate in layer i (kg)

ρ_g = density of grain (kg/m^3)

ρ_c = density of calcium carbonate (kg/m^3)

p_i = porosity in layer i (-)

A = surface area of reactor (m^2)

In this softening model, the porosity of pellets is described by the Richardson-Zaki expansion formula and the pressure drop over height is given by the Equation 2.19

$$\Delta P_i = \Delta x_i \cdot (\rho_{p,i} - \rho_w) \cdot (1 - p_i) \cdot g \qquad \text{[Eq. 2.19]}$$

Where

ΔP_i = pressure drop over layer i (Pa)

$\rho_{p,i}$ = density of pellet in layer i (kg/m^3)

ρ_w = density of water (kg/m^3)

p_i = porosity of layer i (-)

g = gravity (m/s^2)

$\rho_{p,i}$ can be calculated using Equation 2.20

$$\rho_{p,i} = (m_{c,i} + m_{g,i}) \cdot (\frac{m_{c,i}}{\rho_c} + \frac{m_{g,i}}{\rho_g}) \qquad \text{[Eq. 2.20]}$$

The average diameter of pellets in each layer is determined by using the Equation 2.21 assuming the even distribution of mass over the grain.

$$d_{p,i} = d_0 \cdot \sqrt[3]{1 + \frac{m_{c,i}}{m_{g,i}} \cdot \frac{\rho_g}{\rho_c}} \qquad \text{[Eq. 2.21]}$$

Where
$d_{p,i}$ = pellet diameter in i layer (m)
d_0 = initial grain diameter (m)

2.3 Richardson-Zaki method

The Richardson-Zaki method is used to determine the porosity of fluidized beds.

$$p = (\frac{v}{v_0})^{1/n} \qquad \text{[Eq. 2.22]}$$

Where
p = Bed porosity (-)
v = Superficial velocity (m/s)
v_0 = Terminal settling velocity (m/s)
n = Experience exponent (-)

In the case for perfectly round, smooth and uniform particles, the terminal settling velocity can be determined by the Newton-Stokes equation [Bird et al, 1960]:

$$v_0 = \frac{4}{3}\frac{d_p(\rho_p - \rho_w)g}{C_{w2}\rho_w} \qquad \text{[Eq. 2.23]}$$

Where
v_0 = Terminal settling velocity (m/s)
g = Acceleration velocity (m/s^2)
C_{w2} = Drag coefficient Richardson-Zaki (-)

The estimate of C_{w2} is calibrated for pellet softening reactor in drinking water treatment plant Weesperkarspel [Kim van Schagen, 2008]

$$C_{w2} = \frac{24}{R_{e0}}(1 + 0.079 R_{e0}^{0.87}) \qquad \text{[Eq. 2.24]}$$

Where
R_{e0} = Terminal settling Reynolds number (-)

Where the terminal settling Reynolds number is given by

$$Re_0 = \frac{v_0 d_p}{\nu} \qquad \text{[Eq. 2.25]}$$

For the experience exponent n, the following empirical relationship is found

$$n = \begin{cases} 4.6 & \text{for } Re_0 < 0.2, \\ 4.4Re_0^{-0.03} & \text{for } 0.2 \geqslant Re_0 < 1, \\ 4.4Re_0^{-0.1} & \text{for } 1 \geqslant Re_0 < 500, \\ 2.4 & \text{for } Re_0 \geqslant 500. \end{cases}$$

[Eq. 2.26]

Where
n = Experience exponent (-)

In the pellet softening reactor, normally, Re_0 is larger than 500 and n = 2.4 will be applied.
For different pellet reactors, the drag coefficient C_{w2} is different because the shape and size of the pellets differ from each other and it will be generalised:

$$C_{w2} = \frac{24}{R_{e0}}(1 + \beta_1 R_{e0}^{\beta_2}) \qquad \text{[Eq. 2.27]}$$

Where
C_{w2} = Drag coefficient Richardson-Zaki (-)
R_{e0} = Terminal settling Reynolds number (-)
β_1 = Constant 1 (-)
β_2 = Constant 2 (-)

β_1 and β_2 are constants and they need to be calibrated based on experiment data.

2.4 Aeration principles

For aeration in Wim Mensink cascade aeration is applied. The gas transfer has two purposes, aeration and gas stripping. It aims to increase the oxygen and remove carbon dioxide, methane, hydrogen sulphide and other volatile organic compounds. If the gas saturation concentration is reached in water, gas exchange in both directions is equal. The concentration of a volatile compound in the gas phase will be in equilibrium with the concentration in the water as described by Henry's law:

$$c_w = k_H \cdot c_g \qquad \text{[Eq. 2.28]}$$

Where
c_w = Equilibrium concentration of gas in water (g/m^3)
k_H = Henry's constant (-)
c_g = Concentration of gas in air (g/m^3)

The concentration of gas in air can be determined with the universal gas law:

$$\frac{n}{V} = \frac{p}{RT} \qquad \text{[Eq. 2.29]}$$

Where
p = Partial pressure of gas in gas phase (Pa)
V = Total gas volume (m^3)
n = Amount of substances of gas (mol)
R = Universal gas constant, 8.3142 (J/K/mol)
T = Temperature of gas (K)

The gas concentration can be calculated with:

$$c_w = \frac{p}{RT} \cdot MW = \frac{n}{V} \cdot MW \qquad \text{[Eq. 2.30]}$$

Where
MW = molecular weight of gas (g/mol)

3. Model description

3.1. Stimela

Stimela is an environment for standardized mathematical models of drinking water treatment processes. It was developed by Delft University of Technology, DHV and is designed for water quality modelling. Stimela model runs on the Matlab/Simulink® platform and partial differential equations are numerically integrated. Currently, the Stimela model is based on the operational environment in Matlab 6.5.2 and model units consist of standard Simulink models and Stimela models. Because Matlab/Simulink® is used, the models are easily accessible, the structure is open and flexible and all routines, toolboxes and visualization techniques of Matlab/Simulink® can be used [van der Helm and Rietveld, 2002].
All the data, graphical and tabular information in Stimela model will be stored in a sort of temporary storage file with '.sti' form, which consists of '_in.sti', '_out.sti', '_ES.sti' and '_EM.sti' four forms in total. The function of '_in.sti' file is to store all the original input signals; the '_out.sti' file is for storage of the calculated output signals by central Stimela model; the '_ES.sti' will be used to store other additional input signals and the - '_EM.sti' file is the one storing other calculated output results.

3.2 The pellet softening model

The pellet softening model is run under the programming file 'pels25_s.m'. Under the model PS Reactor, the detailed reactor information is shown, see Figure 10. In the left part of the pellet reactor, flow with dark blue tag name HEZ301_FT10 is read from WSControl file and the setpoint for dosing sodium hydroxide is read from dark pink tag PM_THPSM_ONTHARD. In the right part of the pellet reactor, the total hardness for the water is calculated and the extra measurements such as the pellet diameter over different layers, total pressure drop, the pressure drop at the bottom of the reactor over 1 m, the fluidized bed height are displayed.

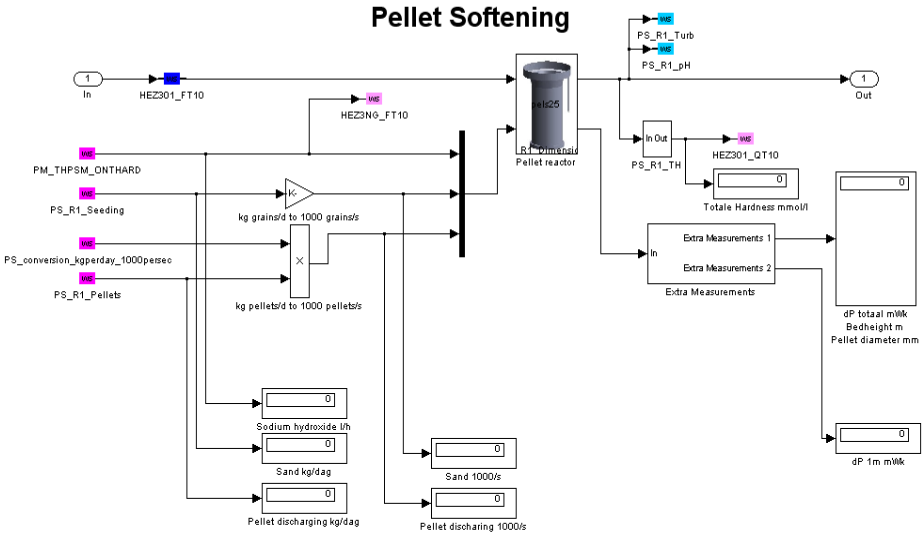


Figure 10: Detailed information of flow chart for each pellet softening reactor

Under the model mask of pellet reactor, the two signals in_1 and in_2 are mixed together to file pels25_s_c and then it is separated to two signal routes to its relevant output. To improve the calculating speed in running the model, the pels25_s_c file run in C++ operational environment replaces the original pels25_s run in standard matlab operational environment. Four PS_R1_Dimensions files are written into the simulator to be used in the central control in future. Within these four dimensions files, PS_R1_Dimensions_in.sti includes all the original input signals such as flow, water quality parameters and PS_R1_Dimensions_out.sti is output file for the calculated result of those water quality parameters in pels25_s_c. PS_R1_Dimensions_ES.sti is the file for other input of signals, such as sodium hydroxide dosing, grain dosing and pellet discharging. PS_R1_Dimensions_EM.sti is the file with new calculated results combing the information from both input files, such as pellet diameters over different layers, total bed height, total pressure drop, pressure drop for 1 meter at the bottom of the reactor. Figure 11 is the example of central control model for pellet softening process.

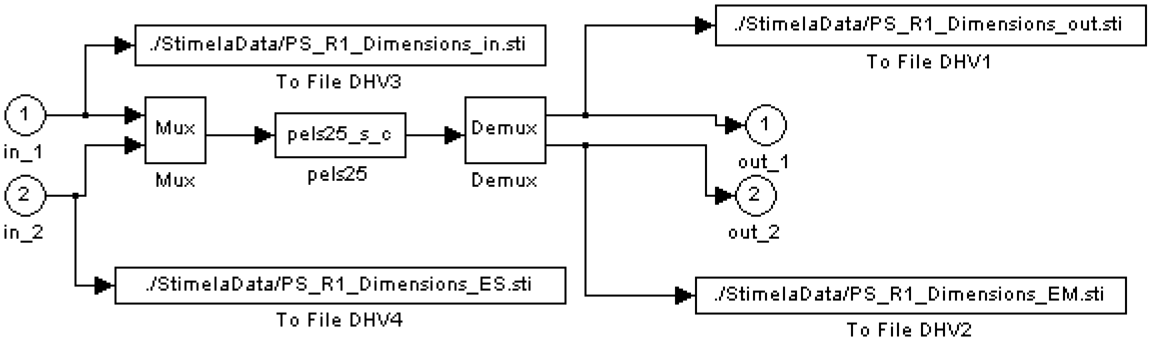


Figure 11: Information of pellet softening reactor under mask

Under this model, the equations of crystallization and fluidized bed height described in chapter 3 are written down to the pels25_s.m file.

3.3 The aeration model

The aeration model consists of two parts: CO_2 dosage and cascade aeration. The theoretical gas exchange process has been described in Chapter 2.2. The model runs under the cascade_s.m file and it was also compiled to C++ code to improve the running speed. The control model block for aeration model is cascade_s_c and the relevant information written down to central control in future will be stored in CAS_FG1_Dimensions_in, CAS_FG1_Dimensions_out, CAS_FG1_Dimensions_EM three '.sti' files.

3.4 The mixing model

The role of mixing model is to mix water flow and all water quality parameters. Apart from the pH value, all the other water quality parameters will be averaged after mixing. The calculation of pH needs to use carbonic equilibrium to get the solution. The basic carbonic equilibrium equations are described in [Eq. 2.3], [Eq. 2.4] and [Eq. 2.5]. The control model block for mixing model is mengpH_s_c and the relevant information written down to central control in future will be stored in PS_Mixer_Retour_in, PS_Mixer_Retour_out, PS_Mixer_Retour_ES three '.sti' files.

3.5 The Wim Mensink model

The Wim Mensink model also consists of standard Simulink and Stimela models. It consists of three lanes, which are filter building 1, filter building 2 and a RO flow. For filter building 1, the train of model block consists of pellet softening reactors, aeration cascades, rapid sand filters. For filter building 2, the train of model block is composed of aeration cascades, rapid sand filters. RO water will be mixed with the flow from filter building 1 and filter building 2. In Wim Mensink model, only one standard model for pellet softening and rapid sand filtration was used, the rest of model blocks are replaced by gains or dummies but the signal will be copied from the only one standard model. The reason for doing that is the physical properties for all the softening reactors or rapid sand filters are the same.

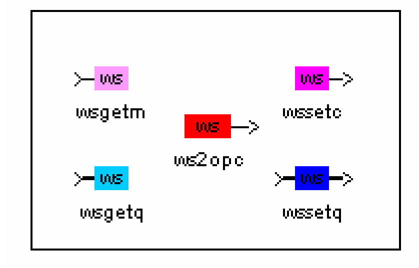


Figure 12: Waterspot tags in Wim Mensink

The signals of water flow or water quality parameters will be read from dark colour waterspot tag or written to light colour waterspot tags. The information in the waterspot tag is read or written into the WSControl file. WSControl file is the water control strategy file. Figure 12 shows different water spot tags [Alex van der Helm, Oct 2008]. The light pink one is extra measurement tag which writes information into the WSControl file; the dark pink one is extra measurement tag which reads information from the WSControl file; the light blue one is water quality or flow tag which writes information into the WSControl file; the dark blue one is water quality or flow tag which reads information from the WSControl file. The red one is for synchronizing time and starting and stopping simulation run.
The total flow chart of Wim Mensink shows the pellet softening, the CO_2 dosage, the weir aeration, the rapid sand filtration and the mixing RO water. The main flow chart is shown in Figure 13.

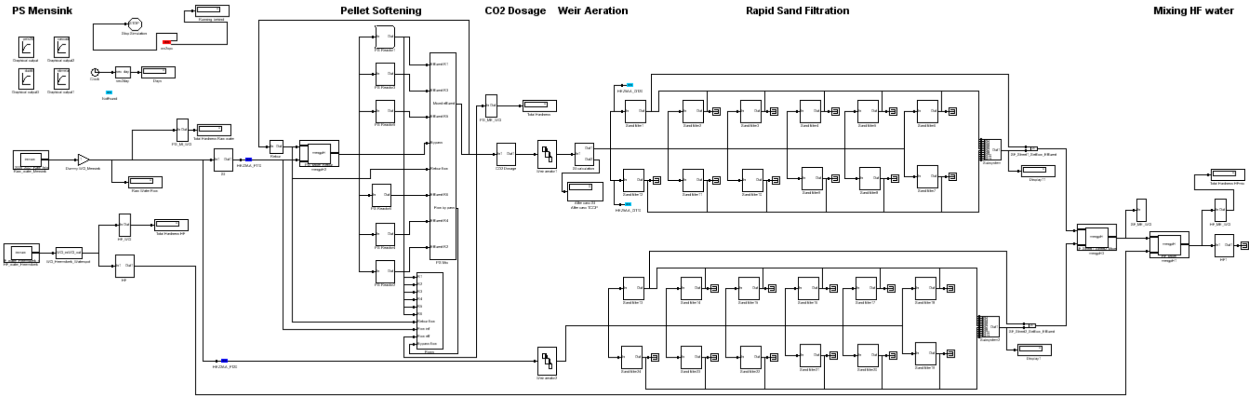


Figure 13: Main flow chart of Wim Mensink

3.6 Control

The water control strategy for Wim Mensink is described in the file WSControl.m. All the commands are assigned from here. Firstly, the information is read from the dark color waterspot tag with 'evalin' matlab function and at the end the new water control information is assigned to the light color waterspot tag with 'assignin' matlab function. The current water control strategy consists of three parts. The first part is the flow distribution part, which includes the bypass and recirculation situation in filter building one. The specific principle about how to distribute the water has been described in Chapter 1 before. The second part is chemical reaction part regarding sodium hydroxide dosage in softening process and carbon dioxide dosing in aeration process. The specific information about them can be found here:

3.6.1 Caustic soda dosage control

According to chemical equation 2.9 in Chapter 2, 1 mmol/l removal Ca^{2+} needs a dose of 1 mmol/l NaOH. Because the molecular weight for NaOH is 40 g/mol, 1 mol NaOH equals to 40 gram NaOH for 100% NaOH solution. For 25% NaOH solution, the actual needs of NaOH is 40 gram * 100% / 25% = 160 gram. The density of 25% NaOH is 1,277 g/l, thus in 1 m^3 water, the volume of 25% NaOH solution is 160 g / 1,277 g/l = 0.125 l.
Assuming the total hardness in raw water is TH_{in} (mmol/l), the total hardness of RO water is TH_{RO}, the flow in filter building 1 is $Flow_{FB1}$, the flow in filter building 2 is $Flow_{FB2}$, the flow in RO permeate water is $Flow_{RO}$,

the final hardness in clean water reservoir TH_{final} can be set as 1.5 mmol/l, thus the softening depth after filter building 1 TH_{out} (mmol/l) can be calculated by mass equilibrium Equation 3.1. In the control system, it is called the Master control.

$$Flow_{FB1} * TH_{out} + Flow_{FB2} * TH_{in} + Flow_{RO} * TH_{RO} = (Flow_{FB1} + Flow_{FB2} + Flow_{RO}) * TH_{final} \qquad \text{[Eq. 3.1]}$$

Where
$Flow_{FB1}$ = Total flow in filter building 1 (m^3/h)
TH_{out} = Total hardness in filter building 1 (mmol/l)
$Flow_{FB2}$ = Total flow in filter building 2 (m^3/h)
TH_{in} = Total hardness in raw water (mmol/l)
$Flow_{RO}$ = Total RO flow (m^3/h)
TH_{RO} = Total hardness in RO permeate (mmol/l)
TH_{final} = Total hardness in final clean water reservoir, 1.5 mmol/l

After that, the set point of NaOH dosing can be calculated in equation 3.2, $Flow_{FB1}$ (m^3/h) is the total raw water flow in filter building 1 and the number of reactors in operation is $N_{reactor}$, thus the removal of calcium is (TH_{out} – TH_{in}) (mmol/l) and the flow for each reactor is (Q_{in} / $N_{reactor}$) (m^3/h). In the end, the equation for dosing NaOH is:

$$D_{NaOH} = Flow_{FB1} * (0.125 * (TH_{in} - TH_{out})) / N_{reactor} \qquad \text{[Eq. 3.2]}$$

Where
D_{NaOH} = Set point of NaOH dosing per pellet reactor (l/h)
$Flow_{FB1}$ = Total flow in filter building 1 (m^3/h)
TH_{in} = Total hardness in raw water (mmol/l)
TH_{out} = Total hardness in filter building 1 (mmol/l)
$N_{reactor}$ = Number of reactors in operation
0.125 = The amount of NaOH dosage to remove 1 mmol/l Ca^{2+} in 1 m^3 water (l/m^3)

The calculated caustic soda dosing will be corrected by the difference between the calculated total hardness and the total hardness before cascade 1 so that the more accurate dosing of caustic soda can be reached. In the real system, it is called the Slave control. The equation for the amount of corrected caustic soda is:

$$D_{corr} = D_{NaOH} + Flow_{FB1} * (0.125 * (TH_{cascade} - TH_{out})) / N_{reactor} \qquad \text{[Eq. 3.3]}$$

Where
D_{corr} = Corrected NaOH dosing (l/h)
D_{NaOH} = Set point of NaOH dosing per pellet reactor (l/h)
$Flow_{FB1}$ = Total flow in filter building 1 (m^3/h)
$TH_{cascade}$ = Total hardness before cascade (mmol/l)
TH_{out} = Total hardness in filter building 1 (mmol/l)
$N_{reactor}$ = Number of reactors in operation

3.6.2 Carbon dioxide dosage control

The CO_2 dosage will decrease the pH value in water and therefore saturation index will also be reduced.
The method to determine the amount of CO_2 dosage is to calculate how much CO_2 will be dosed to neutralize the remaining amount of sodium hydroxide after the softening process. The chemical equation to be used to describe this chemical reaction is in [Eq. 3.4]. In this equation, 1 mmol/l CO_2 needs 1 mmol /l NaOH dosage. According to chemical reaction [Eq. 2.7], 1 mmol/l precipitated calcium ion also needs 1 mmol/l NaOH dosage. Based on that, the equation to determine the amount of CO_2 dosage is presented in [Eq. 3.5].
The dosing amount of CO_2 is determined by the amount of sodium hydroxide dosing, the calcium ion concentration in raw water, the calcium ion concentration after reactor, the flow of each reactor, the number of reactors switched on and the temperature. The master controller and slave controller are integrated into one equation.

$$NaOH + CO_2 \Leftrightarrow HCO_3^- + Na^+ \qquad \text{[Eq. 3.4]}$$

$$D_{CO2} = ((D_{NaOH} * \rho_{NaOH} * 25\% * 1000 / M_{NaOH}) - (Ca_{in} - Ca_{out}) * Q_{reactor}) * N_{reactor} * R * (T + t) / P_{Gas} \qquad \text{[Eq. 3.5]}$$

Where
D_{CO2} = Amount of CO_2 dosage (Nm^3/h)
D_{NaOH} = Set point of NaOH dosing per pellet reactor (l/h)
ρ_{NaOH} = Density of NaOH (kg/m^3)
M_{NaOH} = Molecular weight of NaOH (g/mol)
Ca_{in} = Calcium ion concentration in raw water (mmol/l)
Ca_{out} = Calcium ion concentration after pellet reactor (mmol/l)
$Q_{reactor}$ = Flow for each reactor (m^3/h)
$N_{reactor}$ = Number of reactors in operation
t = Temperature (°C)
R = Universal gas constant, 8.3143 (J/mol/K)
T = Kelvin temperature, 273 (K)
P_{Gas} = Standard atmospheric pressure, 101,325 (Pa)
25% = Mass percentage of sodium hydroxide solution (-)
1000 = Unit transformation coefficient (g/Kg)

The third part of water control strategy involves sand dosing and pellet discharging for pellet softening process. The specific information is found here:

3.6.3 River sand dosage control

The river sand dosage control is calculated as follows:

$$Ca_{removal} = (TH_{raw} - TH_{reactor}) * (M_{Ca} / 1000) * (Q_{reactor} * 24) * Deltatime \qquad \text{[Eq. 3.6]}$$

Where
$Ca_{removal}$ = Amount of calcium to be removed (kg)
TH_{raw} = Total hardness of raw water (mmol/l)
$TH_{reactor}$ = Total hardness after reactor (mmol/l)
$Q_{reactor}$ = Flow for each reactor (m^3/h)
M_{Ca} = Molecular weight of calcium (g/mol)
Deltatime = Time interval for dosing sand per time (d)

In this equation, 40.08 is the molecular weight of calcium. When the amount of calcium is accumulated to 270 kg, the sand starts to dose into the reactor. The amount of sand to be dosed is determined by the experiment result performed before and it is shown in Table 2. The sand will be dosed to a reactor 11 times one second when it has removed 270 kg calcium. The value of the total hardness for calculation after reactor will be determined by the dynamic value of total hardness after reactor. The total amount of sand dosing is 46.9 kg in total for 11 times one second. The result of this experiment 47 kg per dosing batch will be used for this model. The total dosing time of the sand is 7 minutes.

Table 2: Weight of sand for each time

Time	Weight of sand (gram)
1	4,583
2	4,644
3	4,466
4	4,569
5	4,214
6	4,537
7	4,009
8	2,580
9	4,150
10	4,553
11	4,596
Total	46,901

In the model, it will be simulated in a linearized way with unit kg/d and then it is converted to the unit 1000 sands/s with the formula 0.00831 * (1 / Sand diameter (mm))^3. In practice, the sand diameter is 0.4 mm and the result obtained from that formula is 0.1298.

3.6.4 Pellet discharging control

The pellet discharging is dependent on the total pressure drop over the reactor. During operation of the reactors, at every half hour the system checks the reactors in which pressure drops reach up to 1.80 mWc. When it comes to that pressure drop, the pellets will be discharged. If the pressure drop is still higher than this value after discharging, then it will be put in a queue and wait for the next half hour check for the next time discharging.

An experiment was performed for investigating the weights of pellet in one cycle. Reactor 3, reactor 4 and reactor 5 are involved in this investigation. The weighted values for them are 50.2, 50.0 and 48.8 kg/minute for three cycles. Therefore, the average value is calculated as 50.0 kg/minute. Also, it is converted to the unit 1000 pellets/s into the model with the same equation used for sand dosage.

3.6.5 Flow in rapid sand filters control

The flow for the rapid sand filters is adjusted by the buffer system. The inflow consists of two valves and there are 24 valves in total for one street flow. The outflow is adjusted by one valve and there are 12 valves in total for one street flow. The flow is will be evenly divided by the total flow in one street flow.

3.7 Model calibration

The current pellet softening reactor model is based on the work of Kim van Schagen (2008). The drag coefficient (C_{w2}) for porosity, crystallization constant (k_{T20}) and diffusion coefficient (D_f) for crystallization reaction has already been calibrated in previous work in drinking water treatment plant Weesperkaspel. In the drinking water treatment plant Wim Mensink, it still uses the sodium hydroxide to form the precipitation. The seeding material is river sand but not garnet in Weesperkaspel. However, it will not cause a huge change in drag coefficient, crystallization constant and diffusion coefficient, thus the calibration work does not need to be performed.

3.8 Model development

In the previous model, there were problems in signal routes design for bypass and recirculation flow. The problem was that the recirculation flow can not work in a right function with its buffer model. Therefore, the signal routes design for recirculation flow needed to be modified while still satisfying the requirements of bypass flow at the same time. This restoration work was done before the model calibration and validation work.

To explain the model restoration work, two figures are put here. Figure 14 is part of pellet softening with specific information in this model and Figure 15 is the signal information under in-out block (Arrow 1), Figure 16 is the signal information under mixing flow block (Arrow 4).

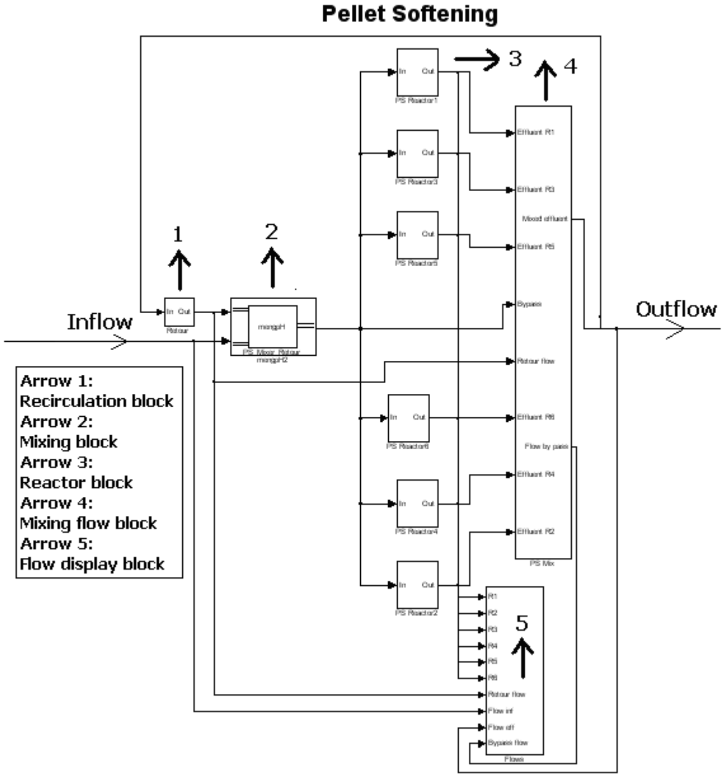


Figure 14: Diagram of pellet softening part in model

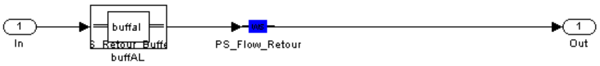


Figure 15: Signal information under in-out (Arrow 1) block

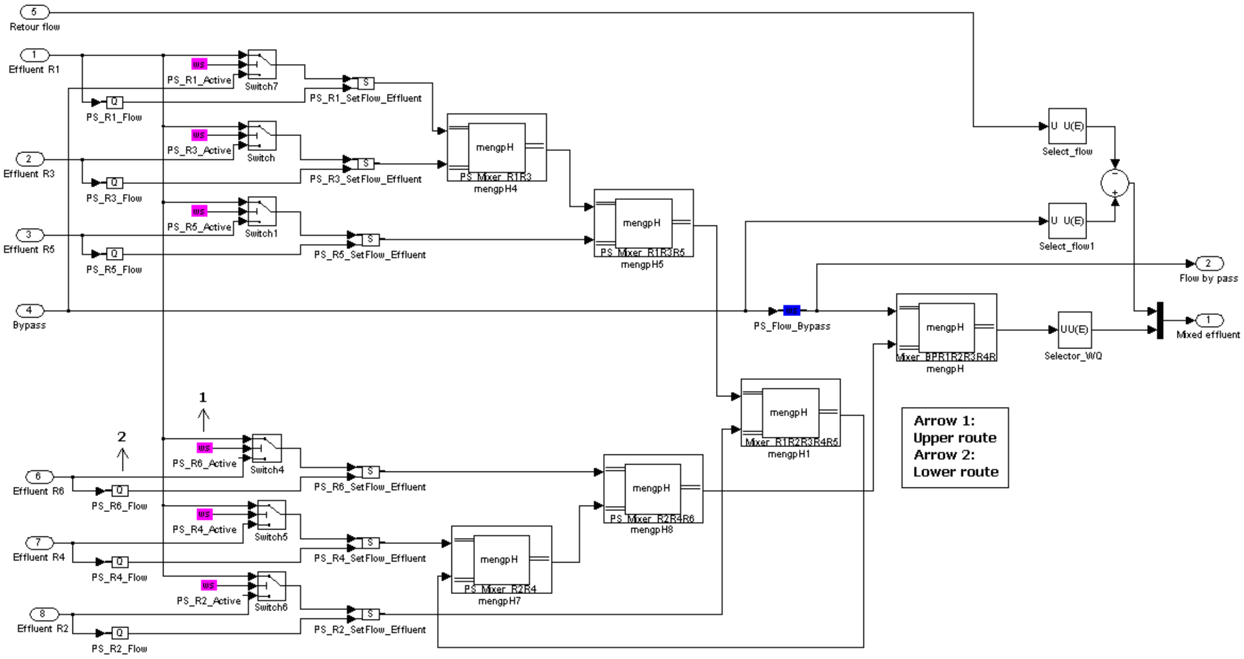


Figure 16: Signal information under mixing flow (Arrow 4) block

From the figures above, it can be seen that when inflow water with excess bypass water comes to the pellet softening reactors, all the signals including water flow and other water quality parameters in the main signal line will be mixed in the mengpH block (Arrow 2) with flow out of the in-out block. Here the recirculation flow is zero and values of other water quality parameters are the same as the ones after softening process. The function of mengpH is to sum the water flow and mix the other water quality parameters with its relevant flow. Therefore, after the first mixing process before softening reactors (Arrow 3), the water flow and water quality are still the same as before entering the softening reactors. After that, the flow for each reactor will be taken and it comes to the softening process. When the softening process is finished, the signals will flow into the mixing flow block. From figure 16 it can be seen, for each reactor, when PS_RX_Active is 1, the switch will be connected to the upper route while it connects the lower route when PS_RX_Active is 0. The water flow and other water quality parameters are separated. The flow will be selected by PS_RX_flow model and other water quality parameters will go in another upper line or lower line. The upper line contains all the water quality information after softening process and the information in lower line means those untreated raw water. Then, the water flow and water quality parameters are mixed again in PS_RX_Setflow_Effluent model. The upper routes for all reactors copy the water quality parameters in reactor 1 because of the same effect of softening after pellet reactors.

The flow and water quality parameters for each reactor will be combined by several mengpH units. In the rightmost side of the mengpH, all the softened water with flow and water quality parameters are mixed with flow and water quality parameters in bypass flow. The bypass flow is read from waterspot tag PS_Flow_Bypass. After this mixing process, all the water quality parameters are selected by a selector model in Simulink dictionary. The flow signal is decided from another route with two selectors in return flow and in bypass flow separately and they are integrated by a multiplier. In this bypass flow case, the return flow is zero, the signal of flow before PS_Flow_Bypass is the original total flow before softening, thus the calculation result is still the original total flow before softening and it matches the case.

In the second case, when recirculation flow happens, firstly, the signal of recirculation flow with its relevant water flow and water quality parameters will be copied from the end of the softening flow mixers. However, before reading the recirculation flow from the waterspot tag PS_Flow_Retour, it goes through a buffer with 120s interval so that the flow out of the recirculation part and the raw water flow can be mixed at the same time. After this process, the water flow and water quality parameters are mixed with original raw water in main route and go to the softening process. With the same principle of signal routes, the water in switched-on reactors is mixed together in the rightmost side mixer, the bypass flow in this case is zero, thus water flow and water quality parameters in the outflow of the mixer still keep the same. In the final selector process, the flow before PS_Flow_Bypass is the original raw water flow plus the recirculation flow, so the final flow is still the original raw water flow. After summing with other water quality parameters, it consists of the final outflow with correct water flow and water quality parameters. All the signals track back as the input signals of recirculation flow to form the cycling routes.

Besides that, the display for all the water flow in reactors, the inflow and outflow, the bypass and recirculation flow are integrated in the model block with Arrow 5.

4. Data acquisition

4.1 Plenty report

Plenty report is the production database of PWN containing flow, pressure and water quality parameters. Almost all the historical data of PWN are stored in Plenty report. In PWN, every measurement is marked with a tag, such as HEZ2AA_FT10, PWM_PO_INF1915, etc.

The data in Plenty report is either laboratory measurement or online measurement. Normally, the laboratory measurement will be sampled every week and the possible problem for that is the results of the laboratory measurement may not represent the actual condition of the water quality parameters because of the time lag for the samples when it is measured in a special laboratory institute.

The storage time for the online measurement will be every 15 minutes in most of the cases so the data can be used to represent the actual condition of the water parameters. The shortage for these data is that it can not describe the overall amount of the water parameters for its limited sampled points and range of sampling.

4.1.1 Selection of sampling locations

The laboratory measurements of the sampling points are the inflow raw water, the outflow after cascade 1, the outflow RO permeate from Heemskerk I and clear water reservoir.

For the online measurement, it is sampled mainly for flow, hardness and pH. It is performed on the sampling location of inflow raw water, the softening reactor, the inflow of cascade 1 and cascade 2, the outflow after cascade 1, the inflow before mixer, the outflow Heemskerk I and the outflow of mixer.

The sampling points are in Figure 17. The triangular marks represent the laboratory measurement locations; the circle marks represent the different online measurement locations.

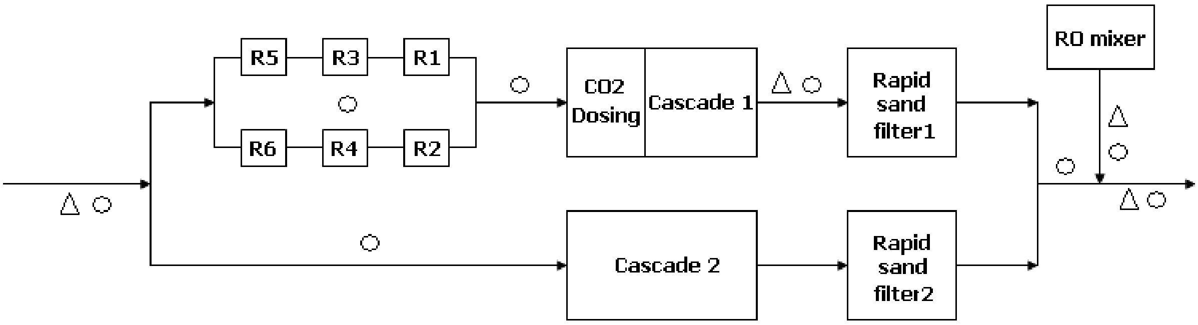


Figure 17: Locations of laboratory and online measurement in Wim Mensink

4.1.2 Selection of sampling time

The sampling time for the laboratory measurement and online measurement should be the same as the period of the experiment of the sieve analysis to obtain a complete dataset. The experiment for the sieve analysis started on January 20th, 2009 and ended on March 11th, 2009. To analyse the data, the selection time of the data in this thesis work was taken from January 20th, 2009 to February 20th, 2009 to match the time of sieve analysis. For the laboratory measurements, most of the water parameters actually start from January 24th, 2009 and end on March 17th, 2009. Therefore, the start data for laboratory measurements should be obtained with the linear interception between the data on January 24th and the data before January 24th. The end of the date can choose the final sampling point just before February 20th so that the first group of measurements start on January 20th and obtain the complete datasets over this period.

After several model runs, the best time interval for sampling the flow is every two hour while still keeping the model in a fast calculating speed. Normally, 30 days running is around 120 minutes and two hours time interval for flow can basically satisfy this need. The start time is of course at 0:00 am on January 20th and the end time is at 0:00 am on March 21st.

4.2 Water quality measurements

The selection of water quality measurements is based on laboratory measurements. Although laboratory measurements can not represent the exact actual time for the water quality parameters, they are situated in important locations where it is important to obtain measurements to validate the model results. The laboratory measurements for raw water and the laboratory measurements for RO water are used as input of model to finish the model calculation work.

Another application of the laboratory measurements is to compare with the calculated water quality parameters from model results for validation work. The laboratory measurements for raw water, the laboratory measurements after weir aerator and the laboratory measurements after RO mixing are selected to compare with the model results for first month. From Appendix III, the laboratory measurements with different measuring points for these data are presented. However, these data must be transferred from time form to number form. The mark "---" means that the data does not exist or it will not be used for this thesis work. Also, the tags for the flow are presented in Appendix II.

4.3 Flow measurements

Flow data is stored in two ways with FQ and FT measurements. The unit for FT is m^3/h and for FQ is $m^3/15$ min. FQ is pulse count and FT is the actual value. The value of FQ is derived from the surface area under FT curve divided by four and it is mainly used by technologists to avoid the large fluctuation of the flow.

In this thesis work, the FT is chosen as the representative value because of the short period for using the database in Plenty report for the model work. Another reason is that the dynamic data of the flow value needs to be used as the original value for the model and it can represent the real condition when compared with the value obtained from pulse count way.

The tags for the flow used in this thesis work can be seen in Appendix II. However, the total flow for the flow of Heemskerk I only has FT flow and it is applied directly to this thesis work.

4.4 Pressure drop measurements

The pressure drop for each reactor is measured by online measurement over the total height of the reactor. The measured values will be used to check the model results. Appendix II shows the tags used in this thesis work.

4.5 Bed height measurements

The bed height measurements are the fluidized bed height. In water treatment plant Wim Mensink, it is measured manually every week for all reactors. In this work, the fluidized bed height was measured at the same time with taking the pellet samples. The fixed bed height was measured when a reactor was not in operation.

The online measurement for the fluidized bed height of reactors was available on reactor 1, reactor 3 and reactor 4. The specific information is put in Appendix III. Due to the water turbulence on January 16th and January 20th, the fluidized bed height was not measured. From January 28th to February 11th, online measurement only happened on reactor 4. Since the start time of February 11th, the online measurements for reactor 1 and reactor 3 started but the online measurement device stopped recording at the time of taking the samples. The online measurements are used to check the accuracy of the manual measuring way. The manual way is performed with a steel plate and chain. The length of the chain is measured when the plate just reaches the surface of the fluidised bed height. The height of the softening reactors is 6.0 m, thus the fluidized bed height is (6.0 m – length of the chain).

4.6 Pellet size distribution

4.6.1 Introduction

The pellet size distribution experiment is performed on 3 reactors (Reactor 3, Reactor 4 and Reactor 6) over different layers in the reactors from the date January 20th to March 11th.

4.6.2 Materials and methods

Pellet reactors

The samples are taken using a long plastic tube. The height of each layer is 0.5 m. The total sampling height is divided into seven layers and the first layer is at the bottom of the reactor.

The plastic tube is connected to the fire hydrant at the side of the plant so that the clean water in the hydrant can be used to flush the tube. When flush stops, the pellets will be sucked out of the reactor as a consequence of a siphon mechanism. Before the tube was inserted into the softening reactors, it was disinfected with H_2O_2.

At the start of the sampling, the valve connecting to the fire hydrant and connecting to the main tube is opened and the valve connecting to the outflow of sampling points is closed. The purpose for that is to fill the tube with clean water. A few seconds later, the valve connecting to the fire hydrant is closed and the valve connecting to the main tube is opened. After waiting for several seconds, the flow with pellets from the reactors will be sucked from the bottom and the switch for outflow of sampling points is opened to take the samples. After finishing the collection of the sample for one layer, the switch for the outflow will be closed again and the valve for the hydrant is opened to flush the pellets in the main tube to the softening reactors.

Sieve analysis

The sieve analysis is performed at the water laboratory of the Delft University of Technology with a sieve shaking machine and different sizes of sieve meshes, which are shown in Figure 18 and Figure 19. After several trial and error experiments with different groups of sieve meshes, the final sieve groups for different layers and reactors and the detailed information is attached in Appendix IV.

For different layers in one reactor, different size groups of sieve meshes are selected. Reactor 2 is divided into 6 layers but not 7 layers compared with other reactors because reactor 2 has not reached up to the maximum fluidised bed height on March 11th. Therefore, the choice of different sieve sizes is significantly different than other reactors with 7 layers. Other reactors have the same groups of sieve meshes in layer 1, layer 2, layer 3, layer 5, layer 6 and layer 7 but only have difference in layer 4. The reason for that is the pellet size is in the transition zone at that height.

The principle for choosing the different sieve meshes is to make the density curve and cumulative going through curve look like the Gaussian distribution. For the same reactors over different time, in this experiment, the sieve meshes are chosen as the same ones.

All the meshes are DIN standard. The units for the sieve meshes are mm. Each time 100 gram pellets was weighed by using an electrical balance. The results of the experiment prove that it can reflect the sieve analysis results because different size of pellets can be distributed over different sieve meshes. Figure 20 is the picture of electrical balance. The weights of the sands are calculated with:

Weight of pellets (g) = Total weight of metal cup and pellets (g) - Weight of metal cup (g)

With the same method, the weight of pellets in each sieve mesh is calculated,

Weight of pellets on sieve mesh (g) = Total weight of sieve mesh and pellets (g) – Weight of sieve mesh (g)

All the results will be weighed for two times and the average value will be used. The purpose for that is to obtain a reliable value for the weight.

Before doing the sieve analysis, the samples were dried in the oven over one night with 60 degrees for every batch.

Figure 18: Picture of electrical balance

Figure 19: Picture of sieve machine

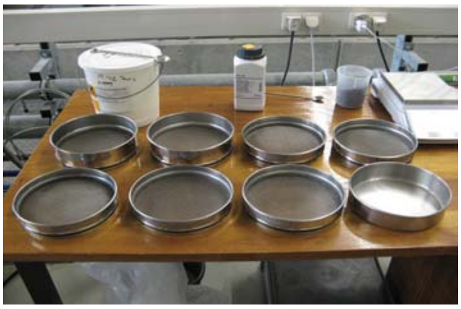


Figure 20: Picture of sieve meshes

4.6.3 Results

The sieve analysis covers the period from January 20th, 2009 to March 11th, 2009 for reactor 3, reactor 4, and reactor 6. The tryout experiment was on January 16th, 2009 with reactor 6. On January 28th, 2009, reactor 6 was out of operation. On March 11th, 2009, reactor 3 was out of operation. Reactor 2 is performed for the first time for the comparison with other reactors on March 11th. Also, reactor 1 was performed on January 20th, 2009 and on January 28th, 2009 for two times and reactor 5 was performed on January 20th for one time.

The sieve analysis is performed with different sieve mesh for each reactor. The results for specific diameters for different reactors over time are shown in Appendix IV:

The specific diameter is calculated with equation [Lab experiments, 2008]:

$$\frac{W}{d_s} = \frac{W_1}{\varphi_1 \sqrt{S_1 S_2}} + \frac{W_2}{\varphi_2 \sqrt{S_2 S_3}} + \frac{W_3}{\varphi_3 \sqrt{S_3 S_4}} + \dots \frac{W_n}{\varphi_n \sqrt{S_n S_{n-1}}}$$ [Eq. 4.1]

Where

W = total weight of the sand sample (g)

W_i = weight on sieve i (g)

S_i = mesh of sieve i (mm)

φ_i = shape factor for fraction between sieve i and sieve i+1 (-)

d_s = specific diameter (mm)

Shape factor is the ratio that one loaded surface area to the total area free to bulge. In this case, the structure of the sieve mesh is made by steel and it has the insufficient elasticity. Therefore, in this calculation process, these shape factors can be assumed to be 1.

The results of sieve analysis for each reactor over different layers against two months are present in table 3 here:

Table 3: Average value of pellet diameters for different reactors over different time [mm]

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
Reactor 3	0.79	0.76	0.59	0.58	0.47	0.43	0.39
Reactor 4	1.00	1.00	0.86	0.72	0.55	0.46	0.41
Reactor 6	0.94	0.93	0.85	0.67	0.52	0.45	0.41

4.6.4 Discussions

In the sieve analysis, pellet diameters in lower layers sometimes are smaller than in higher layers. The possible reason for that is the water turbulence slightly influences the distribution of the pellets over different layers so that the stratification phenomenon is not significant. The inflow water comes into the softening reactors through nozzles at the bottom of the reactors and also the relevant caustic soda dosing flow will be injected by a tiny pipe at the bottom of the reactors. The sand will be dosed into the reactor 11 times one 1 second for each time after the removal of 270 kg Ca as calculated from influent and effluent concentrations. In the meantime, the pellets are discharged as well. The water flow in the reactor will be influenced by turbulence when pellet discharge or grain dosage occurs. In all the calculated specific pellet diameters, there is not even one case of this problem happening in the last three layers (layer 5, layer 6 and layer 7), but it happens on layer 1, layer 2, layer 3 and layer 4 once in a while.

For one reactor in different time, the deviation of diameters does not change so much and it can be stated that this reactor has a constant operation because the constant pellet sizes in different layers can be achieved. In this thesis, the main research points are based on three reactors (Reactor 3, Reactor 4 and Reactor 6). Table 3 are the average values for the three measured reactors. Appendix V shows the deviated values. Below is how the deviated value was calculated.

The deviated value (mm) = Original value (mm) – Average value (mm)

From the results in Appendix IV, it can be seen that the maximum deviation is on the layer 3 of reactor 6 on February 3rd. For most of other results, the value is normally between 0.01-0.1. After that, the accuracy for all the data are also calculated in the way here and Appendix IV also presents the calculated deviated percentage.

The accuracy of datasets = The deviated value (mm) / Average value (mm)

From the calculated deviated percentage, it can be found that reactor 4 is more stable than other two reactors and the values are more reliable than other two reactors. The possible reason for that is the flow turbulence happened when taking the samples. Therefore, the calculated specific diameters are believed to have larger deviated values.

4.6.5 Conclusions

The calculated specific pellet diameters from the sieve analysis over different layers within two months can represent the real situation in softening reactors. The datasets in different time for reactor 3, reactor 4 and reactor 6 are reliable by the overall consideration even though there are larger deviations sometimes. These results will be used for validating the model in the next work.

5. Model validation

The model results were validated for the first month to verify the reliability of the Stimela model applied in Wim Mensink. The model validation work started with one single reactor and then the whole Wim Mensink water treatment system. For the softening reactors, fluidized bed height, total pressure drop, pellet diameters and porosities were validated. For the whole water treatment system, three water quality parameters with three different measured points were also validated The eight water quality parameters are calcium concentration, magnesium concentration, Temperature, pH, conductivity, bicarbonate concentration, saturation index and total hardness and three measuring locations are raw water, after weir aerator and final RO mixing points.

5.1 Measured results

The measured data for specific diameters of pellets over different layers for different reactors were analysed so that they could be compared with the results obtained from the model. Reactor 3, reactor 4 and reactor 6 were performed to see if the three reactors show the similar properties. Reactor 4 gave us the most stable condition. Figure 21 shows the measured results for reactor 4 from January 20th and figures for reactor 3 and reactor 6 are put in Appendix V. Figure 22 shows the result of measured fluidized bed height from January 28th to March 11th. The reason for the data missing on January 20th is that the flow turbulence severely influences the measuring work for fluidized bed height, so it starts on January 28th. For reactor 3, one data was missing at the last time because reactor is out of operation at that time. For reactor 6, the same thing happened on January 28th.

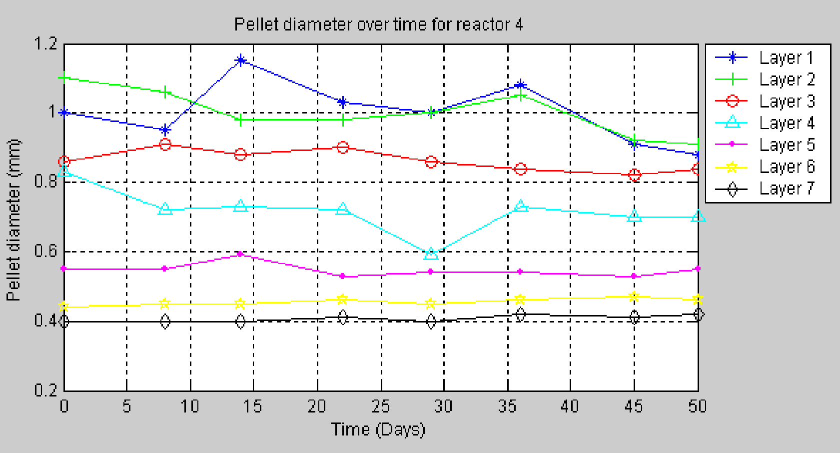


Figure 21: Pellet diameter over two months for reactor 4

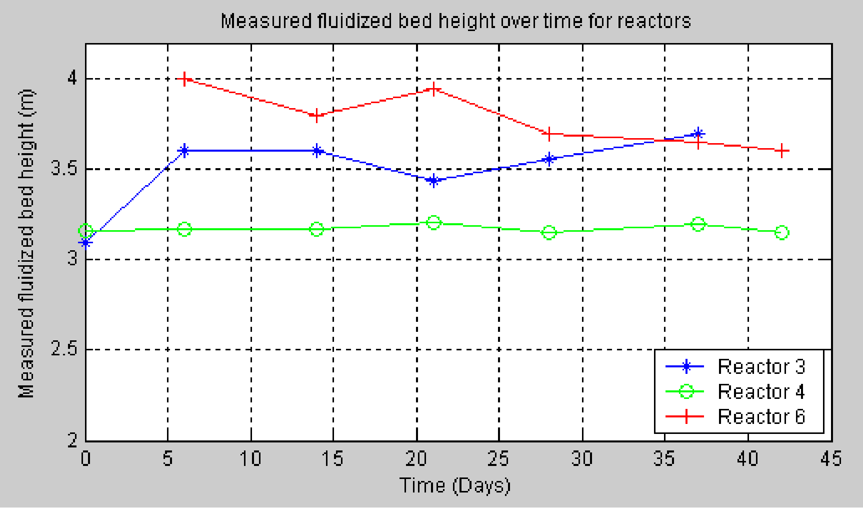


Figure 22: Measured fluidized bed height over two months for three reactors

From the results of the pellet diameters over different layers of the reactors, it can be seen that in low layers, pellet diameters do not always keep constant. This is because the sampling time is not always the exact time as pellet discharging, therefore, large variation of pellet diameters always happen at low layers. However, in higher layer from layer 5, the pellet diameters are constant over time.

In the figure of measured fluidized bed height, all the points plotted in the graph are either measured by online measurement device or in a manual way. If it was measured by two ways, then the results measured by online measurement device will be selected to plot on the graph because of its accuracy.

The results of measured fluidized bed height express that reactor 4 had a more constant height but lower than others and there is no data missing for it over two months.

5.2 Model validation with single reactor

The model validation started with reactor 4. The performed time for the validation work is one month from January 20th to February 20th, 2009. There are two locations which need to import the input values, which are the start 'invruw' block and 'pellet reactor' block.

Set-up of Stimela model

Before running the Wim Mensink model for validation work of reactor 4, some initial parameters were set for the pellet reactor. The input values include the flow and water quality parameters. Because the sampling time for the online measurement in Wim Mensink is 15 minutes, in the Stimela model, the maximum calculation step size is set as 15 * 60 second (15 minutes).

'Invruw' block setting

In the 'invruw' setting block, the flow and other water quality parameters are imported with variable values into the model. The time interval for the flow does not take 15 minutes sampling interval as recorded in Plenty report but take 2 hours. The reason for doing that is to keep a sufficient model running speed. The other water quality parameters are the laboratory measurements in raw water.

Pellet softening reactor setting

The completely mixed reactors are set as 7 layers so that it matches the layers on the experiment performed before. The crystallization constant and diffusion coefficient need to be adjusted to the calibrated values for 7 layers [Kim van Schagen, 2008]. The initial diameter of sand is 0.4 mm after long years' historical record in PWN [Monique Lampe, 2004].

The initial diameter per reactor will be the middle values of average pellet diameters in Table 4 between two layers and the relating porosities, number of grains and initial grain mass can be calculated afterwards.

To calculate the initial grain mass, the porosity needs to be calculated and Richardson-Zaki will be applied for this calculation. The temperature needs to be picked up to calculate the viscosity of the flow and the average temperature over these two months is chosen for the calculation, which is 11.7 °C. The design flow 490 m^3/h is used for this calculation as well.

After calculating the porosity, the number of initial grain mass can be calculated in equation 5.1 here:

$$N = VT * (1-p) * 6 / pi / (d_p\hat{}\ 3) \qquad \text{[Eq. 5.1]}$$

Where

N = Number of pellets in each layer (-)

VT = Volume in each layer (m^3)

p = Porosity in each layer (-)

d_p = Pellet diameter in each layer (m)

The height for each layer is 0.5 m, thus the volume of each layer is VT = A * L = 0.25 * 3.14 * 2.66^2 * 0.5 = 2.8 m^3.

Based on the calculating results of number of pellets for each layer, the total mass for each layer is determined by equation 5.2:

$T_{mass} = N / 6 * pi * d_g^3 * \rho_g$ [Eq. 5.2]

Where
T_{mass} = Total mass of grains in each layer (kg)
N = Number of pellets in each layer (-)
d_g = Diameter of grains (m)
ρ_g = Density of grains (kg/m^3)

According to the calculating steps, the pellet diameters, porosities, number of pellets and mass of grains for different layers are calculated for reactor 4 in Table 5. The results for other reactors are put in Appendix V:

Table 4: Calculated input for reactor 4

	Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	**Layer 7**
Pellet diameter (mm)	1.000	0.930	0.790	0.635	0.505	0.435	0.405
Porosity (-)	0.542	0.557	0.592	0.642	0.700	0.741	0.761
Mass of grains (kg)	220.0	264.6	397.4	670.8	1,118.5	1,511.6	1,723.9

Water control strategies setting

The water control strategy for the single softening reactor model is partly different than the one which applied on the whole water treatment system. The water flow will directly use the variable flow over time in 'invruw' block. The water control strategy for sand dosage and pellet discharge are the same as the whole water treatment system. The CO_2 dosage will be removed and the control strategy for dosage of NaOH will only use Equation 3.2 because the amount of NaOH does not need to be corrected for the case of single reactor. Moreover, the set point for the TH_{out} needs to be set so that the effluent total hardness of reactor can reach 1.3 mmol/l.

5.2.1 Model validation for reactor 4 in first month

The single model validation analysis is performed on reactor 4. The first month is performed from January 20th to February 20th. Figure 23 to Figure 25 are the validated results for fluidized bed height, pellet diameters and the calculated model results for total pressure drop, porosities over different layers

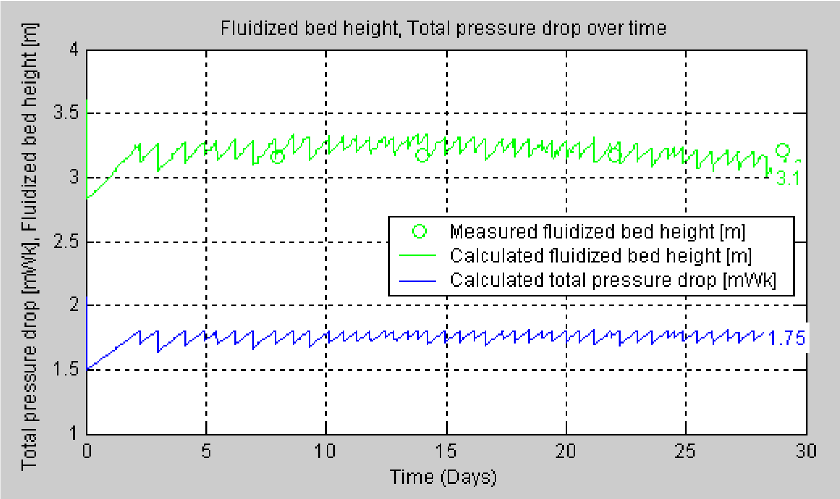


Figure 23: Validated fluidized bed height, calculated total pressure drop for reactor 4

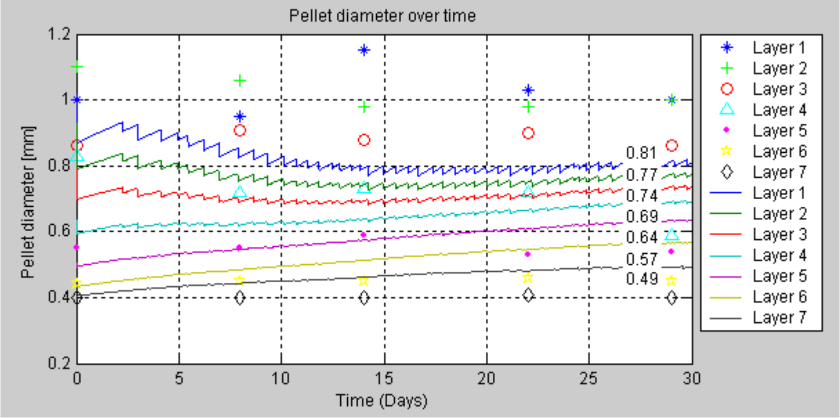


Figure 24: Validated pellet diameters of seven layers over first month for reactor 4

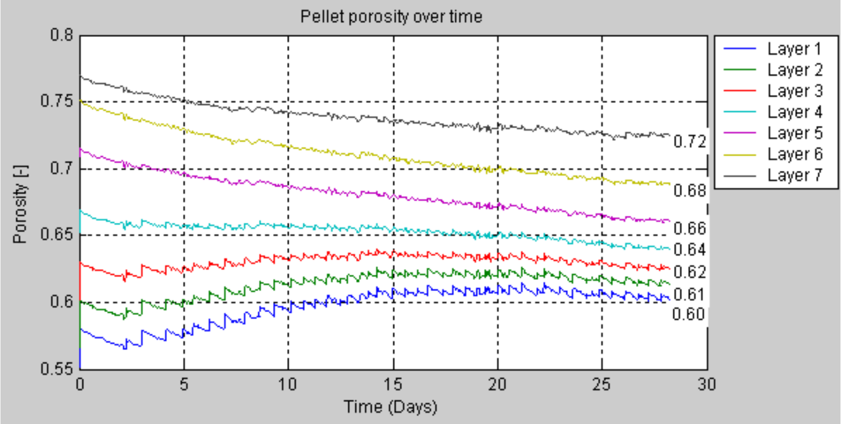


Figure 25: Calculated pellet porosities of seven layers over first month for reactor 4

The calculated model results for reactor 4 show that fluidized bed height under total pressure drop 1.80 mWc over reactor present good results. All the measured results over first month match calculated model results reasonably.

The pellet diameters and porosities over different layer also show good calculated model results. The scatters of the results mean the time for reactors discharging the pellets. After discharging the pellets each time, there will be a sharp pressure drop but it will return to the normal value until the next discharging time happens. One reason for deviations between model results and measured results is the difference between real operation of reactor in Wim Mensink and theoretical calculated model results. Another reason is the input of model values for pellet diameters are the average measured pellet diameters between two layers. However, compared with the calculated porosities from model and the input, fewer deviations happen. That means the model results for pellet diameters are still acceptable.

There is still an increasing trend and the results seem not to reach the stable condition. Therefore, the validation work of whole year for reactor 4 was performed to see if the model can reach the stable validated situation under the long time running.

The pellet softening reactor 4 run over the total year 2008 to validate the softening model results could reach a stable condition in the end. The superficial water velocity is presented here to compare with the results of fluidized bed height, pressure drop, pellet diameters and porosities. The figure of final effluent total hardness is also presented to prove it can still meet the requirements after a long time running.

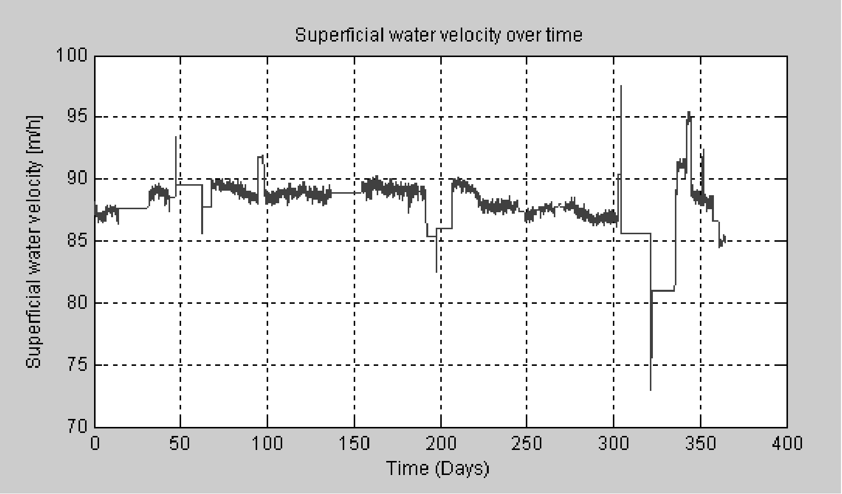


Figure 26: Superficial water velocity over year 2008 for reactor 4

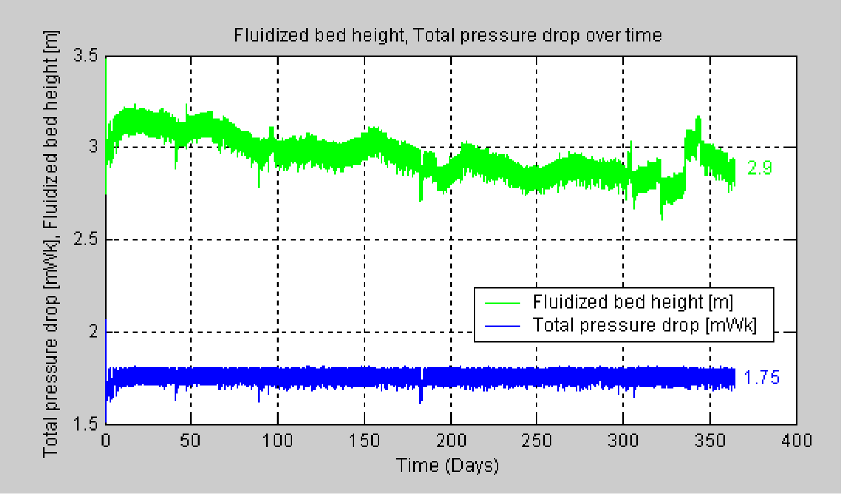


Figure 27: Calculated fluidized bed height, total pressure drop over year 2008 for reactor 4

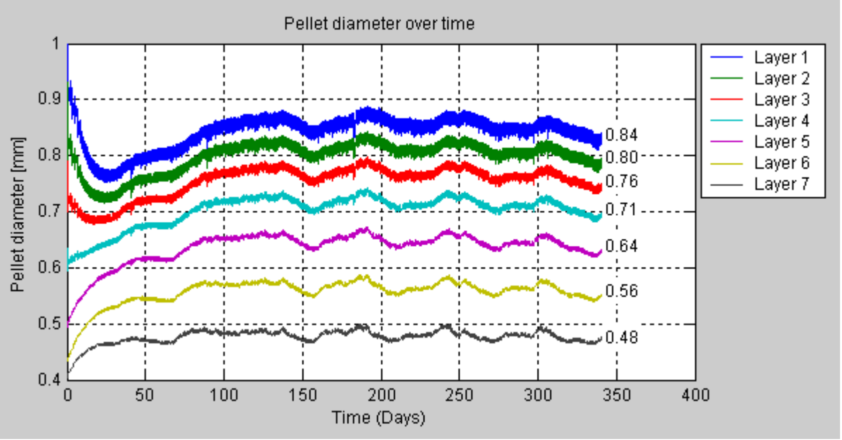


Figure 28: Calculated pellet diameters of seven layers over year 2008 for reactor 4

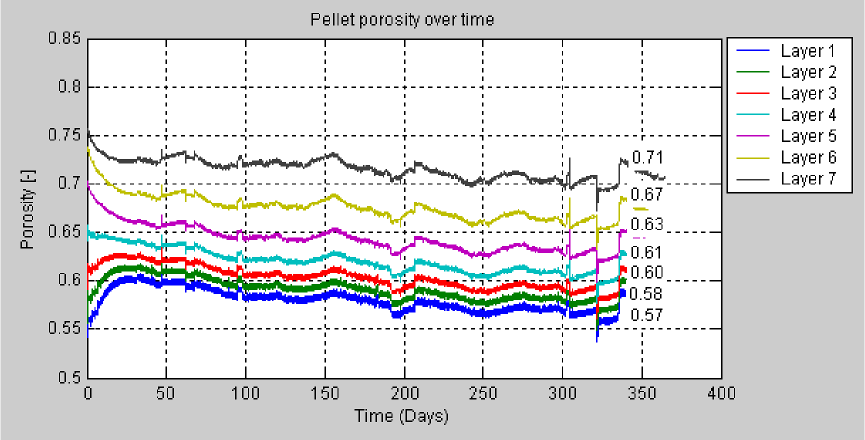


Figure 29: Calculated pellet porosities of seven layers over year 2008 for reactor 4

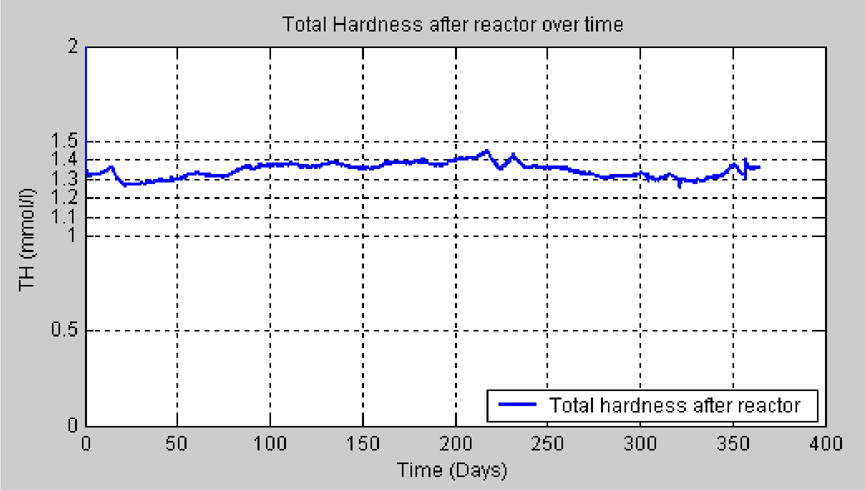


Figure 30: Total hardness in the effluent of reactor over year 2008 for reactor 4

From the figures above, it can be seen that the pellet diameters and porosities can reach the stable condition after long time running. The decreasing trend in the lower layer and increasing trend in the higher layer for pellet diameters and the opposite trends in porosities mean the model needs to reach a stable condition after a dynamic equilibrium calculation. The variation of calculated model results for fluidized bed height, total pressure drop and effluent total hardness changes with the variation of water flow. From the results of fluidized bed height, it can be seen that the condition of higher fluidized bed height happen on the winter time while the lower fluidized bed height occurs on the summer time because of the variation of water viscosity by the different temperature.

5.3 Model validation with whole water treatment system

After validating model results with single reactor, the whole water treatment system also needs to be validated so that the model can be proved reliable for Wim Mensink. The water flow for each reactor is set as 490 m^3/h and other water control strategies are the same as the ones in Wim Mensink. The validation work is divided into two parts at this stage. One is to validate the reactor when it is integrated into the complete system and another is to validate the eight water quality parameters for three laboratory measurements locations.

5.3.1 Model validation with single reactor

As is stated before for the single reactor validation, the same method is applied to the reactor when the whole water treatment system is performed. In this case, the bypass and recirculation condition is added into the system, the sodium hydroxide dosage control is based on the real situation but the flow has to be set with a fixed flow because of the limitations of the Stimela model. The fluidized bed height, total pressure drop, pellet diameters and porosities are plotted here as before.

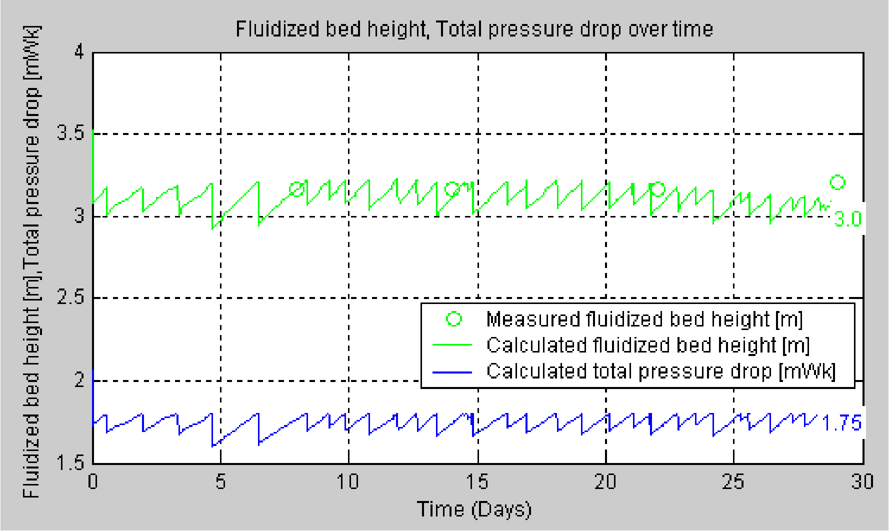


Figure 31: Validated fluidized bed height, calculated total pressure drop for reactor 4 in whole water treatment system

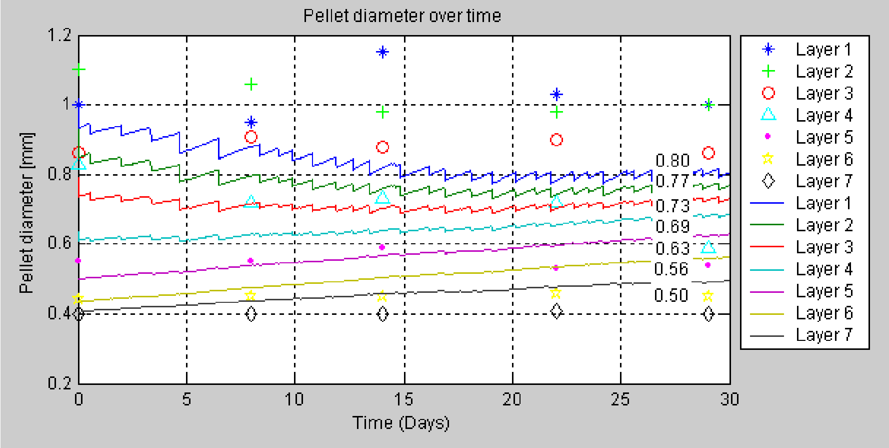


Figure 32: Validated pellet diameters of seven layers for reactor 4 in whole water treatment system

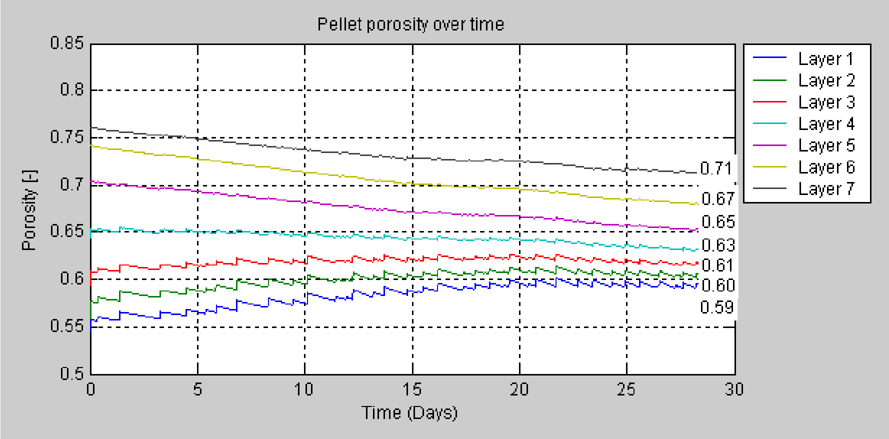


Figure 33: Calculated pellet porosities of seven layers for reactor 4 in whole water treatment system

From the presented results above, it can be seen the softening model can still reach up to a stable condition after 30 days running and the calculated model results are similar as presented before, which means the model can still be used in the whole water treatment system. The specific evaluation work can be performed afterwards to validate the effectiveness of the model results.

5.3.2 Model validation with water quality parameters

In this subchapter, three main water quality parameters are presented here to prove that the model can successfully validate the water quality parameters over two important locations with measured values derived from Plenty report. These three main water quality parameters are total hardness, bicarbonate concentration, and pH. The reason for choosing them is because that they are three important parameters to determine the water quality and part of them will still be used afterwards to evaluate the new possible water control strategies.

Total hardness

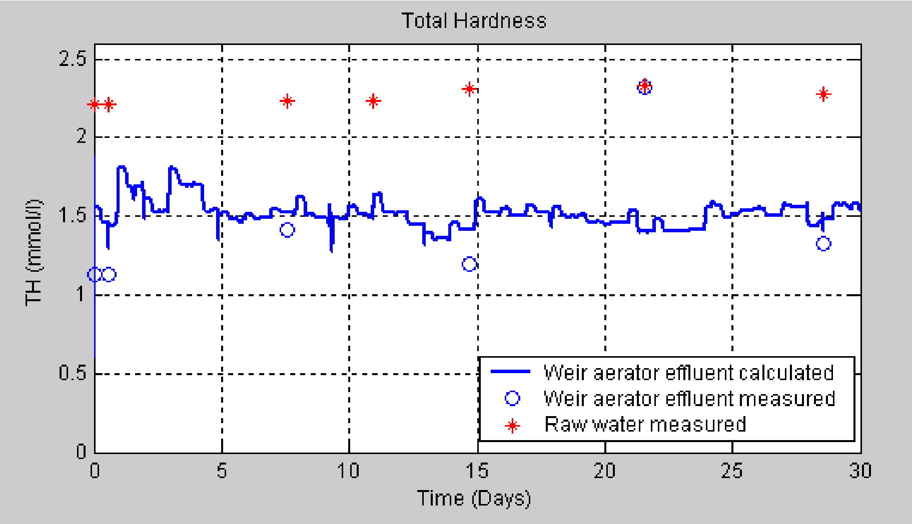


Figure 34: Validated total hardness after weir aerator for first month

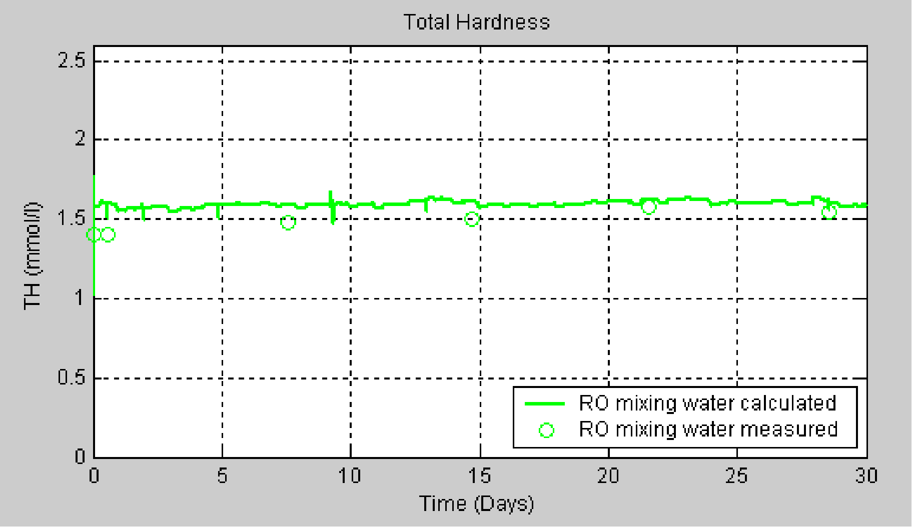


Figure 35: Validated total hardness after RO mixing for first month

The lines are the calculated model results and the stars are laboratory measurements. From the comparison of the model results and measured results, it can be concluded that the calculated model results of two locations for total hardness match reasonably with the measured results. There is one measured error in the weir aerator effluent, where the measured result is larger than others. The graph of RO mixed water shows better validated results than the weir aerator effluent because the measurements are more stable. Another reason is that the recirculation flow after the reactors will influence the variation of water quality; however, after mixing with the flow in filter building 2 and RO flow in Heemskerk I, the extent of the variation will be less.

Bicarbonate concentration

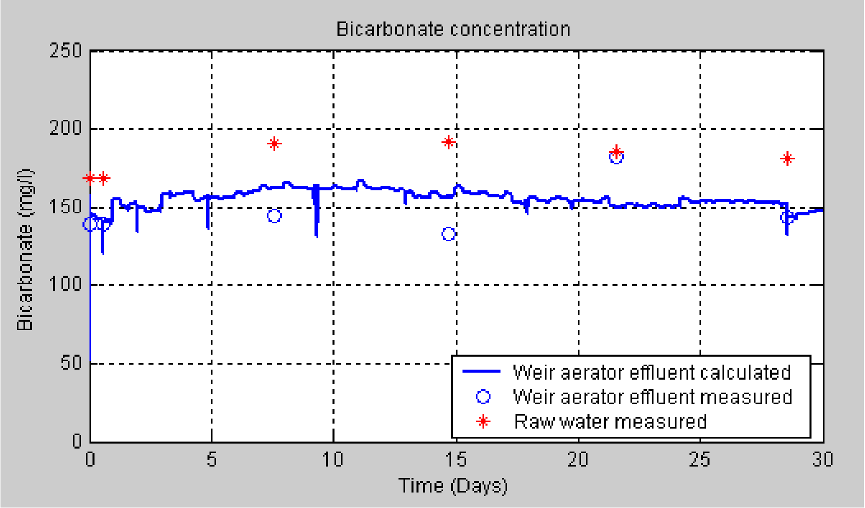


Figure 36: Validated bicarbonate concentration after weir aerator for first month

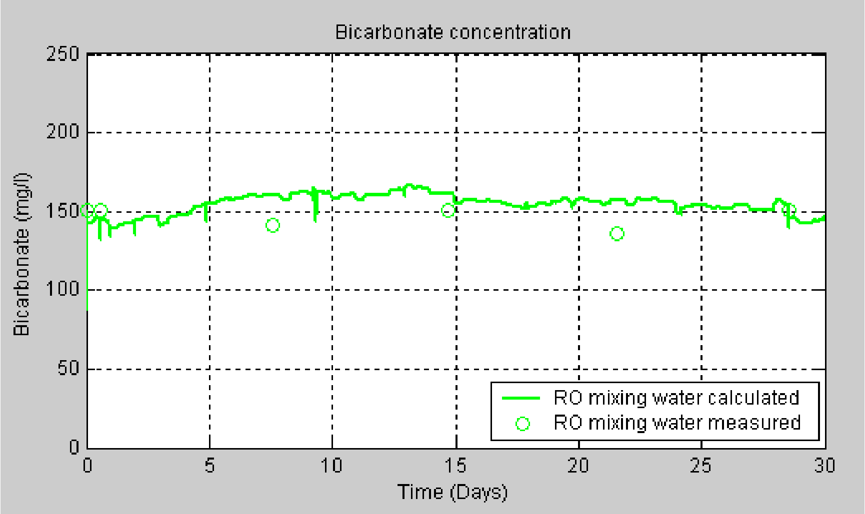


Figure 37: Validated bicarbonate concentration after RO mixing for first month

The conclusion of the validation for bicarbonate concentration is the same as for total hardness presented before. The measurement error occurs again, which proves that there must be a sampling measuring error at that time.

pH

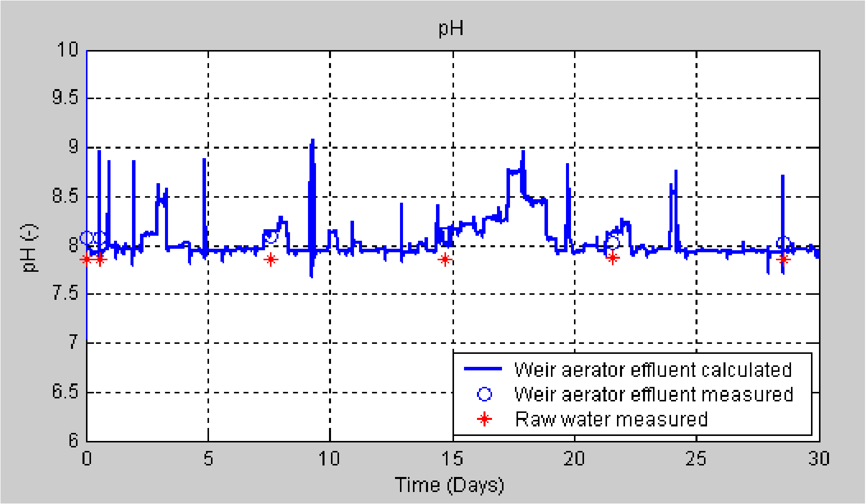


Figure 38: Validated pH after weir aerator for first month

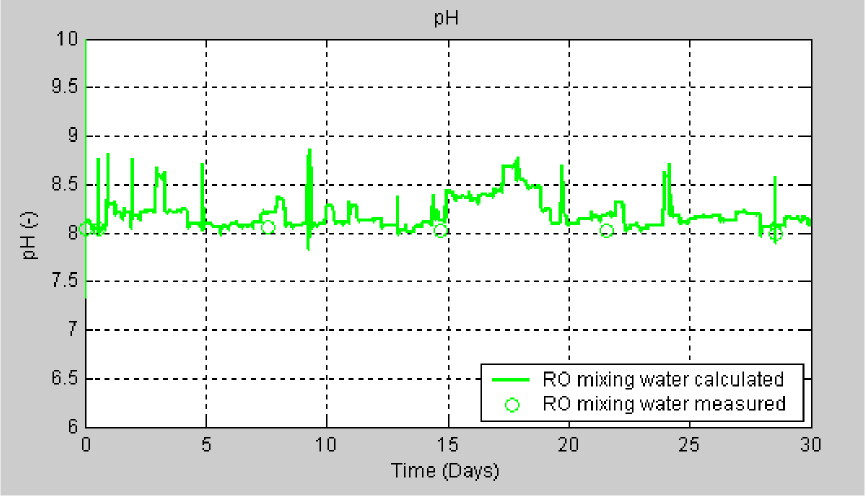


Figure 39: Validated pH after RO mixing for first month

Large variation of model results happens on the pH value because the influence of recirculation flow is higher on pH than on the other two parameters. The recirculation flow will lead higher dosage of sodium hydroxide than the real needs because part of the water is softened again and the calculation of sodium hydroxide is based on the total flow in filter building 1. The excessive sodium hydroxide will bring a higher value of pH. The rising lines are the time points when one reactor is switched off and recirculation flow occurs. It brings a sharp change in the model calculation despite it will not directly influence on the water quality in the real situation.

The reason for slight larger model results than measured results for pH and bicarbonate concentration is the amount of CO_2 dosage in model may less than the real dosage because of the master control and slave control are separated in the real situation, which may lead a more accurate dosing control than the model.

5.4 Evaluation of validated results

5.4.1 Method

After validating the model results, the model results need to be used to compare with the measured results so that model results can be proved reliable. Normally, the simulation results should be at about 10% accuracy [Kim van Schagen, 2008], but it can still be larger according to the actual needs. The specific method used to evaluate the deviation is to use the relative error ((data – model) / data).

Relative error = ((data – model) / data) [Eq. 5.3]

For the model results of fluidized bed height, pressure drop over total height of the reactor and the pellet diameters, porosities over different layers, the relative error method is used to evaluate the results because the pellet discharging time may happen at the same time with the sampling time of the measured results and it will influence on the evaluation of the results. The final simulated model results will be used to compare with the average measured results over two months.

5.4.2 Single reactor validation

With the relative error method, the evaluation of the validated results for the fluidized bed height and total pressure drop for first month is made in Table 5 here. The validation work for the year 2008 is shown in Table 6. In these tables, FH_M is the average measured results and FH_S is the simulated results for the fluidized bed height. PD_M and PD_S are the measured results and simulated results for total pressure drop. The measured results are obtained in Appendix III and the model results are the last calculated model results in the figures shown before. The validation work will be performed for two months and for the total year of 2008. The positive values for the relative error are shown here.

Table 5: Relative error of fluidized bed height and pressure drop for single reactor in first month

	FH_M (m)	**FH_S (m)**	**Relative error (-)**	**PD_M (mWk)**	**PD_S (mWk)**	**Relative error (-)**
Reactor 4	3.17	3.10	0.022	1.80	1.79	0.006

Table 6: Relative error of fluidized bed height and pressure drop for single reactor in year 2008

	FH_M (m)	**FH_S (m)**	**Relative error (-)**	**PD_M (mWk)**	**PD_S (mWk)**	**Relative error (-)**
Reactor 4	3.17	2.90	0.085	1.80	1.75	0.028

With the same method, the pellet diameters and porosities over reactor 4 are presented in Table 7 and Table 8. In these tables, D_M and P_M are the measured pellet diameters and porosities. D1_S is the simulated model results of pellet diameters for first month and D2_S is the simulated model results of pellet diameters for whole year. P1_S is the simulated model results of pellet diameters for first month and P2_S is the simulated model results of pellet diameters for whole year.

Table 7: Relative error of pellet diameters for reactor 4 over first month and year 2008

	D_M (mm)	**D1_S (mm)**	**Relative error 1 (-)**	**D2_S (mm)**	**Relative error 2 (-)**
Layer 1	1.000	0.820	0.180	0.840	0.160
Layer 2	0.930	0.780	0.161	0.800	0.140
Layer 3	0.790	0.740	0.063	0.760	0.038
Layer 4	0.635	0.700	0.102	0.710	0.118
Layer 5	0.505	0.640	0.267	0.640	0.267
Layer 6	0.435	0.570	0.310	0.560	0.287
Layer 7	0.405	0.500	0.235	0.480	0.185

Table 8: Relative error of porosities for reactor 4 over first month and year 2008

	P_M (mm)	P1_S (mm)	Relative error 1 (-)	P2_S (mm)	Relative error 2 (-)
Layer 1	0.542	0.600	0.107	0.570	0.052
Layer 2	0.557	0.610	0.095	0.580	0.041
Layer 3	0.592	0.620	0.047	0.600	0.014
Layer 4	0.642	0.630	0.019	0.610	0.050
Layer 5	0.700	0.650	0.071	0.630	0.100
Layer 6	0.740	0.680	0.081	0.670	0.095
Layer 7	0.761	0.720	0.054	0.710	0.067

All the results for the fluidized bed height, total pressure drop and porosities meet the requirements of evaluation standards. However, most of the results for the pellet diameters are higher than this standard. The reason for that is that the pellets over different layers are sampled manually and the average values are selected as the measured value, which may lead to a larger deviation. However, the model is still reliable because the relative errors for porosities are still in the appropriate range, which means that larger deviations of pellet diameters are still acceptable.

5.4.3 The whole system validation

After the validation work for the single reactor, it needs to be performed for the whole water treatment system for Wim Mensink. Firstly, the softening pellet reactor will be validated to see if it can still keep the good performance with the water control strategy for the whole system. Reactor is the performance for first month.

Table 9: Relative error of fluidized bed height and pressure drop for reactor over first month

	FH_M (m)	FH_S (m)	Relative error (-)	PD_M (mWk)	PD_S (mWk)	Relative error (-)
Reactor	3.17	3.10	0.022	1.80	1.79	0.006

Table 10: Relative error of pellet diameters for reactor over first month

	D_M (mm)	D_S (mm)	Relative error (-)
Layer 1	0.775	0.810	0.045
Layer 2	0.675	0.770	0.141
Layer 3	0.585	0.730	0.248
Layer 4	0.525	0.690	0.314
Layer 5	0.450	0.630	0.400
Layer 6	0.410	0.560	0.366
Layer 7	0.400	0.490	0.225

Table 11: Relative error of porosities for reactor over first month

	P_M (mm)	P_S (mm)	Relative error (-)
Layer 1	0.596	0.590	0.010
Layer 2	0.628	0.600	0.045
Layer 3	0.662	0.610	0.079
Layer 4	0.690	0.630	0.087
Layer 5	0.731	0.650	0.111
Layer 6	0.758	0.670	0.116
Layer 7	0.765	0.710	0.072

As is discussed before, the same conclusions are for the validation of reactors in the whole treatment system, which means the reactor can still operate in a good situation under the whole treatment system validation.

5.5 Discussions and conclusions

The validation process consists of two parts. One is the softening pellet reactor validation and another is the water quality parameter validation in two different locations (after weir aerator location and final RO mixing location). For the softening pellet reactor validation, firstly a single reactor was validated and afterwards the whole treatment system. The validation period chosen was the month from January 20th to February 20th because the experiments of sieve analysis were performed during this month as well. In this way, the measured pellet diameters over different layers will be used to compare with the calculated model results. The validation work for the single reactor was performed with three reactors because a complete dataset could be obtained for these three reactors. The calculated model results for year 2008 was also applied for the single reactor validation to check if the model can show the stable validation results over long time and if temperature has influence on the model results over different period. For the water quality parameters validation, two locations (after weir aerator location and final RO mixing location) were validated with measured results for two months of data so that the water control strategies could be validated efficiently in Stimela model as well.

From the results of relative error, most of the results were around 10% accuracy but only the pellet diameters were higher than that percentage. However, the calculated porosities based on the calculated results of pellet diameters after that prove that higher deviations of pellet diameters were still acceptable and proved the effectiveness of model results. For the validation of the water quality parameters, the model results presented the reasonable trends with the measured results. However, some measured inaccuracies happen on the measured results.

In summary, the validation process proved that the Stimela model is reliable and robust to predict the results Also, it can be used to evaluate alternative control strategies.

6. Evaluation of water control strategies

In this chapter five water control strategies are defined and compared using the Stimela water quality model. Different combinations of these five water control strategies are also presented to obtain the optimal control strategies. Based on the validation work illustrated in Chapter 5, Stimela model can be seen as a reliable and stable tool to predict the future possible changes and it is used as the tool for the evaluation of the alternatives.
For the ranking of the control strategies the key performance indicators in Table 1 are used. To set up the alternative control strategies, first the effects of five water control strategies are explored. After that, another six water control strategies developed by Kim van Schagen and Jasper Wuister are evaluated.

6.1 Reference situation

To determine the effects of the individual control rules a reference dataset of input data for the Stimela model was determined. For this the dataset reference situation is defined, existing of historic data from January 20th to February 20th was selected. The data is considered to be representative because realistic changes in water quantity and water quality occur. The dataset is used to judge if an individual control rule could contribute significantly to an alternative control strategy. In evaluation of the water quality, bicarbonate concentration will not be used any more because good results of pH can represent the good ones of bicarbonate concentration and it has been validated in Chapter 5 before. So for comparison of the water quality parameters, Figure 35 and Figure 39 are selected as the reference figures.

6.2 Effects of individual improvements

To set up alternative water control strategies, first the effects of individual improvements on the key performance indicators were evaluated. Each of these five water control strategies has its unique objective. In the specific work, five water control strategies are independent and they can be integrated as a whole. Different combinations of these five water control strategies can be applied in the real situation.

6.2.1 Water control strategy 1

Objective: Maximal usage the RO water discharged into the dune area

In the drinking water treatment plant Wim Mensink, around 5% of the RO water from Heemskerk is discharged into the dune areas and it is always better to use this part of water as much as possible. The RO water produced by Heemskerk will be mixed with less amount of clean water from clear water reservoir to adjust the SI firstly and then flow to Bergen and Wim Mensink. In this way, 5% of the RO water is discharged into the dune.

Implementation in Stimela model

In this new water control strategy, the Stimela model uses the flow in this way:
Input RO flow = Total RO flow in Heemskerk + Less clean water flow to adjust SI – Total RO flow in Bergen.
The total inflow of filter building 1 plus filter building 2 still keep the same amount of water flow. The results in Figure 40 and Figure 41 present the final total hardness and pH after RO mixing location can still reach the final clean water standard. The situation does not change so much compared with Figure 35 and Figure 39 in reference situation.

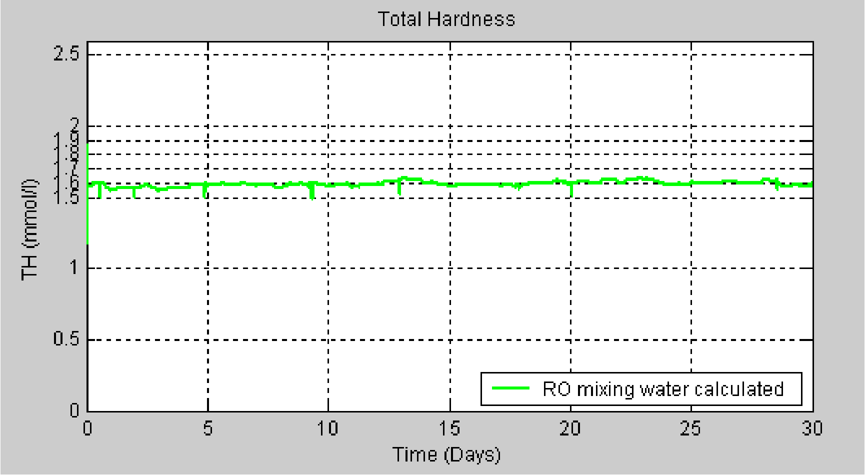


Figure 40: New total hardness after maximal mixing RO water

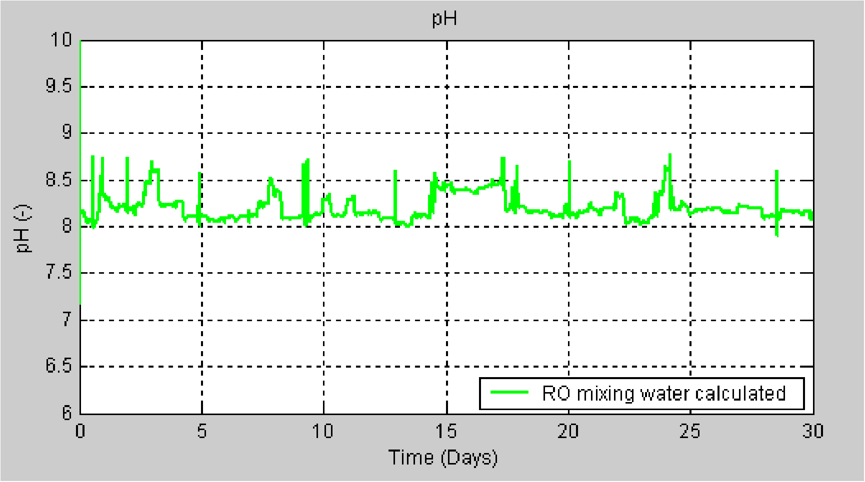


Figure 41: New pH after maximal mixing RO water

The RO water from Heemskerk could be fully used. With the same total amount of supplying water of filter building 1 and filter building 2 in Wim Mensink, the extra increase of mixing of RO water to Heemskerk does not influence the final total hardness and pH much and the quality standards for drinking water can be met. The model results only provide the theoretical possibilities for the maximal usage of RO discharging water but the current water control system may not fully achieve the zero discharge of RO water to the dune area because of the limitations of the operation for RO membrane modules. Different combinations of membrane modules may be applied to fit the new situation.

6.1.2 Water control strategy 2

Objective: Maximal increase of the fluidized bed height of the pellet softening reactor

The actual fluidized bed height is between 3 m and 3.5 m above the reactor bottom. The weir of the collection canal is at 5.2 m above the reactor bottom. Increasing the bed height will lead to an increase of the available crystallization surface in the reactor and less over saturation in the reactor's effluent.

Implementation in Stimela model

Currently, the fluidized bed height is around 3.0 m based on the model results in Figure 31 and the pellet diameter is around 0.80 mm based on the model results in Figure 32. When changing the pressure drop over complete bed to discharge the pellets from 1.80 mWc to 2.60 mWc, the maximal fluidized bed height can even reach up to 4.50 m and the discharged pellet diameter increases to 0.90 mm, which means the pellet can be further fully used and it also leads to less remaining of NaOH after pellet reactors under the same amount of NaOH dosage. Therefore, less CO_2 will be dosed before aeration process, which is presented in Figure 45 and Figure 46. The porosities over different layer is similar compared with the reference situation, which means the pellets will not clog the reactor or stick together and the reactors can keep in normal operation.

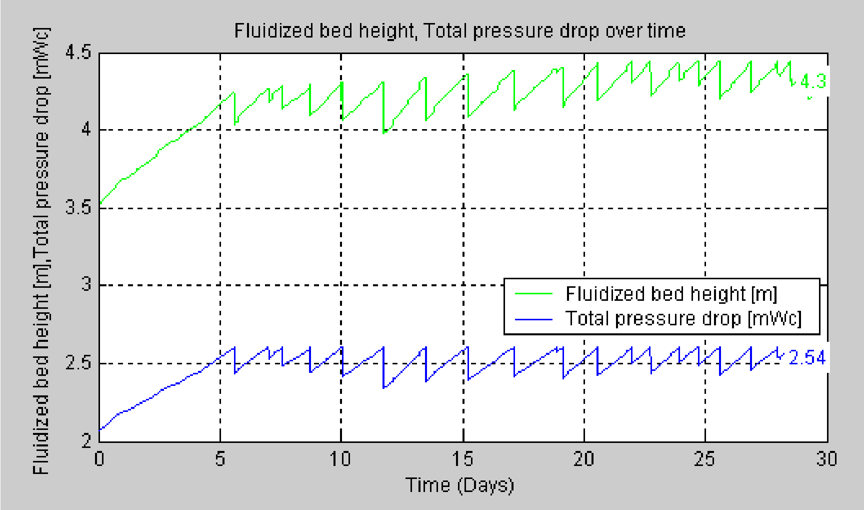


Figure 42: Improved fluidized bed height, total pressure drop

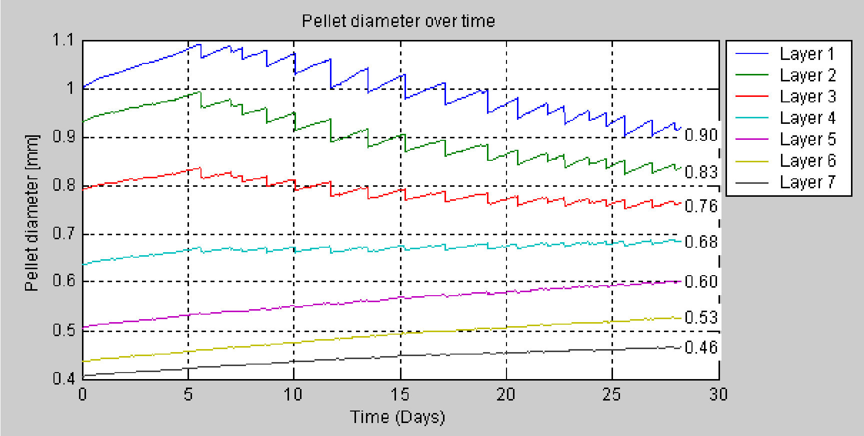


Figure 43: Improved pellet diameters of seven layers

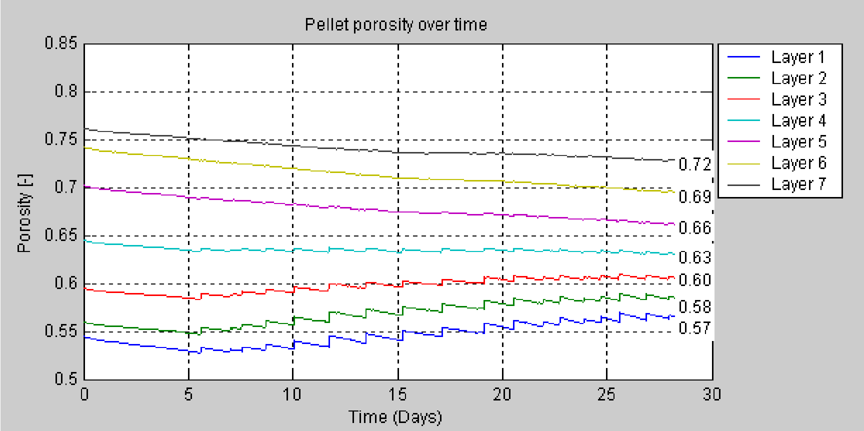


Figure 44: Improved pellet porosities of seven layers

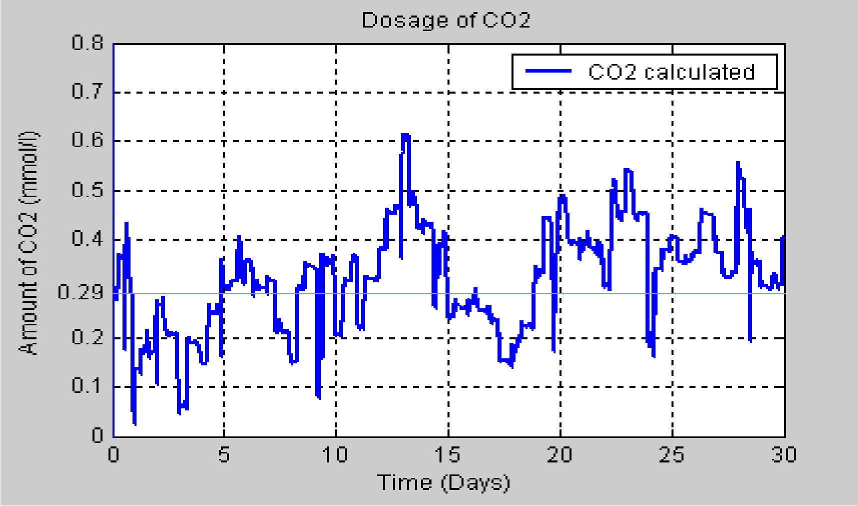


Figure 45: Original dosage of CO2

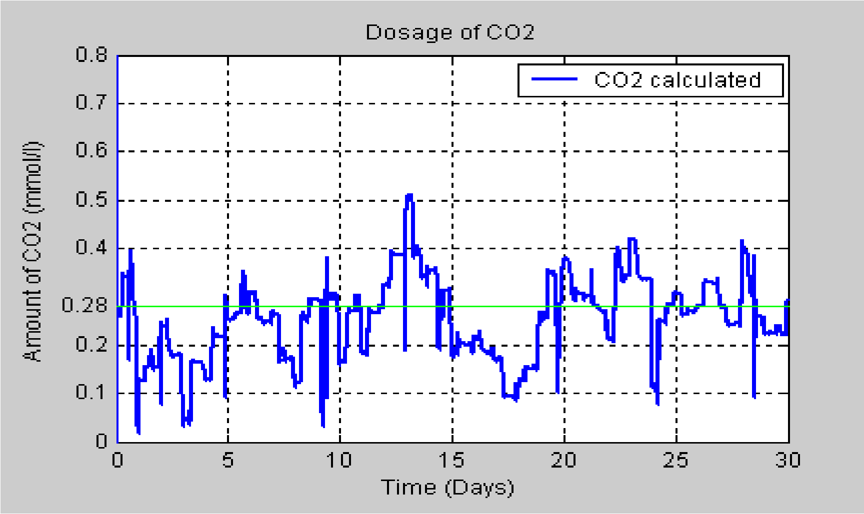


Figure 46: Improved dosage of CO2

By changing the required pressure drop to discharge the pellets, the height of the fluidized bed could be further increased so that more sodium hydroxide could react with calcium ions in raw water and it leads to less consumption of CO_2 in the next step for neutralizing the excess amount of sodium hydroxide in the water. It can be easily found in Figure 45 and Figure 46 by comparison of the graphs for original dosage of CO_2 and improved dosage of CO_2. The total dosing amount of CO_2 decreases from the average value 0.29 mmol/l to 0.28 mmol/l. Besides that, the pellets will be discharged in a less frequency than before while keeping a large allowable pellet diameter, which means the pellet can be further used to form a larger diameter. Therefore, the costs for dosing the CO_2 and sand can be saved.

A risk of increasing the fluidized bed height is the discharge of river sand when the flow suddenly increases or viscosity increases. In different seasons, the viscosity of the water is different over the variation of temperature, which leads to different fluidized bed height over different months and may lead the overflow of fluidized bed.

6.1.3 Water control strategy 3

Objective: Cost saving for caustic soda and carbon dioxide

This water control strategy is developed to see if there are still some potentials in saving caustic soda and carbon dioxide by changing caustic soda dosage system. The water quality should still meet the requirements of the key performance indicators. The work is performed on the water control of dosing caustic soda.

Implementation in Stimela model

In the current water control strategy, the dosing amount of caustic soda consists of master control and slave control. The amount of caustic soda dosage is determined by the total flow in filter building 1 and it is replaced by flow for each reactor to achieve more accurate caustic soda dosage control. In the model, the flow is set as 490 m^3/h for each reactor. In the real situation, it will be determined by the Plenty tag for each reactor.

The slave control is a feedback control for the whole water treatment system. It was cancelled to reach the possible minimal caustic soda dosage. From Figure 50 and Figure 51, it can be seen the total hardness and pH in clear water reservoir can still meet the requirements under this condition.

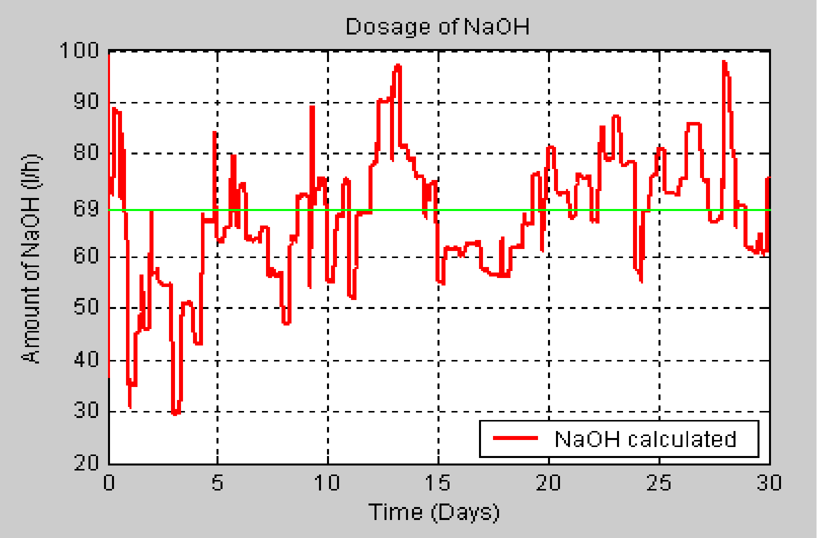


Figure 47: Original dosage of NaOH

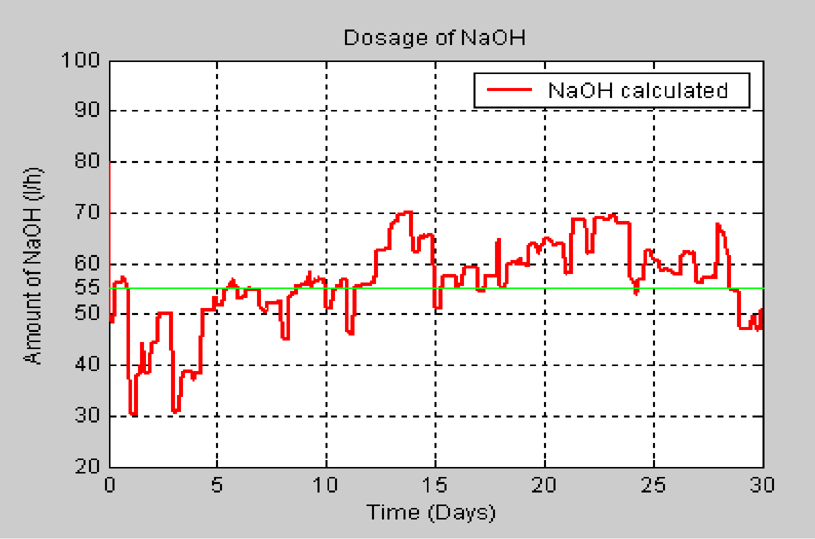


Figure 48: Improved dosage of NaOH

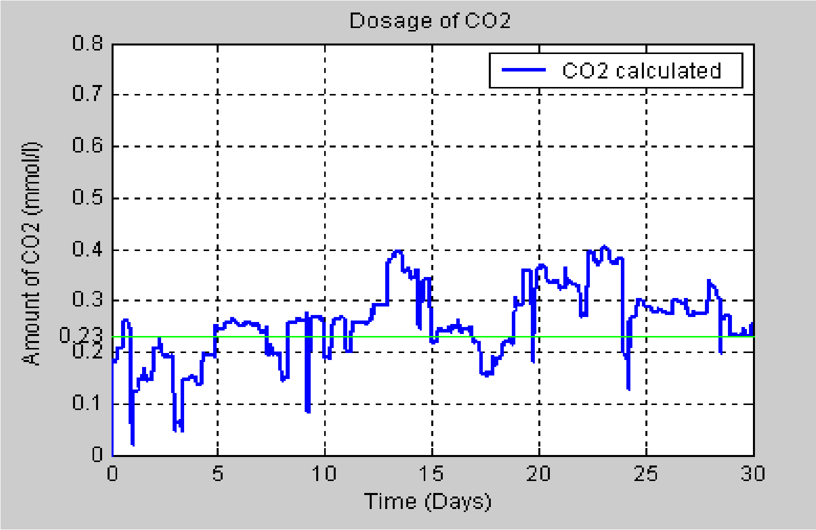


Figure 49: Improved dosage of CO2

From Figure 47 and Figure 48, it can be seen that the dosing amount of caustic soda has been reduced significantly from the average value 69 l/h to 55 l/h. As a consequence of the elimination of the caustic soda dosage slave control, Figure 49 proves that the dosing amount of CO_2 can be reduced to an average value 0.23 mmol/l with a more stable dosage compared with Figure 45. After that, the water quality parameters in the clear water reservoir also need to be checked to see if they still meet the requirements of the key performance indicators.

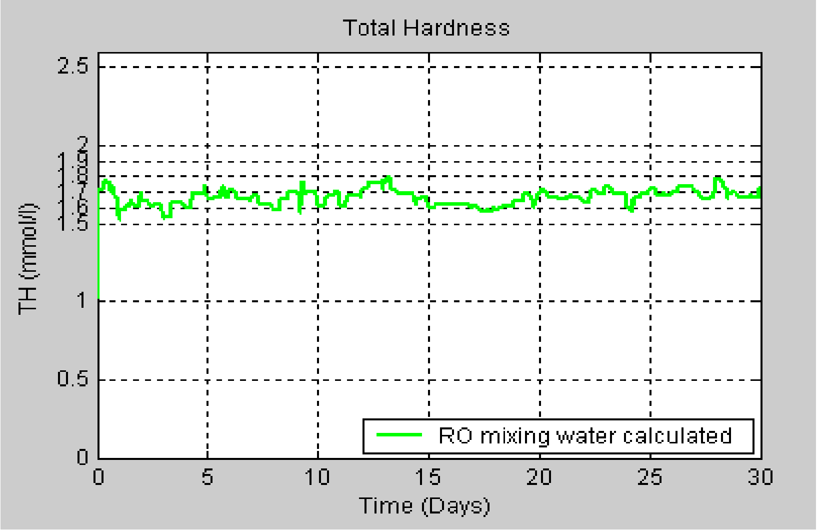


Figure 50: Improved total hardness after RO mixing

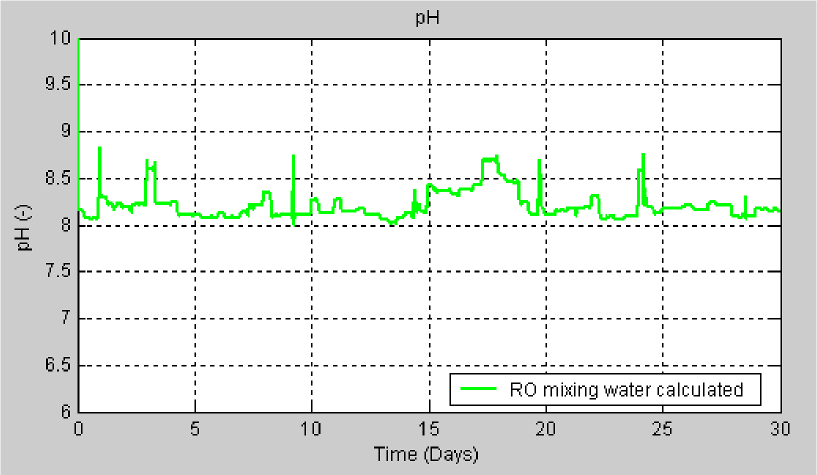


Figure 51: Improved pH after RO mixing

From the calculated model results of water control strategy 3, it can be seen from Figure 50 that final total hardness can still reach the requirements. Figure 51 shows less sharp scatters for pH happen and the model shows a more stable trend, which means the effect of water quality parameters have been improved by this step. The reason for that is less amount of caustic soda is dosed into the reactors and bypass can play the role as a buffer before dosing CO_2. The existing scatters are caused by the recirculation flow because it will cause more dosing of sodium hydroxide. The calculation of CO_2 is based on the actual needs of neutralizing excessive sodium hydroxide for each reactor. In this case, less CO_2 will be dosed into the system and it leads to a more stable operation.

In this water control strategy, the feedback control is cancelled which may lead to higher total hardness between desired one and realized one. Another problem is the setpoint flow for each reactor in the master control command. In the real operational system, it must be determined by the online flow measurements of each reactor. This may lead the real control situation less robust.

6.1.4 Water control strategy 4

Objective: Elimination of recirculation flow in filter building 1

From hydraulic perspective, the recirculation flow within filter building 1 must be investigated and it should be avoided. Small deviations in the water flow extracted by the softening reactors or an unexpected shut down or startup of a reactor can be without risk of water hammer or cavitations. From the chemical perspective, the total hardness of the influent of the reactors decreases when the recirculation flow occurs and it contains sodium hydroxide in the influent. The actual calculation of the sodium hydroxide dosage is based on the total hardness in raw water and effluent water after reactors. Therefore, it will lead to more caustic soda dosage than the expected amount. The dosing amount of carbon dioxide can not fully neutralize the existing amount of caustic soda and it will lead the oversaturation and higher pH after weir aerator.

Implementation in Stimela model

The flow to determine the reactors switched on or off must be larger than the multiple integer flow of reactors. Otherwise, it will cause the recirculation flow. In water control strategy 4, all the flow is set as the integer flow of reactors and the final results show that the problem of the scatters have been removed while the final water quality can still meet the key performance indicators in Table 1. The only scatter happens close to the 30 days because the shortage of laboratory measurements after that time. The model needs to calculate the results again so that it causes the reset of the model.
Reactors switched on and off with the following amounts:
- 490; 980; 1,470; 1,960; 2,450 and 2,940 m^3/h

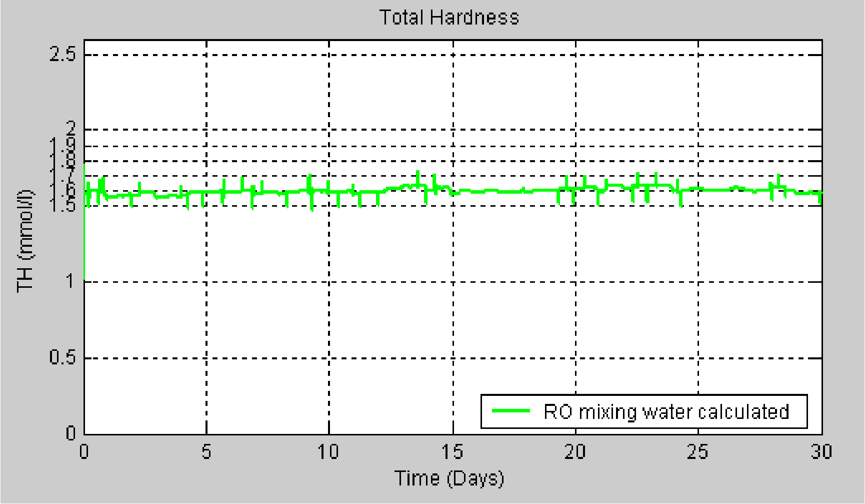


Figure 52: Improved total hardness after RO mixing

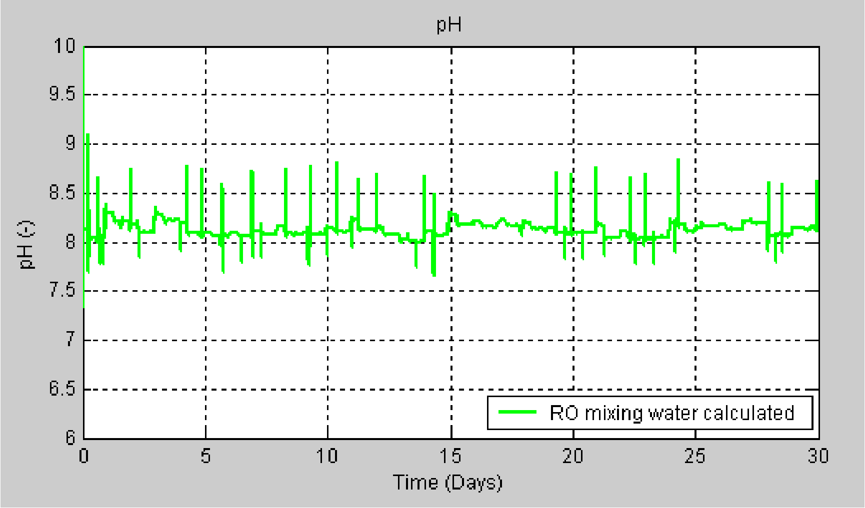


Figure 53: Improved pH after RO mixing

The integral multiple of reactor flow to determine the reactors switched on and off will avoid the recirculation flow in the system so that the stable values of water quality parameters can be reached. Also, it strengthens the role of bypass flow and it will have a positive influence on the costs of sodium hydroxide.
From Figure 52 and Figure 53, it can be seen that scatters happen when reactors switch on or off and it should be avoided. This water control strategy only provides the method to avoid the recirculation flow in the real system but not illustrates clearly what will be the maximal bypass flow the whole treatment. It will be elaborated more in the next water control strategy 5.

6.1.5 Water control strategy 5

Objective: Searching for the theoretical maximal bypass flow in filter building 1

The task of this water control strategy is to use the bypass flow as maximal as possible to compensate the final CO_2 dosage to see if it can be totally shut down and save the energy costs for switching on the new reactors. The limitation conditions are the final water qualities.

Implementation in Stimela model

The maximal flow in one street is 3,600 m^3/h on the basis of maximal treatment capacities of rapid sand filters (Jasper Wuister, Kim van Schagen, 2009). Therefore, when the flow reaches up to 3,600 m^3/h, the sixth reactor is switched on and the theoretical maximal bypass flow can be found. In this case, the maximal bypass flow can be calculated in this way:
Assuming the bypass flow is x m^3/h, thus x + 490 m^3/h * 5 = 3600 m^3/h, x = 1150 m^3/h.
Reactors switched on and off with the following amounts:
- 1,150; 1,640; 2,130; 2,620; 3,110 and 3,600 m^3/h

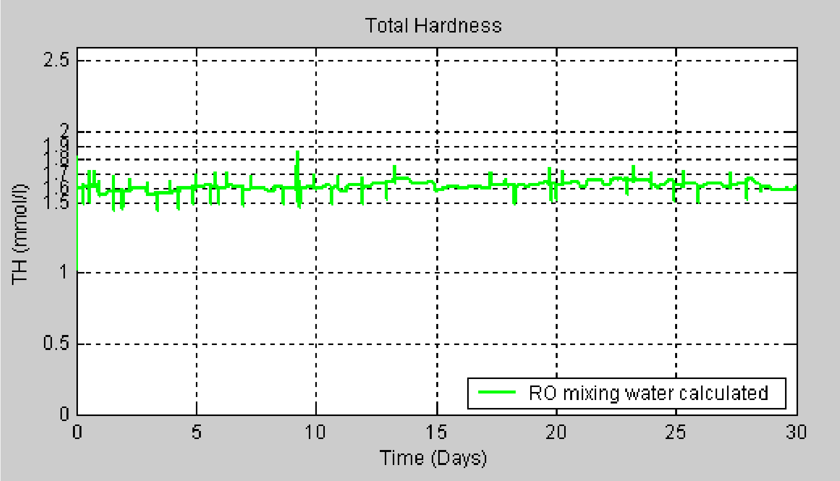


Figure 54: Total hardness after RO mixing under theoretical maximal bypass flow

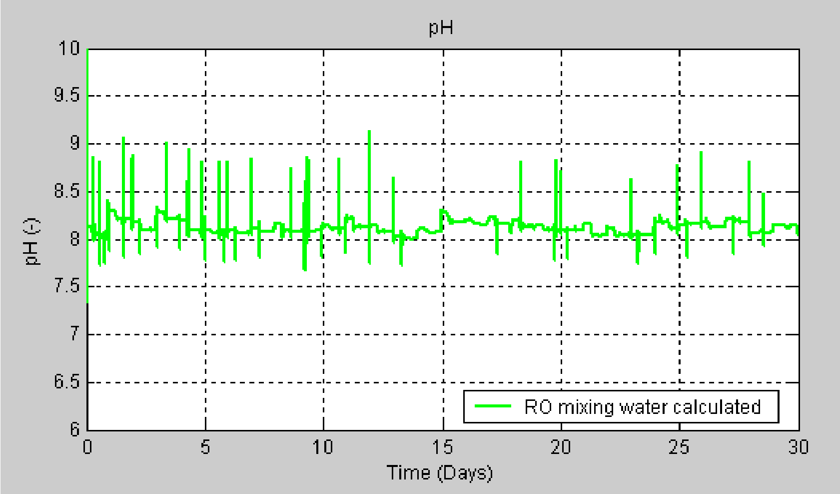


Figure 55: Improved pH after RO mixing under theoretical maximal bypass flow

The results show that the total hardness and pH can give the satisfactory results under this extremely condition. However, the dosing of carbon dioxide can not be cancelled in the end and the case with maximal bypass flow is recommended as the optimal plan.

In this water control strategy, the theoretical maximal bypass flow is found. The theoretical one gives out an upper value for the possible maximal bypass flow as a recommendable maximal bypass flow for the application in future.
Despite that the applicable maximal flow is 1,150 m^3/h and the final water quality can still satisfy the water quality standards, the exact true value to fit the real operational situation in the long year running still needs to be further searched in the real operational system because of the possible any disturbances in reality and the existing discrepancies between model and the real control environment.

6.2 Evaluation of other water control strategies

6.2.1 Other water control strategies

In the report 'Flexibiliseren ontharding PS Mensink – Procesbesturing', six other control strategies are also developed based on minimal usage of reactors and keeping reactors running as long as possible so that the robustness of the process from switching on reactors and numbers of switching on/off reactors can be improved. These control strategies are (Jasper Wuister, Kim van Schagen, 2009):

Table 12: Six other water control strategies

Name	Strategy	Desired effect
A. Min	Minimal possible reactors in operation, but always with minimal RO overflow	Minimal RO overflow; Minimal caustic soda dosage
B. Hold	As long as possible the same reactors in operation, until extra RO must be overflowed or total hardness can not be reached	Minimal RO overflow; Minimal number of switched on/off reactors
C. 2 & Min	Minimal possible reactors in operation, but always with minimal 2 reactors to prevent excessive reactors switched on/off	Reducing the number of switched on/off reactors
D. 2 & Hold	As long as possible the same reactors in operation, but always with minimal 2 reactors to prevent excessive reactors switched on/off	Reducing the number of switched on/off reactors
E. 3 & Hold	As long as possible the same reactors in operation, but always with minimal 3 reactors	Reducing the number of switched on/off reactors
F. 4 & Hold	As long as possible the same reactors in operation, but always with minimal 4 reactors	Reducing the number of switched on/off reactors

The main work in this subchapter is to run the Stimela model to see if the water quality can still meet the requirements under those water control strategies and see if stable model results can be reached. The advantages and limitations of these six water control strategies are presented in the report 'Flexibiliseren ontharding PS Mensink – Procesbesturing'. The validation work is based on the combinations of water control strategies 1+2+3+5 to see the comprehensive effects and the maximal bypass flow is analysed as the extreme situation here.

6.2.2 Evaluation of water control strategy A

Under the condition of combinations of water control strategies 1+2+3+5, the situation of minimal possible reactors in operation can be reached with the maximal bypass flow. Also, in this case, zero RO overflow and minimal dosing amount of caustic soda exist and it can satisfy the requirements of desired effect. The results are presented in Figure 55 and Figure 56:

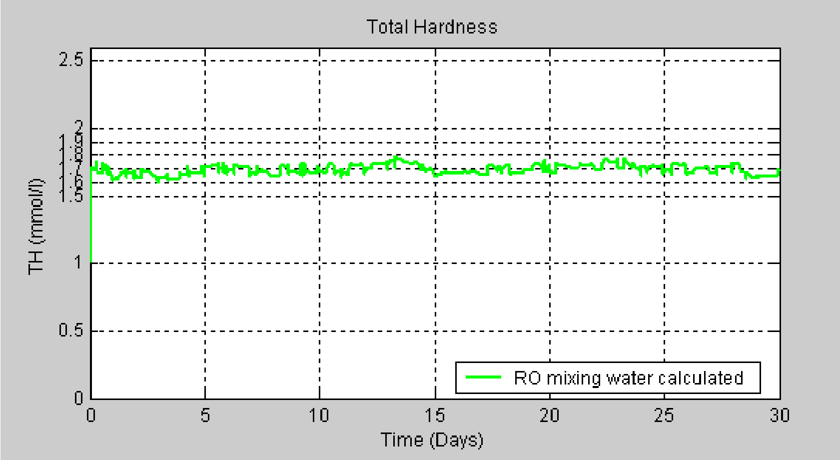


Figure 56: Total hardness after RO mixing under water control strategy A

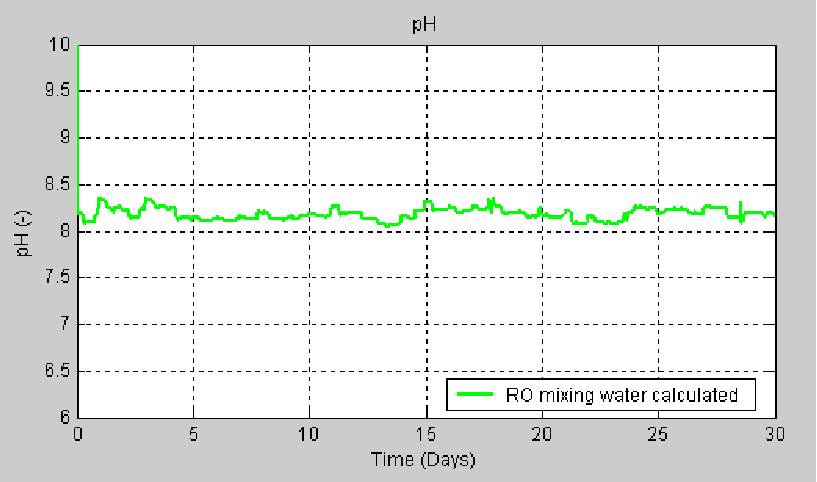


Figure 57: pH after RO mixing under water control strategy A

The water quality parameters for total hardness and pH satisfy the key performance indicators under this extreme condition. Also, the disappearance of model scatters means the number of reactors switched on or off is minimal. The dynamic model results successfully validate the results in static analysis.

6.2.3 Evaluation of water control strategy B

In this water control strategy, the method to determine reactors switched on or off from the flow changes to the final total hardness. Based on the total water quality standard of total hardness in Table 1, when the final total hardness is higher than 1.7 mmol/l, new reactor will be switched on. When it is lower than 1.3 mmol/l, then it will be switched off. The recirculation flow can not be avoided under water control strategy B. Two water quality parameters (TH, pH) in final effluent RO mixing location are validated here.

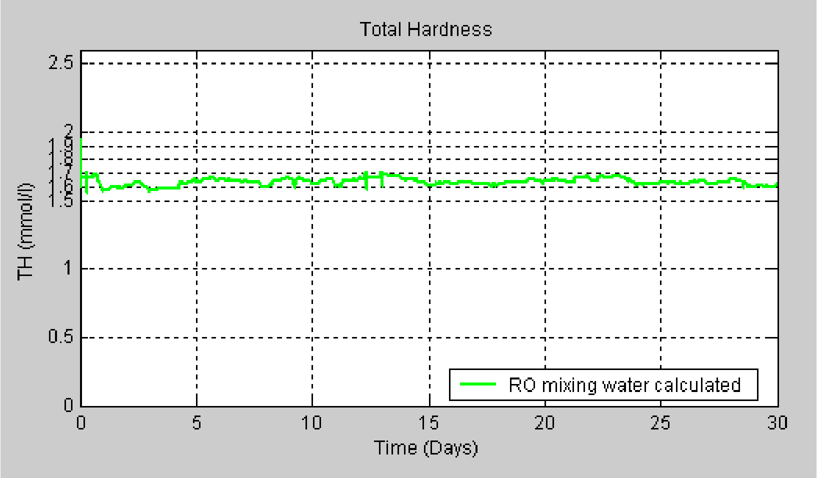


Figure 58: Total hardness after RO mixing under water control strategy B

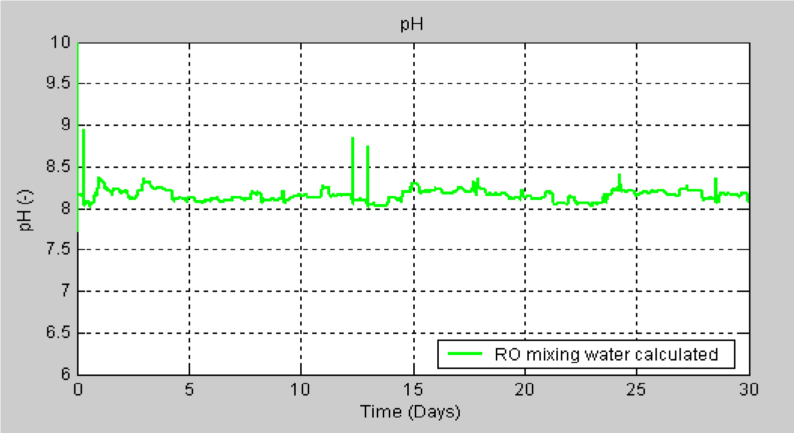


Figure 59: pH after RO mixing under water control strategy B

After evaluation of the two water quality parameters, it can be found water quality parameters total hardness and pH are in the required range and the conclusion of this water control strategy is it can be applied. Only less number of reactors switching on happens here.

6.2.4 Evaluation of water control strategy C

The water control strategy C is similar to water control strategy A but with two reactors always in operation to save excessive reactors switched on or off.

Reactors will be switched on and off with the following amounts so that there will be always two reactors in operation.

- 0; 0; 2,130; 2,620; 3,110 and 3,600 m^3/h

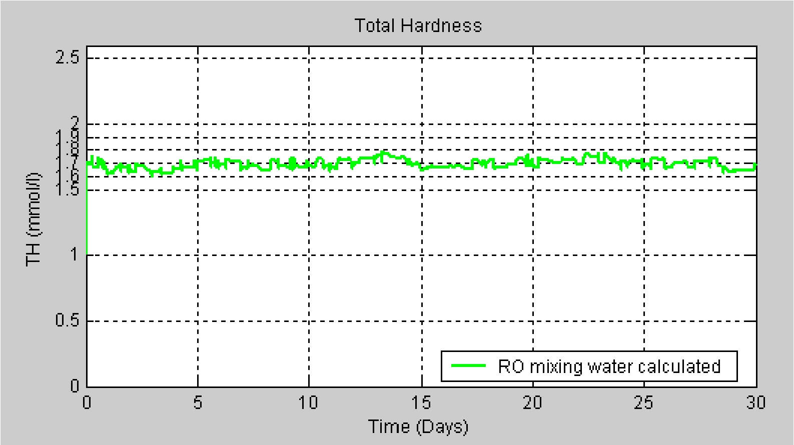


Figure 60: Total hardness after RO mixing under water control strategy C

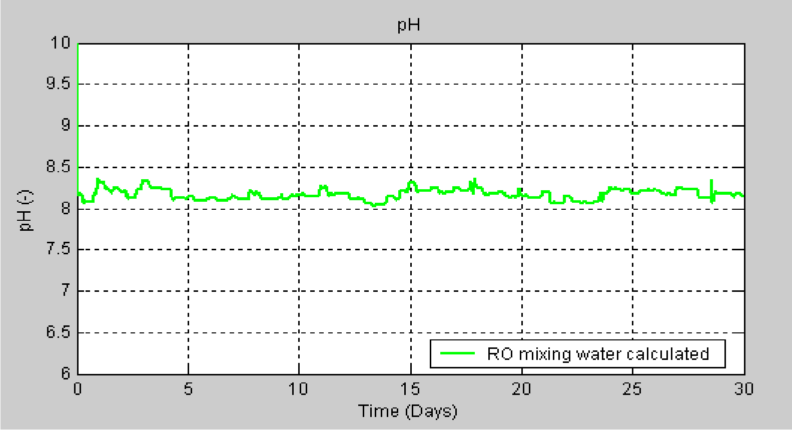


Figure 61: pH after RO mixing under water control strategy C

6.2.5 Evaluation of water control strategy D

Water control strategy D is the same as water control strategy B except for two reactors are always switched on. The switch for first reactor and second reactor will be always set as 'on' condition so that two reactors keep the condition of switching on.

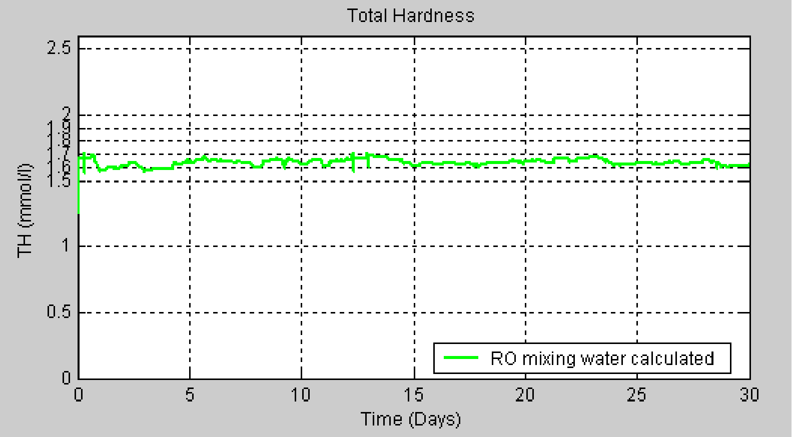


Figure 62: Total hardness after RO mixing under water control strategy D

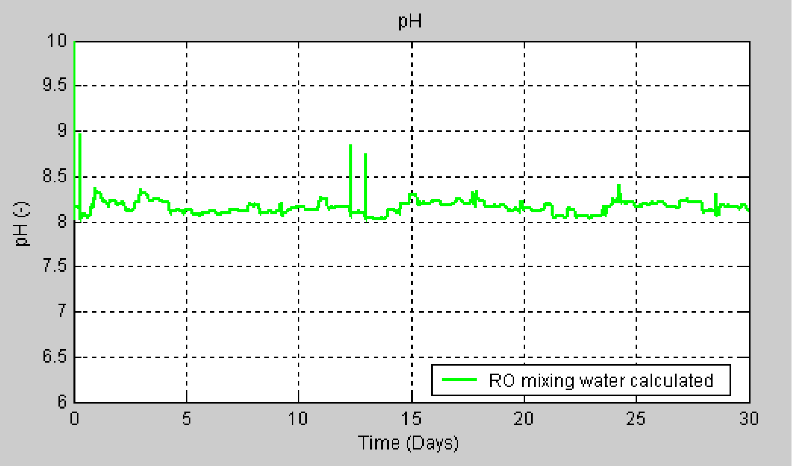


Figure 63: pH after RO mixing under water control strategy D

The graphs of two water quality parameters are the same as water control strategy B, it means that water quality will not change a lot based on this water control strategy.

6.2.6 Evaluation of water control strategy E

Water control strategy E keeps three reactors switched on. The conclusions about the results are very similar as water control strategy B.

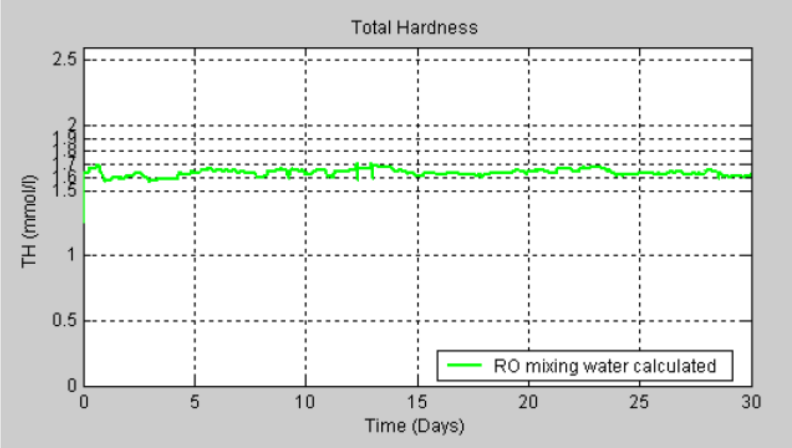


Figure 64: Total hardness after RO mixing under water control strategy E

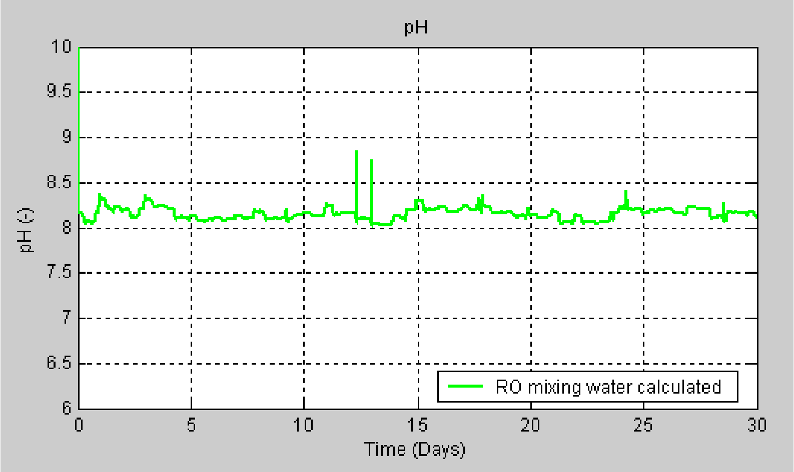


Figure 65: pH after RO mixing under water control strategy E

6.2.7 Evaluation of water control strategy F

Water control strategy F keeps four reactors switched on. Two water quality parameters are still under the required range but the peak happens on the different time.

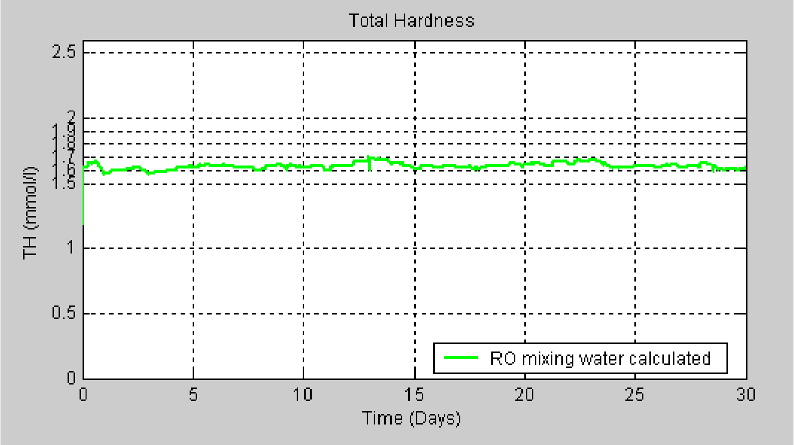


Figure 66: Total hardness after RO mixing under water control strategy F

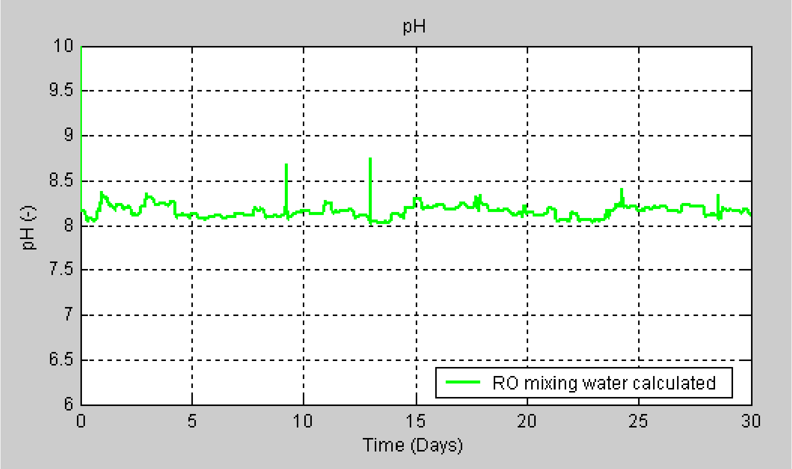


Figure 67: pH after RO mixing under water control strategy F

6.3 Discussions and conclusions

The drinking water treatment plant Wim Mensink can improve the current control conditions by using the five water control strategies. The specific work for each water control strategy is summarized in Table 14:

Table 13: Specific work for each water control strategy

	Specific work
Water control strategy 1	Input of RO water = Total RO flow in Heemskerk + Less clean water flow to adjust SI – Total RO flow in Bergen
Water control strategy 2	Pressure drop to determine pellet discharge from 1.80 mWc to 2.60 mWc
Water control strategy 3	Setpoint flow for each reactor instead of total flow in filter building 1 in NaOH master control; Cancellation of NaOH slave control
Water control strategy 4	Reactors switched on and off: 490; 980; 1,470; 1,960; 2,450 and 2,940 m^3/h
Water control strategy 5	Reactors switched on and off: 1,150; 1,640; 2,130; 2,620; 3,110 and 3,600 m^3/h

For water control strategy 1, the input of 5% discharged RO missing water to the reference situation will not change the water quality largely. Therefore, zero discharge will not have a significant influence on the effluent water quality. The reason for the 5% discharged RO water needs to be further investigated. The possible condition is that the current membrane module operation could not reach it.

For water control strategy 2, the model results prove that the fluidized bed height of the reactor could be further used to optimize the properties of the reactor and maximally use the river sand. The dosing amount of CO_2 is reduced but the overflow problem of reactor should be avoided.

For water control strategy 3, it illustrates that the costs of caustic soda and carbon dioxide could be further cut down while still keeping the satisfied water quality at the effluent location.

For water control strategy 4, it is concluded that the prevention of the recirculation flow, contributes to a higher and more stable water quality in terms of two water quality parameters (TH and pH) in the final effluent locations. It will bring a more stable water quality for Wim Mensink.

The final water control strategy provides a plan with possible maximal bypass flow. The dosing amount of CO_2 can not be totally cancelled and the final water quality parameters (TH and pH) still meet the requirements of key performance indicators.

For water control strategy 4 and water control strategy 5, one of them will be selected for the real situation depending on the different needs. The water control strategy 5 will only be selected when Wim Mensink needs to save the cost of carbon dioxide in a short time because long time running with maximal flow will lead to high risk of higher final total hardness, which may exceeds the upper limitation. Therefore, the maximal number combinations of different water control strategies are 1+2+3+4 or 1+2+3+5. Apart from the combination of water control strategy 4+5, any combinations of these water control strategies are possible.

In terms of the advantages and limitations for each water control strategy, Table 15 presents the summary of them.

Table 14: Advantages and limitations for each water control strategy

	Advantages	**Limitations**
Water control strategy 1	5% discharged RO water can be reused	Real operation of RO membrane system
Water control strategy 2	Maximally usage the fluidized bed height; Maximally usage of the river sand; Cost saving for CO_2	Overflow of fluidized bed height
Water control strategy 3	Cost saving for NaOH and CO_2	Final water quality close to the upper limit of operational window
Water control strategy 4	More stable water quality	---
Water control strategy 5	Theoretical maximal flow can be found	Dosage of CO_2 can not be cancelled

With regard to the cost saving during step development of water control strategies, Table 16 provides the total chemical dosage cost varying in water control strategy 2 water control strategy 3 over the first month. No cost comparisons are present for other water control strategies because no significant states for costs happen.
The time interval for the sampling model points in this calculation are the same as the time interval of input online measurements, which is 2 hours time interval.

Table 15: Costs of chemical dosage over first month

	Caustic soda (euro)	**Carbon dioxide (euro)**
Reference situation	7,884	717
Water control strategy 2	---	690
Water control strategy 3	6,234	378

This table illustrates that the chemical dosage will decrease with regarding to the relevant water control strategies to lower down the amount of chemical consumption, which can be seen as the example of the model for the real situation. The unit dosage cost for caustic soda and carbon dioxide in PWN are 0.15 euro/l and 0.06 euro/Nm^3 respectively.

For the evaluation of other six water control strategies, Stimela model have shown that the mentioned strategies are able to meet the objectives of this study. Firstly, these water control strategies were concluded using a static water quality model. Now the dynamic Stimela model is used to determine the effectiveness of each alternative by evaluation of each water control strategy. From the evaluation results, water control strategy A and water control strategy C are better than others because less amounts of reactors switched on and/or off happen than others. Water control strategy C is better than water control strategy A because two reactors are always in switched on condition will keep a more stable operational situation in long time running. The essential points of these water control strategies are to improve the robustness of the system by less numbers of switching on or off different reactors while still keeping the required final effluent water quality.

In summary, the developed new water control strategies and the strategies developed by Jasper Wuister and Kim van Schagen in this thesis study focus on minimizing the RO discharge, caustic soda dosage, carbon dioxide dosage while keeping total hardness, pH and saturation index within the operational windows.

7. Conclusions and Recommendations

In this chapter, the conclusions from the model validation process and new water control strategies are summarized. The possible research topics, the application of Stimela model and the method for working with Stimela model are recommended.

7.1 Conclusions

1. A Stimela water quality model of the pellet softening of Wim Mensink has been validated with historic data in first month of the year 2009.
2. Three water quality parameters (TH, bicarbonate and pH) are validated by Stimela model in two different locations with whole water treatment system in first month of the year 2009.
3. The Stimela model of Wim Mensink can be used to compare control strategies for the pellet softening reactors and mixing of RO water.
4. The discharge of RO water for the first month in 2009 could have been prevented completely simply by supplying all water produced by the RO filtration at Heemkserk decreased by the flow supplied to drinking water treatment plant Bergen, to drinking water treatment plant Wim Mensink. No modifications in the pellet softening control of Wim Mensink are necessary to meet the water quality standards for TH and pH when the extra water is supplied.
5. Increasing of the fluidized bed height in the reactors from circa 3.0 m to circa 4.5 m will lead to saving of carbon dioxide.
6. If the caustic soda dosage is based on the flows through the individual reactors instead of the flow through filter building 1, caustic soda can be saved, without violating the operational window for total hardness.
7. The slave control of the caustic soda dosage is not required to meet the operational window for total hardness in the upper cascade location while still keeping the final water quality in operational window. Elimination of this slave control will save caustic soda dosage.
8. The elimination of the recirculation flow within filter building 1 will lead to a more stable water quality of the final clear water reservoir.
9. When the by pass within filter building is maximized, the carbon dosage can not be cancelled when the final water quality within the operational window.
10. Six other water control strategies are successfully evaluated by TH and pH in the clear water reservoir to prove that they can be applied on the real operation.

7.2 Recommendations

1. Stopping the discharge of RO water by supplying all available RO water to Wim Mensink.
2. If discharging of RO water cannot be prevented in practice, investigation of a more flexible operation of the RO treatment plant is necessary
3. Users of Stimela should meet regularly to exchange experiences when modeling drinking water treatment processes.
4. The calculation speed of Stimela should be increased to be able to do more model runs at the same time.
5. The Stimela working team needs to be trained so that the future work can be performed more efficiently.

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12. J. Wuister, K.M. Schagen, Flexibiliseren ontharding PS Mensink – Procesbesturing, May/June, 2009.

Appendices

Appendix Ⅰ

Properties of basic information

Basic information about softening chemicals

Number	**Name**	**Character**
1	Softening chemical	NaOH
2	Supplier	Rossmark
4	Concentration of supplied product	50% NaOH
5	Number of tanks for NaOH	2
6	Volume of each storage tank	62 m^3
7	Dilution of supplied product	Yes
8	Type of diluted water	Reverse osmosis water
9	Concentration of NaOH in the tank	25% NaOH
10	Amount of dosage	50 g NaOH/m^3
11	Dosage method	Dosage pump for every reactor

Basic information about dimensions of softening reactors

Number	**Name**	**Character**
1	Type of reactor	Cylindrical reactor
2	Design capacity per reactor	500 m^3/h
3	Number of reactors	6
4	Bottom construction of reactor	Bottom caps
5	Number of water entry points	144
6	Number of lye entry points	52
7	Number of pellet discharge points	3
8	Overflow gutter	Inside
9	Shape of overflow gutter	Rectangular shape
10	Total reactor height	6,700 mm (including raw water inflow)
11	Height of cylindrical part of reactor	6,000 mm (excluding raw water inflow)
12	Height of overflow gutter	5,110 mm
13	Diameter of reactor bottom	2,660 mm
14	Diameter of cylindrical part of reactor	2,660 mm
15	Diameter of effluent opening	400 mm

Basic information of process and installation of softening reactors

Number	**Name**	**Character**
1	Necessary time for maintenance	4 hours per week
2	Number of maintenance times	1 time per week
3	Time for shutdown reactors	2-3 weeks
4	Number of shutdown times	1 time per 2 years
5	Time for failure events*	1 hour per week
6	Number of failure events times	20 times per year
7	Height of fixed bed	2,000 mm
8	Height of fluidised bed	circa 3,500 mm
9	Grain distribution d_{10}	Approximately 1,0 mm
10	Grain distribution d_{50}	Approximately 1,3 mm
11	d_{60}/d_{10}	1,2-1,6
12	Frequency of pellet discharge	2 times per hour
13	Diameter of discharged pellets	3.6 mm
14	Type of discharged pellets pump	Centrifugal pump
15	Capacity	10 m^3/h
16	Type of valve	Butterfly valve

* The failures have been limited to failure of valves, broken thermostat and leaking acid. Because there are 6 reactors in total, there will be no influence on the final water quality when one reactor is in failure.

Appendix II

Useful plenty report tags

Tags for water quality parameters

PWM_PO_INF1915	Temperature of inflow in raw water for Wim Mensink
PWM_PO_INF2210	pH of inflow in raw water for Wim Mensink
PWM_PO_INF2810	Total hardness of inflow in raw water for Wim Mensink
PWM_PO_INF2670	Calcium ion concentration of inflow in raw water for Wim Mensink
PWM_PO_INF2700	Magnesium ion concentration of inflow in raw water for Wim Mensink
PWM_PO_INF2420	Bicarbonate ion concentration of inflow in raw water for Wim Mensink
PWM_PO_INF2310	Saturation index of inflow in raw water for Wim Mensink
PWM_PO_INF1685	Electrical conductivity of inflow in raw water for Wim Mensink
PWM_CASC_EFF2210	pH of outflow in cascade 1 for Wim Mensink
PWM_CASC_EFF2810	Total hardness of outflow in cascade 1 for Wim Mensink
PWM_CASC_EFF2670	Calcium ion concentration of outflow in cascade 1 for Wim Mensink
PWM_CASC_EFF2700	Magnesium ion concentration of outflow in cascade 1 for Wim Mensink
PWM_CASC_EFF2420	Bicarbonate ion concentration of outflow in cascade 1 for Wim Mensink
PWM_CASC_EFF2310	Saturation index of outflow in cascade 1 for Wim Mensink
PWM_CASC_EFF1685	Electrical conductivity of outflow in cascade 1 for Wim Mensink
PLG_TL1_HF2210	pH of inflow for Heemskerk I
PLG_TL1_HF2810	Total hardness of inflow for Heemskerk I
PLG_TL1_HF2670	Calcium ion concentration of inflow for Heemskerk I
PLG_TL1_HF2420	Bicarbonate ion concentration of inflow for Heemskerk I
PLG_TL1_HF2310	Saturation index of inflow for Heemskerk I
PLG_TL1_HF1685	Electrical conductivity of inflow for Heemskerk I
PWM_PO_RW1915	Temperature of outflow for drinking water reservoir
PWM_PO_RW2210	pH of outflow for drinking water reservoir
PWM_PO_RW2810	Total hardness of outflow for drinking water reservoir
PWM_PO_RW2670	Calcium ion concentration of outflow for drinking water reservoir
PWM_PO_RW2700	Magnesium ion concentration of outflow for drinking water reservoir
PWM_PO_RW2420	Bicarbonate ion concentration of outflow for drinking water reservoir
PWM_PO_RW2310	Saturation index of outflow for drinking water reservoir
PWM_PO_RW1685	Electrical conductivity of outflow for drinking water reservoir
HEZ3AF_QT10	Total hardness after all reactors
HEZ5AA_QT20	pH dosing before rapid sand filter 1-6 for filter building 1
HEZ5AA_QT10	pH dosing before rapid sand filter 7-12 for filter building 1
HEZ0CG_FT10	Carbon dioxide dosing in east point before in cascade 1
HEZ0CG_FT20	Carbon dioxide dosing in west point before in cascade 1

Tags for flow rates

HEZ2AA_FT10	Inflow raw water for FB1
HEZ2AA_FT20	Inflow raw water for FB2
HEZ9AA_FT30	Total inflow of mixer for Heemskerk I

Tags for pressure drop

HEZ303_PT10	Pressure drop for reactor 3
HEZ304_PT10	Pressure drop for reactor 4
HEZ306_PT10	Pressure drop for reactor 6

Appendix III

Database for laboratory measurements

First datasets starting from January 20th to February 20th, 2009

Laboratory measurements for raw water (PWM_PO_INF)							
Calcium concentration (mg/l) **(PWM_PO_INF2670)**		**Magnesium concentration (mg/l)** **(PWM_PO_INF2700)**		**Temperature (°C)** **(PWM_PO_INF1915)**		**pH (-)** **(PWM_PO_INF2210)**	
1/20/2009 00:00:00	70.577	1/20/2009 00:00:00	11.067	1/20/2009 00:00:00	11.684	1/20/2009 00:00:00	7.854
1/20/2009 13:19:00	70.443	1/20/2009 13:19:00	10.989	1/20/2009 13:19:00	11.700	1/20/2009 13:19:00	7.850
1/27/2009 14:23:00	71.119	1/27/2009 14:23:00	11.217	1/27/2009 14:23:00	11.100	1/27/2009 14:23:00	7.850
2/3/2009 16:02:00	73.251	2/3/2009 16:02:00	11.769	2/3/2009 16:02:00	11.000	2/3/2009 16:02:00	7.860
2/10/2009 12:53:00	73.629	2/10/2009 12:53:00	11.990	2/10/2009 12:53:00	9.800	2/10/2009 12:53:00	7.870
2/16/2009 22:00:01	73.629	2/16/2009 22:00:01	11.990	2/17/2009 13:07:00	10.300	2/17/2009 13:07:00	7.860
2/17/2009 13:07:00	72.238	2/17/2009 13:07:00	11.597	---	---	---	---
Laboratory measurements for raw water (PWM_PO_INF)							
Conductivity (ms/m) **(PWM_PO_INF1685)**		**Bicarbonate concentration (mg/l)** **(PWM_PO_INF2420)**		**Total hardness (mmol/l)** **(PWM_PO_INF2810)**			
1/20/2009 00:00:00	70.700	1/20/2009 00:00:00	1/20/2009 00:00:00	1/20/2009 00:00:00	2.220		
1/20/2009 13:19:00	70.700	1/20/2009 13:19:00	1/20/2009 13:19:00	1/20/2009 13:19:00	2.213		
1/27/2009 14:23:00	71.200	1/27/2009 14:23:00	1/27/2009 14:23:00	1/27/2009 14:23:00	2.239		
2/3/2009 16:02:00	71.600	1/30/2009 22:00:01	1/30/2009 22:00:01	1/30/2009 22:00:01	2.239		
2/10/2009 12:53:00	71.700	2/3/2009 16:02:00	2/3/2009 16:02:00	2/3/2009 16:02:00	2.315		
2/17/2009 13:07:00	72.100	2/10/2009 12:53:00	2/10/2009 12:53:00	2/10/2009 12:53:00	2.334		
---	---	2/17/2009 13:07:00	2/17/2009 13:07:00	2/17/2009 13:07:00	2.283		

Laboratory measurements for RO water (PWM_TL1_HF)							
Calcium concentration (mg/l) (PWM_TL1_HF2670)		**pH (-)** (PWM_TL1_HF2210)		**Conductivity (ms/m)** (PWM_TL1_HF1685)		**Bicarbonate concentration (mg/l)** (PWM_TL1_HF2420)	
1/20/2009 00:00:00	1.999	1/20/2009 00:00:00	9.750	1/20/2009 00:00:00	13.730	1/20/2009 00:00:00	44.680
1/20/2009 13:20:00	1.999	1/20/2009 13:20:00	9.750	1/20/2009 13:20:00	13.730	1/20/2009 13:20:00	44.680
1/27/2009 14:23:00	2.532	1/27/2009 14:23:00	9.710	1/27/2009 14:23:00	15.430	1/27/2009 14:23:00	47.860
2/3/2009 16:03:00	2.563	2/3/2009 16:03:00	9.930	2/3/2009 16:03:00	15.130	2/3/2009 16:03:00	42.240
2/10/2009 12:54:00	2.836	2/10/2009 12:54:00	9.780	2/10/2009 12:54:00	15.710	2/10/2009 12:54:00	52.840
2/16/2009 22:00:01	2.836	2/17/2009 13:08:00	9.910	2/17/2009 13:08:00	15.500	2/17/2009 13:08:00	45.190
2/17/2009 13:08:00	2.351	---	---	---	---	---	---

Laboratory measurements after weir aerator (PWM_CASC_EFF)					
Total hardness (mmol/l) (PWM_CASC_EFF2810)		**Bicarbonate concentration (mg/l)** (PWM_CASC_EFF2420)		**pH (-)** (PWM_CASC_EFF2210)	
1/20/2009 00:00:00	1.156	1/20/2009 00:00:00	140.126	1/20/2009 00:00:00	8.071
1/20/2009 13:20:00	1.135	1/20/2009 13:20:00	139.420	1/20/2009 13:20:00	8.070
1/27/2009 14:23:00	1.412	1/27/2009 14:23:00	144.280	1/27/2009 14:23:00	8.100
2/3/2009 16:02:00	1.191	2/3/2009 16:02:00	133.120	2/3/2009 16:02:00	8.110
2/10/2009 12:54:00	2.320	2/10/2009 12:54:00	182.760	2/10/2009 12:54:00	8.020
2/17/2009 13:07:00	1.330	2/17/2009 13:07:00	143.740	2/17/2009 13:07:00	8.030

Laboratory measurements after RO mixing (PWM_PO_RW)					
Total hardness (mmol/l) (PWM_PO_RW2810)		**Bicarbonate concentration (mg/l)** (PWM_PO_RW2420)		**pH (-)** (PWM_PO_RW2210)	
1/20/2009 00:00:00	1.410	1/20/2009 00:00:00	149.708	1/20/2009 00:00:00	8.042
1/20/2009 13:33:00	1.399	1/20/2009 13:33:00	150.720	1/20/2009 13:33:00	8.040
1/27/2009 14:24:00	1.481	1/27/2009 14:24:00	140.980	1/27/2009 14:24:00	8.060
2/3/2009 16:04:00	1.502	2/3/2009 16:04:00	150.860	2/3/2009 16:04:00	8.030
2/10/2009 12:54:00	1.578	2/10/2009 12:54:00	135.760	2/10/2009 12:54:00	8.030
2/17/2009 13:08:00	1.545	2/17/2009 13:08:00	150.530	2/17/2009 13:08:00	7.990

Fluidized bed height over different time

	Reactor 3	**Reactor 4**	**Reactor 6**
Jan 28th	3.1	3.2	(Fixed) 2.4
		(Online) 3.16	
Feb 3rd	3.6	3.2	4.0
		(Online) 3.17	
Feb 11th	3.6	3.2	3.8
		(Online) 3.17	
Feb 18th	3.6	3.3	3.95
	(Online) 3.442	(Online) 3.21	
Feb 25th	3.65	3.3	3.7
	(Online) 3.56	(Online) 3.15	
Mar 6th	3.7	3.2	3.65
Mar 11th	---	3.2	3.6
		(Online) 3.15	

Appendix IV

Sieve analysis results for different reactors

Different sieve meshes for reactors

Reactor 3

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
1	3.15	3.15	2.50	0.9	0.8	0.8	0.8
2	2.50	2.50	2	0.8	0.63	0.63	0.63
3	2	2	1.8	0.710	0.56	0.56	0.56
4	1.8	1.8	1.6	0.63	0.5	0.5	0.5
5	1.6	1.6	1	0.56	0.425	0.425	0.425
6	1	1	0.8	0.5	0.355	0.355	0.355
7	0.5	0.5	0.5	0.425	0.300	0.300	0.300

Reactor 4

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
1	3.15	3.15	2.50	1.4	0.8	0.8	0.8
2	2.50	2.50	2	1.25	0.63	0.63	0.63
3	2	2	1.8	1	0.56	0.56	0.56
4	1.8	1.8	1.6	0.9	0.5	0.5	0.5
5	1.6	1.6	1	0.8	0.425	0.425	0.425
6	1	1	0.8	0.710	0.355	0.355	0.355
7	0.5	0.5	0.5	0.63	0.300	0.300	0.300

Reactor 6

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
1	3.15	3.15	2.50	0.9	0.8	0.8	0.8
2	2.50	2.50	2	0.8	0.63	0.63	0.63
3	2	2	1.8	0.710	0.56	0.56	0.56
4	1.8	1.8	1.6	0.63	0.5	0.5	0.5
5	1.6	1.6	1	0.56	0.425	0.425	0.425
6	1	1	0.8	0.5	0.355	0.355	0.355
7	0.5	0.5	0.5	0.425	0.300	0.300	0.300

Specific pellet diameters for different reactors over different time and layers

Reactor 3

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
Jan 20th	0.81	0.71	0.60	0.55	0.46	0.42	0.40
Jan 28th	0.81	0.78	0.53	0.53	0.47	0.41	0.39
Feb 3rd	0.80	0.73	0.46	0.54	0.46	0.42	0.39
Feb 11th	0.74	0.77	0.63	0.58	0.48	0.42	0.39
Feb 18th	0.84	0.76	0.55	0.58	0.47	0.42	0.39
Feb 25th	0.74	0.81	0.69	0.63	0.48	0.44	0.39
Mar 6th	0.82	0.78	0.65	0.62	0.49	0.45	0.40

Reactor 4

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
Jan 20th	1.00	1.10	0.86	0.83	0.55	0.44	0.40
Jan 28th	0.95	1.06	0.91	0.72	0.55	0.45	0.40
Feb 3rd	1.15	0.98	0.88	0.73	0.59	0.45	0.40
Feb 11th	1.03	0.98	0.90	0.72	0.53	0.46	0.41
Feb 18th	1.00	1.00	0.86	0.59	0.54	0.45	0.40
Feb 25th	1.08	1.05	0.84	0.73	0.54	0.46	0.42
Mar 6th	0.91	0.92	0.82	0.70	0.53	0.47	0.41
Mar 11th	0.88	0.91	0.84	0.70	0.55	0.46	0.42

Reactor 6

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
Jan 16th	1.07	1.02	0.87	0.61	0.46	0.42	0.39
Jan 20th	1.13	1.05	0.94	0.67	0.49	0.44	0.41
Feb 3rd	0.98	0.94	1.15	0.80	0.57	0.47	0.43
Feb 11th	0.96	0.97	0.82	0.66	0.52	0.45	0.41
Feb 18th	0.93	0.96	1.08	0.73	0.57	0.47	0.43
Feb 25th	0.97	1.03	0.67	0.65	0.52	0.46	0.41
Mar 6th	0.79	0.77	0.62	0.61	0.51	0.45	0.41
Mar 11th	0.70	0.72	0.68	0.63	0.51	0.45	0.41

Deviated value for different reactors

Reactor 3

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
Jan 20th	0.02	-0.05	0.01	-0.03	-0.01	-0.01	0.01
Jan 28th	0.02	0.02	-0.06	-0.05	0.00	-0.02	0.00
Feb 3rd	0.01	-0.03	-0.13	-0.04	-0.01	-0.01	0.00
Feb 11th	-0.05	0.01	0.04	0.00	0.01	-0.01	0.00
Feb 18th	0.05	0.00	-0.04	0.00	0.00	-0.01	0.00
Feb 25th	-0.05	0.05	0.10	0.05	0.01	0.01	0.00
Mar 6th	0.03	0.02	0.06	0.04	0.02	0.02	0.01

Reactor 4

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
Jan 20th	0.00	0.10	0.00	0.12	0.00	-0.02	-0.01
Jan 28th	-0.05	0.06	0.05	0.00	0.00	0.00	-0.01
Feb 3rd	0.15	-0.02	0.02	0.01	0.04	0.00	-0.01
Feb 11th	0.03	-0.02	0.04	0.00	-0.02	0.01	0.00
Feb 18th	0.00	0.00	0.00	-0.13	-0.01	0.00	-0.01
Feb 25th	0.08	0.05	-0.02	0.01	-0.01	0.01	0.01
Mar 6th	-0.09	-0.08	-0.04	-0.02	-0.02	0.02	0.00
Mar 11th	-0.12	-0.09	-0.02	-0.02	0.00	0.01	0.01

Reactor 6

	Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	**Layer 7**
Jan 16th	0.13	0.09	0.02	-0.06	-0.06	-0.03	-0.02
Jan 20th	0.19	0.12	0.09	0.00	-0.03	-0.01	0.00
Feb 3rd	0.04	0.01	***0.30***	0.13	0.05	0.02	0.02
Feb 11th	0.02	0.04	-0.03	-0.01	0.00	0.00	0.00
Feb 18th	-0.01	0.03	0.23	0.06	0.05	0.02	0.02
Feb 25th	0.03	0.10	-0.18	-0.02	0.00	0.01	0.00
Mar 6th	-0.15	-0.16	-0.23	-0.06	-0.01	0.00	0.00
Mar 11th	-0.24	-0.21	-0.17	-0.04	-0.01	0.00	0.00

Deviated percentage for different reactors

Reactor 3

	Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	**Layer 7**
Jan 20th	0.02	-0.07	0.02	-0.04	-0.03	-0.01	0.02
Jan 28th	0.02	0.02	-0.10	-0.08	-0.01	-0.04	-0.01
Feb 3rd	0.01	-0.04	-0.22	-0.06	-0.03	-0.01	-0.01
Feb 11th	-0.07	0.01	0.07	0.01	0.02	-0.01	-0.01
Feb 18th	0.06	0.00	-0.06	0.01	-0.01	-0.01	-0.01
Feb 25th	-0.07	0.06	0.18	0.09	0.02	0.03	-0.01
Mar 6th	0.03	0.02	0.11	0.08	0.04	0.06	0.02

Reactor 4

	Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	**Layer 7**
Jan 20th	0.00	0.10	0.00	0.16	0.00	-0.03	-0.02
Jan 28th	-0.05	0.06	0.05	0.01	0.00	-0.01	-0.02
Feb 3rd	0.15	-0.02	0.02	0.02	0.08	-0.01	-0.02
Feb 11th	0.03	-0.02	0.04	0.01	-0.03	0.01	0.01
Feb 18th	0.00	0.00	0.00	-0.17	-0.01	-0.01	-0.02
Feb 25th	0.08	0.05	-0.03	0.02	-0.01	0.01	0.03
Mar 6th	-0.09	-0.08	-0.05	-0.02	-0.03	0.03	0.01
Mar 11th	-0.12	-0.09	-0.03	-0.02	0.00	0.01	0.03

Reactor 6

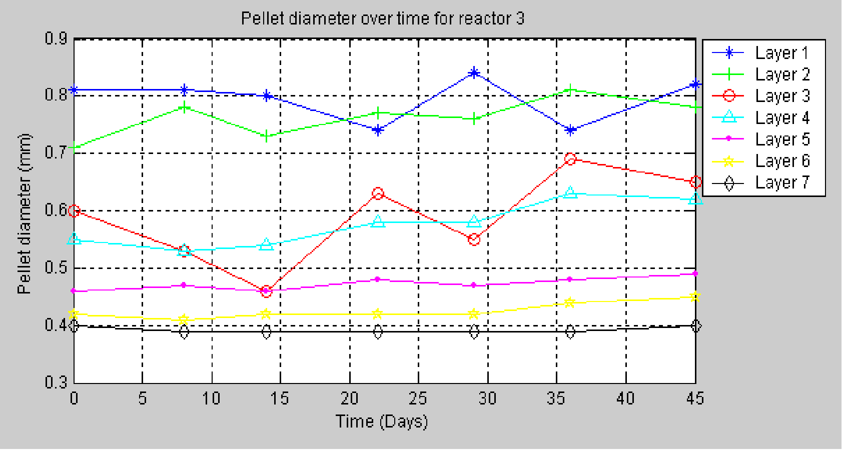
	Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	**Layer 7**
Jan 16th	0.14	0.09	0.02	-0.09	-0.11	-0.07	-0.05
Jan 20th	0.20	0.13	0.10	0.00	-0.06	-0.02	-0.01
Feb 3rd	0.04	0.01	***0.35***	0.19	0.10	0.04	0.04
Feb 11th	0.02	0.04	-0.04	-0.01	0.00	0.00	-0.01
Feb 18th	-0.01	0.03	0.27	0.09	0.10	0.04	0.04
Feb 25th	0.03	0.10	-0.22	-0.03	0.00	0.02	-0.01
Mar 6th	-0.16	-0.17	-0.27	-0.09	-0.02	0.00	-0.01
Mar 11th	-0.26	-0.23	-0.20	-0.06	-0.02	0.00	-0.01

Appendix V

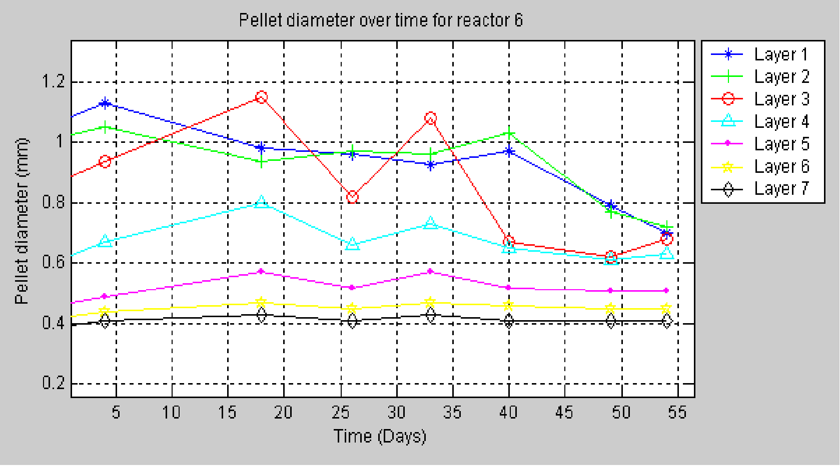
Model validation information for other two reactors

Measured results for specific diameters

Reactor 3

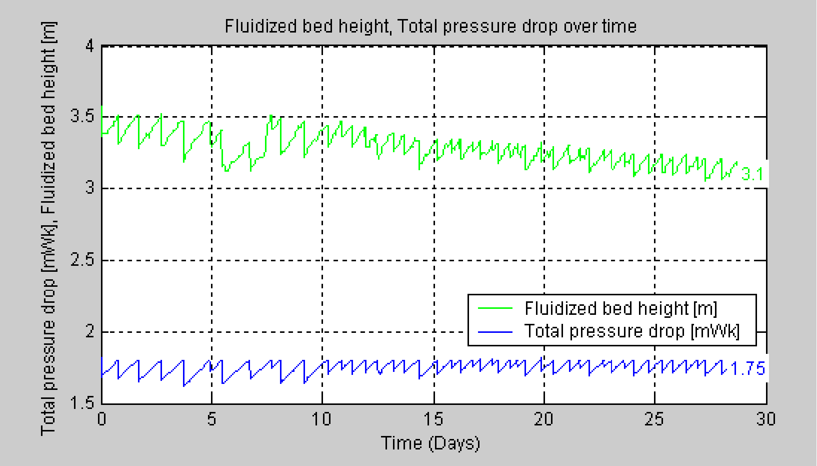


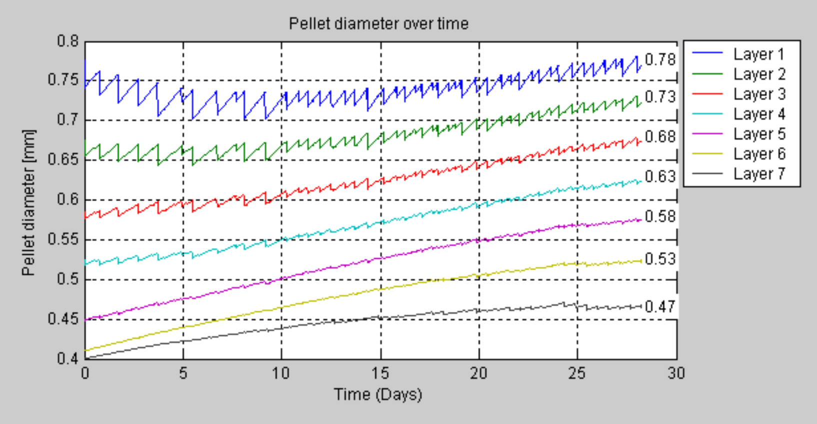
Reactor 6

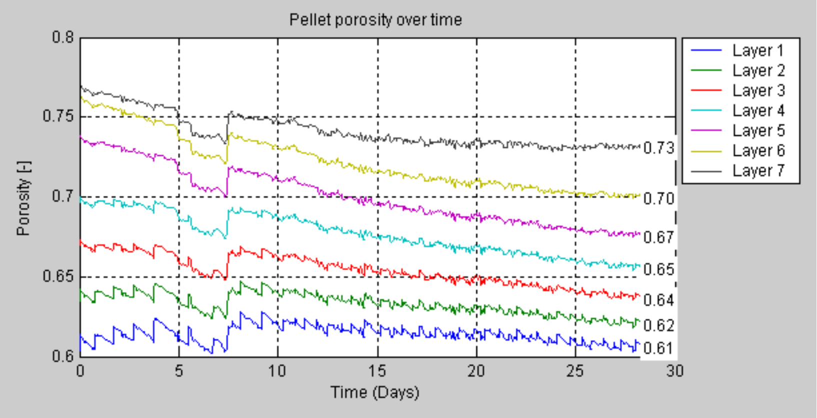


Single reactor calculated results for fluidized bed height, total pressure drop, pellet diameters and porosities in first month

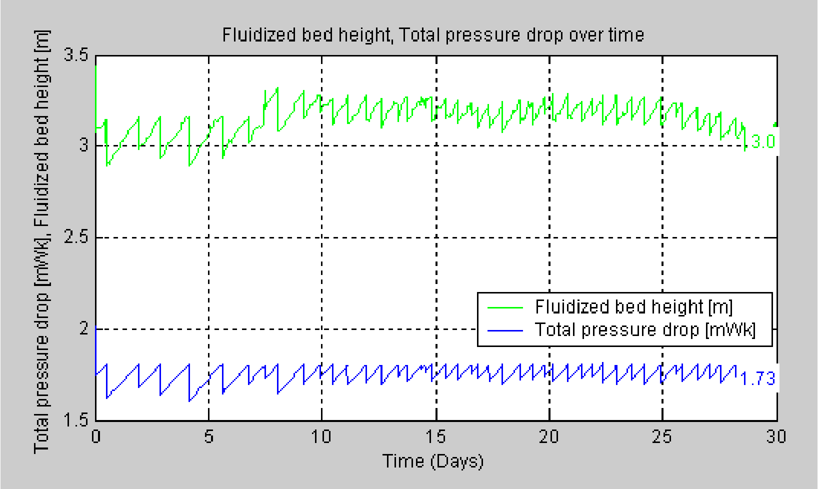
Reactor 3

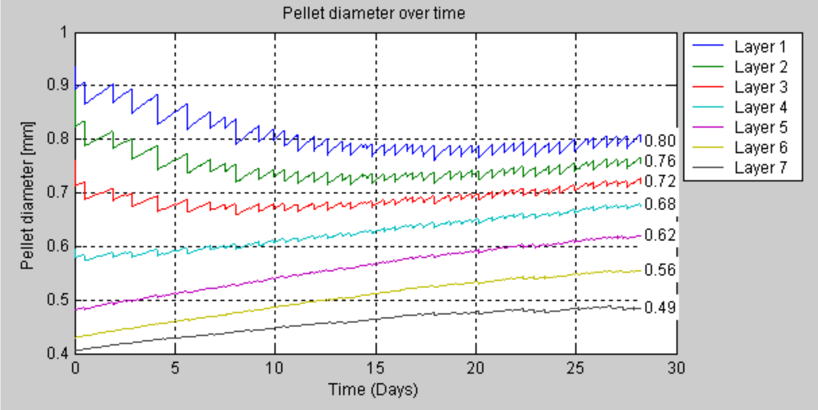


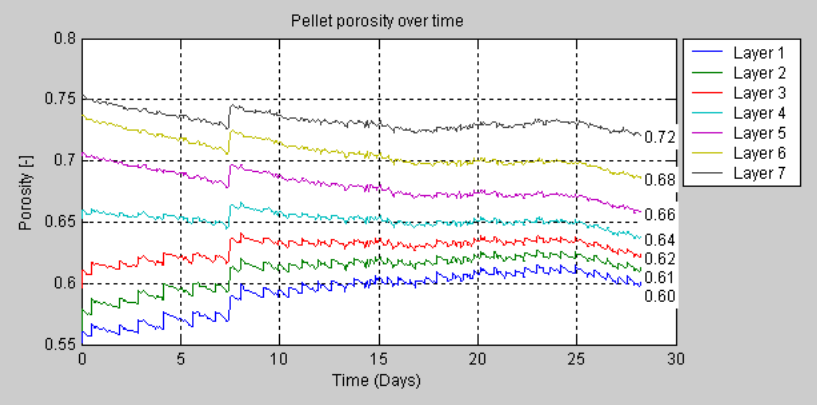




Reactor 6

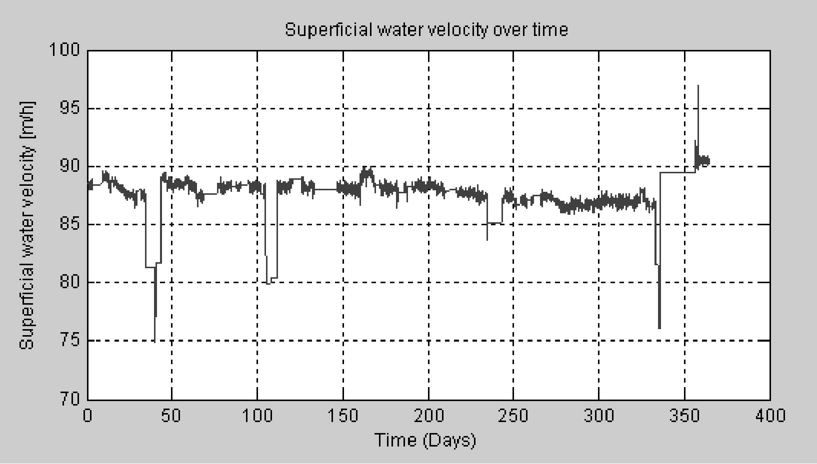

Fluidized bed height, Total pressure drop over time
Total pressure drop [mWk], Fluidized bed height [m]
3.5
3
2.5
2
1.5
0
5
10
15
20
25
30
Time (Days)
Fluidized bed height [m]
Total pressure drop [mWk]
3.0
1.73

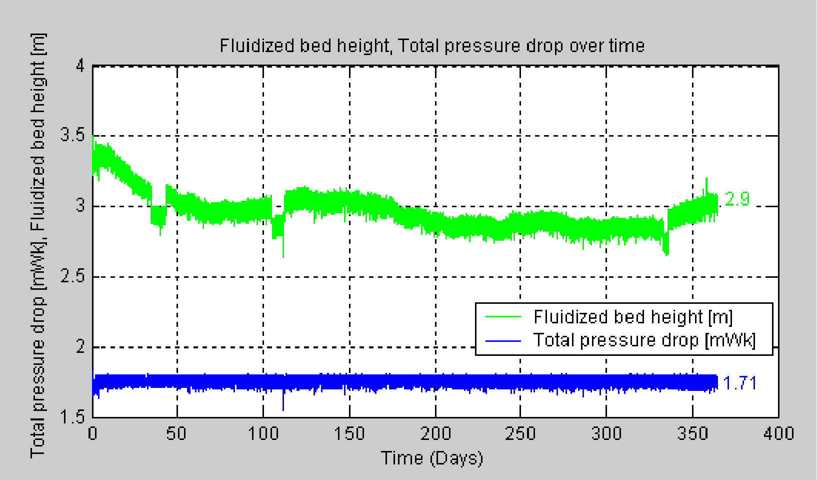

Pellet diameter over time
Pellet diameter [mm]
1
0.9
0.8
0.7
0.6
0.5
0.4
0
5
10
15
20
25
30
Time (Days)
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Layer 7
0.80
0.76
0.72
0.68
0.62
0.56
0.49

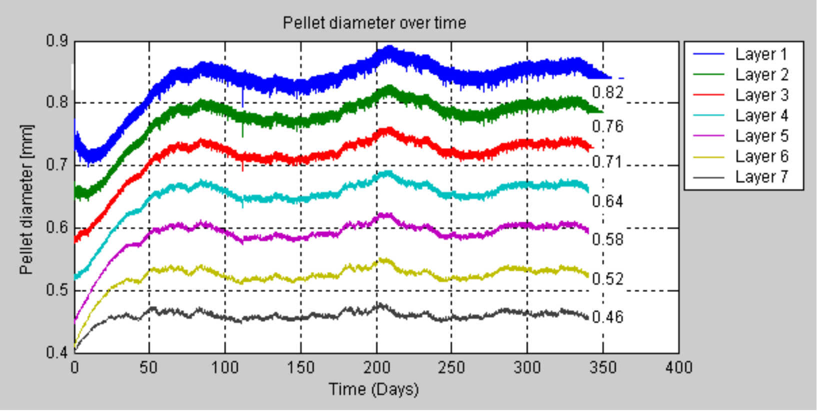

Pellet porosity over time
Porosity [-]
0.8
0.75
0.7
0.65
0.6
0.55
0
5
10
15
20
25
30
Time (Days)
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Layer 7
0.72
0.68
0.66
0.64
0.62
0.61
0.60

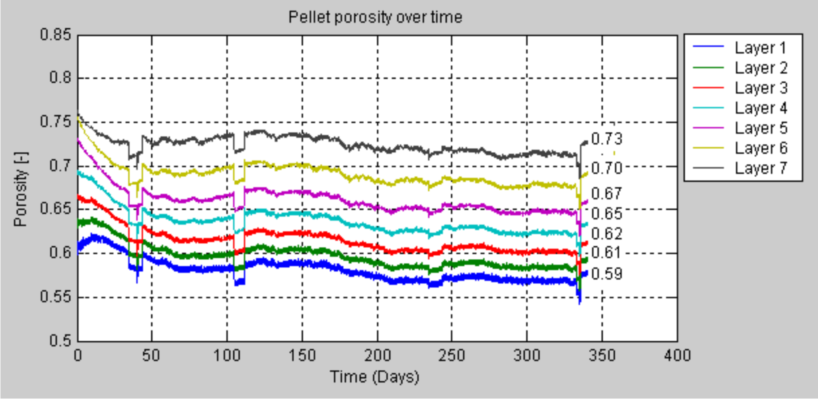
Single reactor calculated results for superficial water velocity, fluidized bed height, total pressure drop, pellet diameters, porosities and effluent total hardness in year 2008

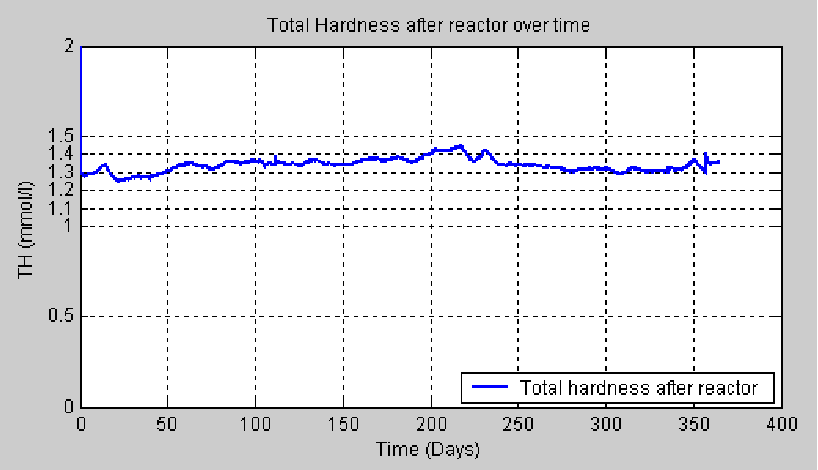
Reactor 3



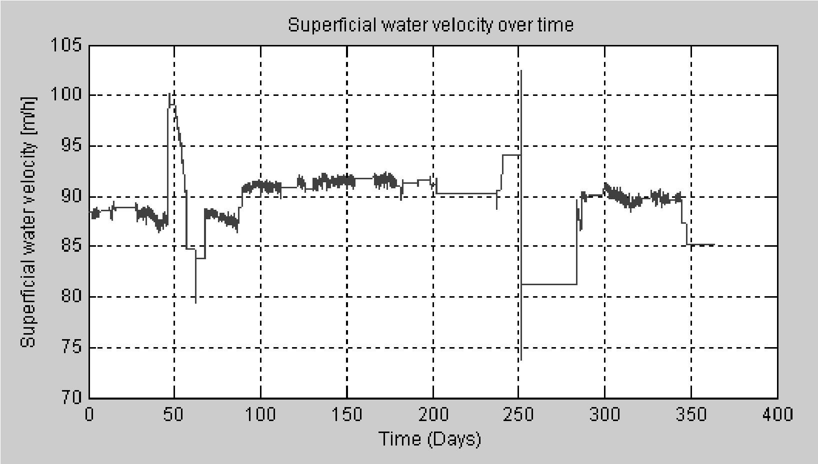


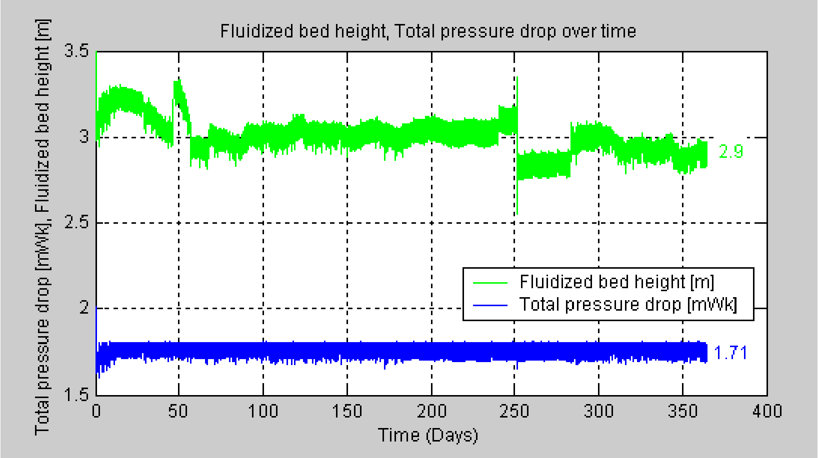


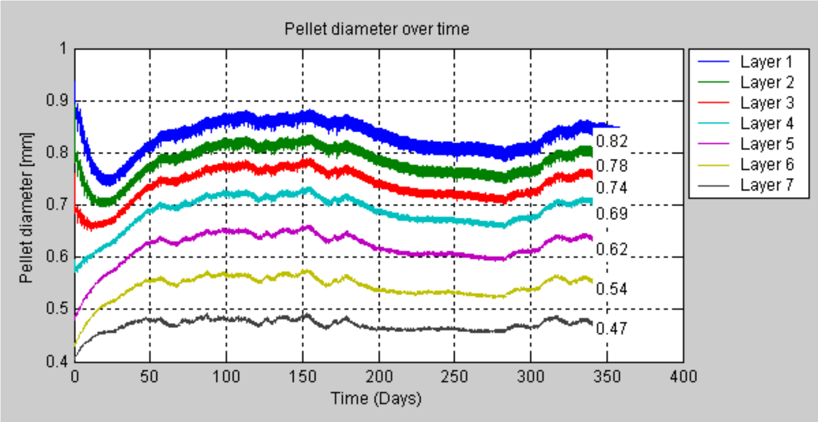

Pellet porosity over time
Porosity [-]
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0
50
100
150
200
250
300
350
400
Time (Days)
0.73
0.70
0.67
0.65
0.62
0.61
0.59
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Layer 7

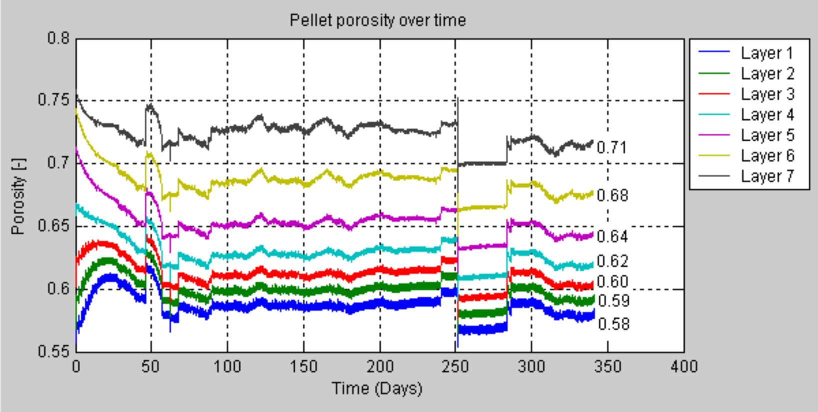

Total Hardness after reactor over time
TH (mmol/l)
2
1.5
1.4
1.3
1.2
1.1
1
0.5
0
0
50
100
150
200
250
300
350
400
Time (Days)
Total hardness after reactor

Reactor 6


Superficial water velocity over time
Superficial water velocity [m/h]
105
100
95
90
85
80
75
70
0
50
100
150
200
250
300
350
400
Time (Days)


Fluidized bed height, Total pressure drop over time
Total pressure drop [mWk], Fluidized bed height [m]
3.5
3
2.5
2
1.5
0
50
100
150
200
250
300
350
400
Time (Days)
2.9
1.71
Fluidized bed height [m]
Total pressure drop [mWk]


Pellet diameter over time
Pellet diameter [mm]
1
0.9
0.8
0.7
0.6
0.5
0.4
0
50
100
150
200
250
300
350
400
Time (Days)
0.82
0.78
0.74
0.69
0.62
0.54
0.47
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Layer 7


Pellet porosity over time
Porosity [-]
0.8
0.75
0.7
0.65
0.6
0.55
0
50
100
150
200
250
300
350
400
Time (Days)
0.71
0.68
0.64
0.62
0.60
0.59
0.58
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Layer 6
Layer 7


Total Hardness after reactor over time
TH (mmol/l)
2
1.5
1.4
1.3
1.2
1.1
1
0.5
0
0
50
100
150
200
250
300
350
400
Time (Days)
Total hardness after reactor

Calculated input

Reactor 3

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
Pellet diameter (mm)	0.775	0.675	0.585	0.525	0.450	0.410	0.400
Porosity (-)	0.596	0.628	0.662	0.690	0.731	0.758	0.765
Mass of grains (kg)	416.5	581.1	809.9	1,029.3	1,415.7	1,686.6	1,761.9

Reactor 6

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6	Layer 7
Pellet diameter (mm)	0.935	0.890	0.760	0.595	0.485	0.430	0.405
Porosity (-)	0.555	0.566	0.600	0.658	0.711	0.744	0.761
Mass of grains (kg)	261.0	295.6	436.9	779.3	1,217.2	1,545.0	1,723.9

Relative errors for first month and year 2008

Pellet diameters for reactor 3

	D_M (mm)	D1_S (mm)	Relative error 1 (-)	D2_S (mm)	Relative error 2 (-)
Layer 1	0.775	0.780	0.006	0.820	0.058
Layer 2	0.675	0.730	0.081	0.760	0.126
Layer 3	0.585	0.680	0.162	0.710	0.214
Layer 4	0.525	0.630	0.200	0.640	0.219
Layer 5	0.450	0.580	0.289	0.580	0.289
Layer 6	0.410	0.530	0.293	0.520	0.268
Layer 7	0.400	0.470	0.175	0.460	0.150

Porosities for reactor 3

	P_M (mm)	P1_S (mm)	Relative error 1 (-)	P2_S (mm)	Relative error 2 (-)
Layer 1	0.596	0.610	0.023	0.590	0.010
Layer 2	0.628	0.620	0.013	0.610	0.029
Layer 3	0.662	0.640	0.033	0.620	0.063
Layer 4	0.690	0.650	0.058	0.650	0.058
Layer 5	0.731	0.670	0.083	0.670	0.083
Layer 6	0.758	0.700	0.077	0.700	0.077
Layer 7	0.765	0.730	0.046	0.730	0.046

Pellet diameters for reactor 6

	D_M (mm)	D1_S (mm)	Relative error 1 (-)	D2_S (mm)	Relative error 2 (-)
Layer 1	0.935	0.800	0.144	0.820	0.123
Layer 2	0.890	0.760	0.146	0.780	0.124
Layer 3	0.760	0.720	0.053	0.740	0.026
Layer 4	0.595	0.680	0.143	0.690	0.160
Layer 5	0.485	0.620	0.278	0.620	0.278
Layer 6	0.430	0.560	0.302	0.540	0.256
Layer 7	0.405	0.490	0.210	0.470	0.160

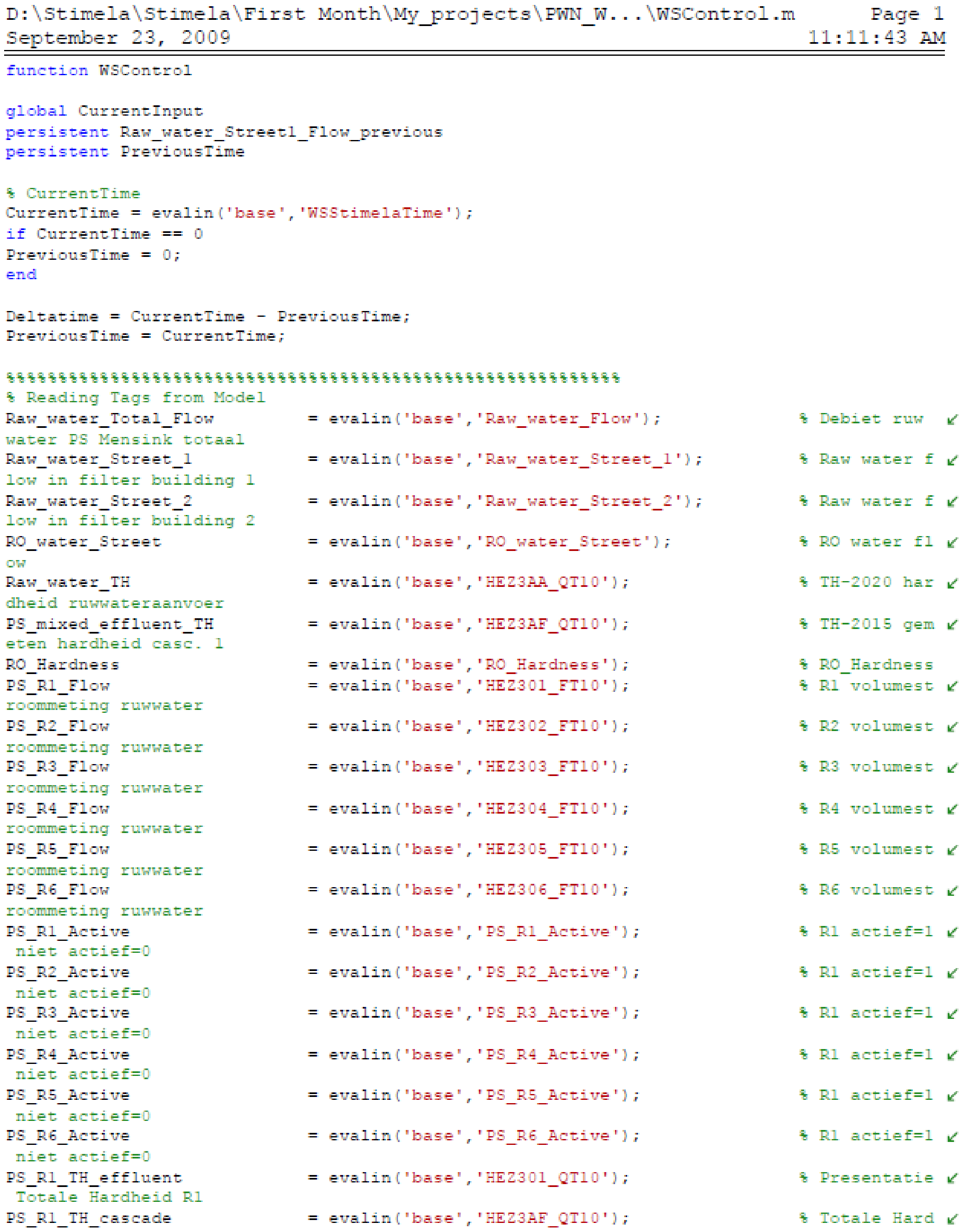
Porosities for reactor 6

	P_M (mm)	P1_S (mm)	Relative error 1 (-)	P2_S (mm)	Relative error 2 (-)
Layer 1	0.555	0.600	0.081	0.580	0.045
Layer 2	0.566	0.610	0.078	0.590	0.042
Layer 3	0.600	0.620	0.033	0.600	0.000
Layer 4	0.658	0.640	0.027	0.620	0.058
Layer 5	0.711	0.660	0.072	0.640	0.100
Layer 6	0.744	0.680	0.086	0.680	0.086
Layer 7	0.761	0.720	0.054	0.710	0.067

Appendix VI

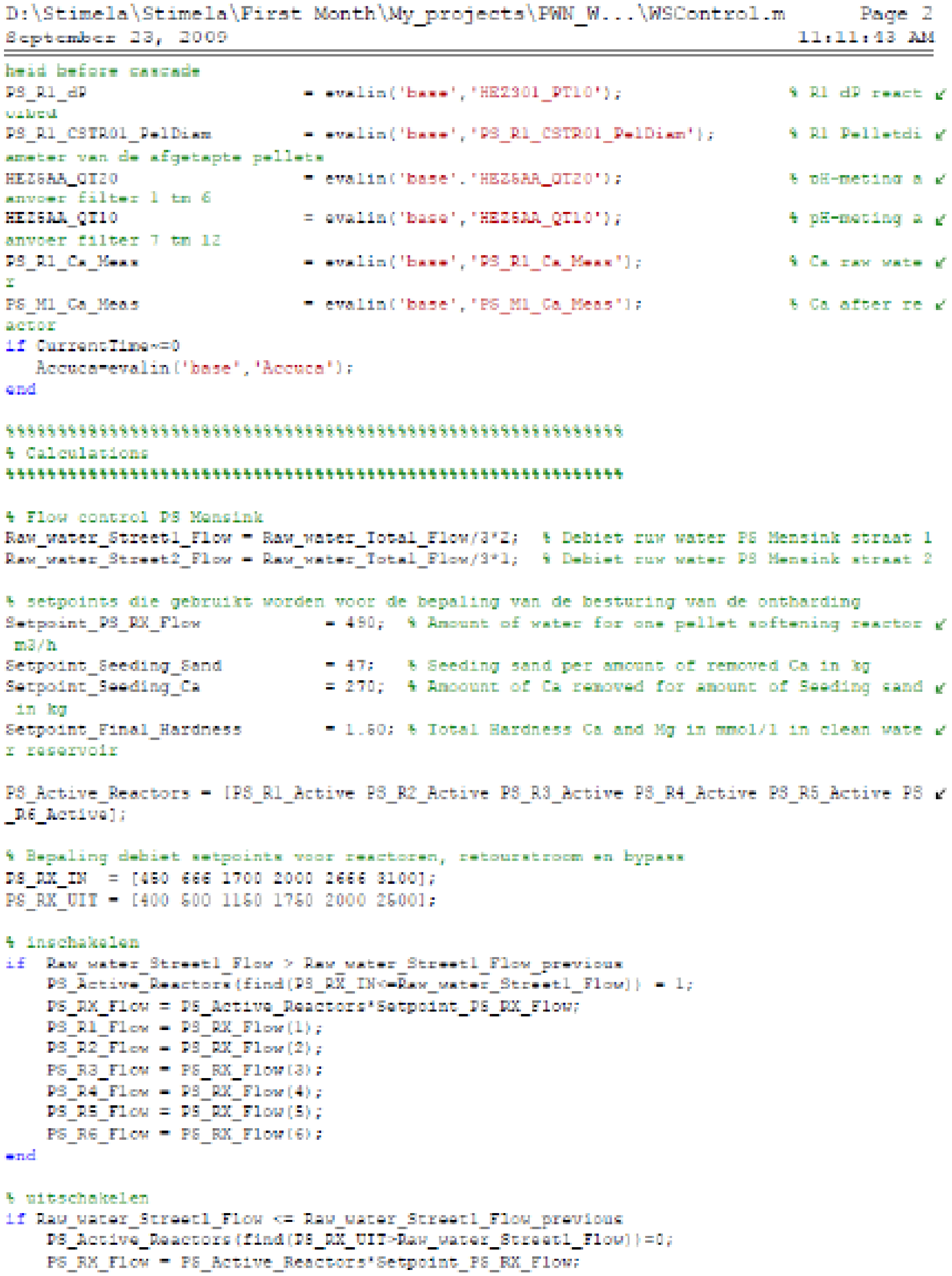
Matlab original codes

Original water control strategy file



```
D:\Stimela\Stimela\First Month\My_projects\PWN_W...\WSControl.m       Page 1
September 23, 2009                                                  11:11:43 AM
function WSControl

global CurrentInput
persistent Raw_water_Street1_Flow_previous
persistent PreviousTime

% CurrentTime
CurrentTime = evalin('base','WSStimelaTime');
if CurrentTime == 0
PreviousTime = 0;
end

Deltatime = CurrentTime - PreviousTime;
PreviousTime = CurrentTime;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Reading Tags from Model
Raw_water_Total_Flow         = evalin('base','Raw_water_Flow');              % Debiet ruw  ↙
water PS Mensink totaal
Raw_water_Street_1           = evalin('base','Raw_water_Street_1');          % Raw water f ↙
low in filter building 1
Raw_water_Street_2           = evalin('base','Raw_water_Street_2');          % Raw water f ↙
low in filter building 2
RO_water_Street              = evalin('base','RO_water_Street');             % RO water fl ↙
ow
Raw_water_TH                 = evalin('base','HEZ3AA_QT10');                 % TH-2020 har ↙
dheid ruwwateraanvoer
PS_mixed_effluent_TH         = evalin('base','HEZ3AF_QT10');                 % TH-2015 gem ↙
eten hardheid casc. 1
RO_Hardness                  = evalin('base','RO_Hardness');                 % RO_Hardness
PS_R1_Flow                   = evalin('base','HEZ301_FT10');                 % R1 volumest ↙
roommeting ruwwater
PS_R2_Flow                   = evalin('base','HEZ302_FT10');                 % R2 volumest ↙
roommeting ruwwater
PS_R3_Flow                   = evalin('base','HEZ303_FT10');                 % R3 volumest ↙
roommeting ruwwater
PS_R4_Flow                   = evalin('base','HEZ304_FT10');                 % R4 volumest ↙
roommeting ruwwater
PS_R5_Flow                   = evalin('base','HEZ305_FT10');                 % R5 volumest ↙
roommeting ruwwater
PS_R6_Flow                   = evalin('base','HEZ306_FT10');                 % R6 volumest ↙
roommeting ruwwater
PS_R1_Active                 = evalin('base','PS_R1_Active');                % R1 actief=1 ↙
 niet actief=0
PS_R2_Active                 = evalin('base','PS_R2_Active');                % R1 actief=1 ↙
 niet actief=0
PS_R3_Active                 = evalin('base','PS_R3_Active');                % R1 actief=1 ↙
 niet actief=0
PS_R4_Active                 = evalin('base','PS_R4_Active');                % R1 actief=1 ↙
 niet actief=0
PS_R5_Active                 = evalin('base','PS_R5_Active');                % R1 actief=1 ↙
 niet actief=0
PS_R6_Active                 = evalin('base','PS_R6_Active');                % R1 actief=1 ↙
 niet actief=0
PS_R1_TH_effluent            = evalin('base','HEZ301_QT10');                 % Presentatie ↙
 Totale Hardheid R1
PS_R1_TH_cascade             = evalin('base','HEZ3AF_QT10');                 % Totale Hard ↙
```

]



```
D:\Stimela\Stimela\First Month\My_projects\PWN_W...\WSControl.m       Page 2
September 23, 2009                                                 11:11:43 AM
heid before cascade
PS_R1_dP                    = evalin('base','HEZ301_PT10');             % R1 dP react ↙
uibrd
PS_R1_CSTR01_PelDiam        = evalin('base','PS_R1_CSTR01_PelDiam');    % R1 Pelletdi ↙
ameter van de afgetapte pellets
HEZ6AA_QT20                 = evalin('base'.'HEZ6AA_QT20');             % pH-meting a ↙
anvoer filter 1 tm 6
HEZ6AA_QT10                 = evalin('base','HEZ6AA_QT10');             % pH-meting a ↙
anvoer filter 7 tm 12
PS_R1_Ca_Meas               = evalin('base','PS_R1_Ca_Meas');           % Ca raw wate ↙
r
PS_M1_Ca_Meas               = evalin('base','PS_M1_Ca_Meas');           % Ca after re ↙
actor
if CurrentTime~=0
   Accuca=evalin('base','Accuca');
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Flow control PS Mensink
Raw_water_Street1_Flow = Raw_water_Total_Flow/3*2;  % Debiet ruw water PS Mensink straat 1
Raw_water_Street2_Flow = Raw_water_Total_Flow/3*1;  % Debiet ruw water PS Mensink straat 2

% setpoints die gebruikt worden voor de bepaling van de besturing van de ontharding
Setpoint_PS_RX_Flow            = 450;  % Amount of water for one pellet softening reactor ↙
 m3/h
Setpoint_Seeding_Sand          = 47;   % Seeding sand per amount of removed Ca in kg
Setpoint_Seeding_Ca            = 270;  % Amount of Ca removed for amount of Seeding sand ↙
 in kg
Setpoint_Final_Hardness        = 1.60; % Total Hardness Ca and Mg in mmol/l in clean wate ↙
r reservoir

PS_Active_Reactors = [PS_R1_Active PS_R2_Active PS_R3_Active PS_R4_Active PS_R5_Active PS ↙
_R6_Active];

% Bepaling debiet setpoints voor reactoren, retourstroom en bypass
PS_RX_IN  = [450 666 1700 2000 2666 3100];
PS_RX_UIT = [400 600 1150 1750 2000 2600];

% inschakelen
if  Raw_water_Street1_Flow > Raw_water_Street1_Flow_previous
    PS_Active_Reactors(find(PS_RX_IN<=Raw_water_Street1_Flow)) = 1;
    PS_RX_Flow = PS_Active_Reactors*Setpoint_PS_RX_Flow;
    PS_R1_Flow = PS_RX_Flow(1);
    PS_R2_Flow = PS_RX_Flow(2);
    PS_R3_Flow = PS_RX_Flow(3);
    PS_R4_Flow = PS_RX_Flow(4);
    PS_R5_Flow = PS_RX_Flow(5);
    PS_R6_Flow = PS_RX_Flow(6);
end

% uitschakelen
if Raw_water_Street1_Flow <= Raw_water_Street1_Flow_previous
    PS_Active_Reactors(find(PS_RX_UIT>Raw_water_Street1_Flow))=0;
    PS_RX_Flow = PS_Active_Reactors*Setpoint_PS_RX_Flow;
```

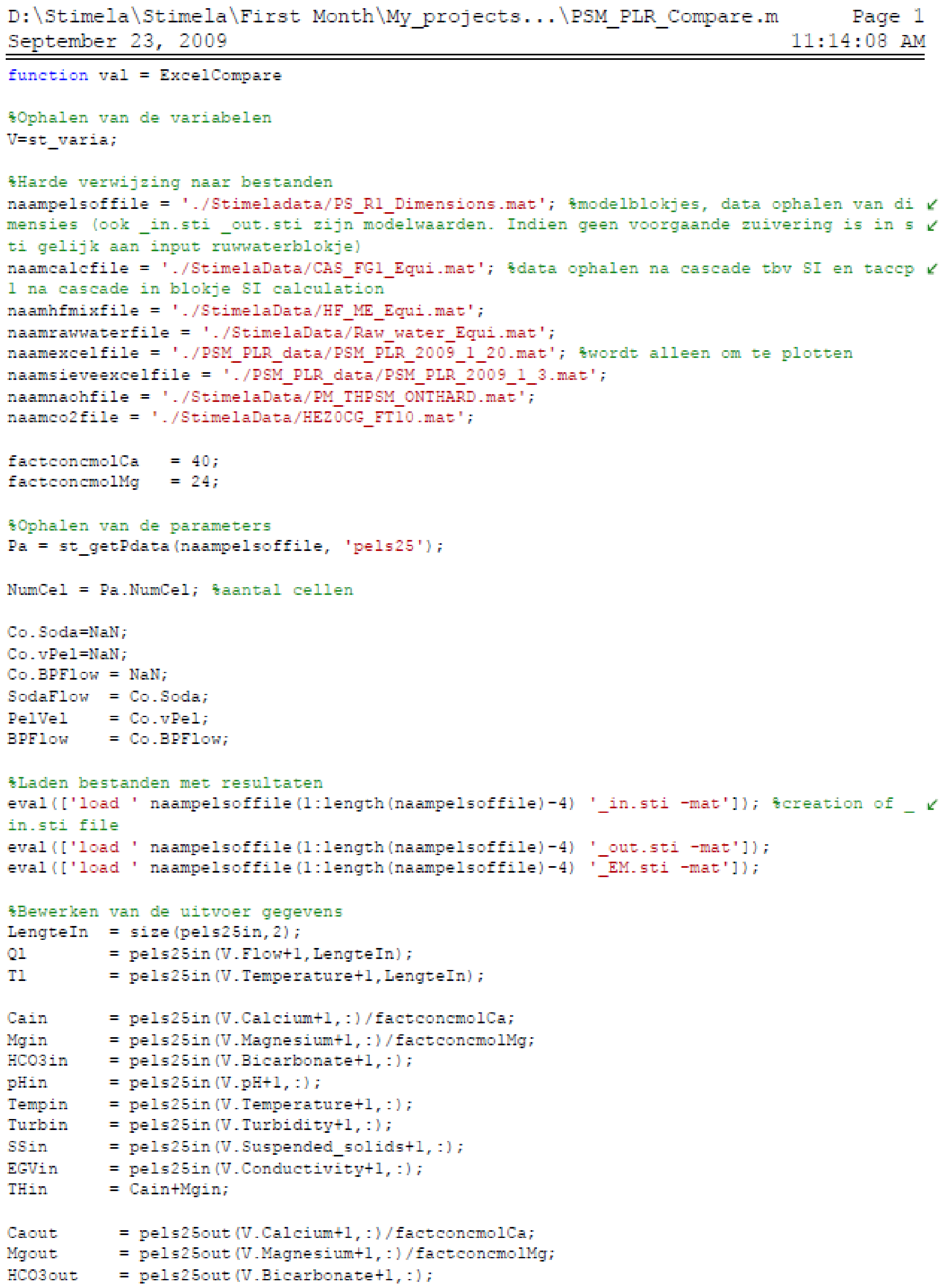
```
    PS_R1_Flow = PS_RX_Flow(1);
    PS_R2_Flow = PS_RX_Flow(2);
    PS_R3_Flow = PS_RX_Flow(3);
    PS_R4_Flow = PS_RX_Flow(4);
    PS_R5_Flow = PS_RX_Flow(5);
    PS_R6_Flow = PS_RX_Flow(6);
end
PS_RX_Flow_Total = PS_R1_Flow+PS_R2_Flow+PS_R3_Flow+PS_R4_Flow+PS_R5_Flow+PS_R6_Flow;
if Raw_water_Street1_Flow < PS_RX_Flow_Total
    PS_Flow_Retour = PS_RX_Flow_Total-Raw_water_Street1_Flow;
    PS_Flow_Bypass = 0;
else
    PS_Flow_Retour = 0;
    PS_Flow_Bypass = Raw_water_Street1_Flow - PS_RX_Flow_Total;
end
PS_Active_Reactors_Total = sum(PS_Active_Reactors);

% Determination of pellet softeners that are active
PS_R1_Active = PS_Active_Reactors(1,1);
PS_R2_Active = PS_Active_Reactors(1,2);
PS_R3_Active = PS_Active_Reactors(1,3);
PS_R4_Active = PS_Active_Reactors(1,4);
PS_R5_Active = PS_Active_Reactors(1,5);
PS_R6_Active = PS_Active_Reactors(1,6);



% Pellet Softening control

% Bepaling natronloogdebiet in l/h
Setpoint_PS_mixed_effluent_TH = ((Raw_water_Street_1+Raw_water_Street_2+RO_water_Street)* ↙
Setpoint_Final_Hardness-RO_Hardness*RO_water_Street-Raw_water_TH*Raw_water_Street_2)/Raw_ ↙
water_Street_1;
PS_R1_NaOH_dosage_1 = (Raw_water_TH - Setpoint_PS_mixed_effluent_TH)*0.125*Raw_water_Stre ↙
et1_Flow/PS_Active_Reactors_Total;
PS_R1_NaOH_dosage = PS_R1_NaOH_dosage_1+(PS_R1_TH_cascade-Setpoint_PS_mixed_effluent_TH)* ↙
0.125*Raw_water_Street1_Flow/PS_Active_Reactors_Total;

if PS_mixed_effluent_TH > Raw_water_TH
    PS_R1_NaOH_dosage = 0;
end
if PS_R1_NaOH_dosage <= 10
    PS_R1_NaOH_dosage = 0;
end

% Determination of CO2 dosage on the basis of pH of the effluent of the weir aerator
CO2_Dosage_min = 0;   % Nm3/hour

CO2_Dosage_Total = ((PS_R1_NaOH_dosage*1.277*0.25*1000/40) - ((PS_M1_Ca_Meas - PS_R1_Ca_M ↙
eas)/1000*1000*Setpoint_PS_RX_Flow))*PS_Active_Reactors_Total*(8.31*(273+12))/101325;


if CO2_Dosage_Total >= 2*76
  CO2_Dosage_Total = 2*76;
end
if CO2_Dosage_Total <= CO2_Dosage_min
  CO2_Dosage_Total = CO2_Dosage_min;
```

```
end
HEZ0CG_FT10 = CO2_Dosage_Total/2;
HEZ0CG_FT20 = CO2_Dosage_Total-HEZ0CG_FT10;

% Bepaling van aantal sand
if CurrentTime==0
   Accuca = 0;
end
Ca = (Raw_water_TH-PS_R1_TH_effluent)*(40.08/1000)*(PS_R1_Flow*24)*Deltatime/3600/24;
Accuca = Accuca + Ca;
if Accuca >= Setpoint_Seeding_Ca
   PS_R1_Seeding = Setpoint_Seeding_Sand/7.0*24*60;
   Accuca = 0;
else
   PS_R1_Seeding = 0;
end

% Bepaling van aantal pellets voor aftap obv de drukval over het bed
if PS_R1_dP >= 1.80
PS_R1_Pellets = 50*60*24;
else
PS_R1_Pellets = 0;
end

% Conversion of units for pellets discharge from kg/day to 1000 pellets/s
PS_conversion_kgperday_1000persec = (6/(2700*3.14*1000*24*3600))*(1/(PS_R1_CSTR01_PelDiam ↙
/1000))^3;

% Flow for rapid sand filters
% Filter building 1
PipeID_SF_F01_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F01_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ501_OA03 = Raw_water_Street1_Flow/12;

PipeID_SF_F02_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F02_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ502_OA03 = Raw_water_Street1_Flow/12;

PipeID_SF_F03_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F03_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ503_OA03 = Raw_water_Street1_Flow/12;

PipeID_SF_F04_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F04_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ504_OA03 = Raw_water_Street1_Flow/12;

PipeID_SF_F05_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F05_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ505_OA03 = Raw_water_Street1_Flow/12;

PipeID_SF_F06_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F06_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ506_OA03 = Raw_water_Street1_Flow/12;

PipeID_SF_F07_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F07_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ507_OA03 = Raw_water_Street1_Flow/12;
```

```
PipeID_SF_F08_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F08_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ508_OA03 = Raw_water_Street1_Flow/12;

PipeID_SF_F09_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F09_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ509_OA03 = Raw_water_Street1_Flow/12;

PipeID_SF_F10_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F10_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ510_OA03 = Raw_water_Street1_Flow/12;

PipeID_SF_F11_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F11_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ511_OA03 = Raw_water_Street1_Flow/12;

PipeID_SF_F12_syphonA = Raw_water_Street1_Flow/24;
PipeID_SF_F12_syphonB = Raw_water_Street1_Flow/24;
ValveID_HEZ512_OA03 = Raw_water_Street1_Flow/12;

% Filter building 2

PipeID_SF_F13_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F13_syphonB = Raw_water_Street2_Flow/24;
ValveID_HEZ513_OA03 = Raw_water_Street2_Flow/12;

PipeID_SF_F14_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F14_syphonB = Raw_water_Street2_Flow/24;
ValveID_HEZ514_OA03 = Raw_water_Street2_Flow/12;

PipeID_SF_F15_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F15_syphonB = Raw_water_Street2_Flow/24;
ValveID_HEZ515_OA03 = Raw_water_Street2_Flow/12;

PipeID_SF_F16_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F16_syphonB = Raw_water_Street2_Flow/24;
ValveID_HEZ516_OA03 = Raw_water_Street2_Flow/12;

PipeID_SF_F17_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F17_syphonB = Raw_water_Street2_Flow/24;
ValveID_HEZ517_OA03 = Raw_water_Street2_Flow/12;

PipeID_SF_F18_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F18_syphonB = Raw_water_Street2_Flow/24;
ValveID_HEZ518_OA03 = Raw_water_Street2_Flow/12;

PipeID_SF_F19_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F19_syphonB = Raw_water_Street2_Flow/24;
ValveID_HEZ519_OA03 = Raw_water_Street2_Flow/12;

PipeID_SF_F20_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F20_syphonB = Raw_water_Street2_Flow/24;
ValveID_HEZ520_OA03 = Raw_water_Street2_Flow/12;

PipeID_SF_F21_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F21_syphonB = Raw_water_Street2_Flow/24;
```

```
ValveID_HEZ521_OA03 = Raw_water_Street2_Flow/12;

PipeID_SF_F22_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F22_syphonB = Raw_water_Street2_Flow/24;
ValveID_HEZ522_OA03 = Raw_water_Street2_Flow/12;

PipeID_SF_F23_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F23_syphonB = Raw_water_Street2_Flow/24;
ValveID_HEZ523_OA03 = Raw_water_Street2_Flow/12;

PipeID_SF_F24_syphonA = Raw_water_Street2_Flow/24;
PipeID_SF_F24_syphonB = Raw_water_Street2_Flow/24;
ValveID_HEZ524_OA03 = Raw_water_Street2_Flow/12;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% writing resulting data to control input
assignin('base','HEZ2AA_FT10',                       Raw_water_Street1_Flow);
assignin('base','HEZ2AA_FT20',                       Raw_water_Street2_Flow);
assignin('base','HEZ301_FT10',                       PS_R1_Flow);
assignin('base','HEZ302_FT10',                       PS_R2_Flow);
assignin('base','HEZ303_FT10',                       PS_R3_Flow);
assignin('base','HEZ304_FT10',                       PS_R4_Flow);
assignin('base','HEZ305_FT10',                       PS_R5_Flow);
assignin('base','HEZ306_FT10',                       PS_R6_Flow);
assignin('base','PS_Flow_Retour',                    PS_Flow_Retour);
assignin('base','PS_Flow_Bypass',                    PS_Flow_Bypass);
assignin('base','PS_R1_Active',                      PS_R1_Active);
assignin('base','PS_R2_Active',                      PS_R2_Active);
assignin('base','PS_R3_Active',                      PS_R3_Active);
assignin('base','PS_R4_Active',                      PS_R4_Active);
assignin('base','PS_R5_Active',                      PS_R5_Active);
assignin('base','PS_R6_Active',                      PS_R6_Active);
assignin('base','PM_THPSM_ONTHARD',                  PS_R1_NaOH_dosage);
assignin('base','PS_R1_Seeding',                     PS_R1_Seeding);
assignin('base','PS_R1_Pellets',                     PS_R1_Pellets);
assignin('base','PS_conversion_kgperday_1000persec', PS_conversion_kgperday_1000persec);
assignin('base','HEZ0CG_FT10',                       HEZ0CG_FT10);
assignin('base','HEZ0CG_FT20',                       HEZ0CG_FT20);
assignin('base','Accuca',                            Accuca);
assignin('base','PipeID_SF_F01_syphonA',             PipeID_SF_F01_syphonA);
assignin('base','PipeID_SF_F01_syphonB',             PipeID_SF_F01_syphonB);
assignin('base','ValveID_HEZ501_OA03',               ValveID_HEZ501_OA03);
assignin('base','PipeID_SF_F02_syphonA',             PipeID_SF_F02_syphonA);
assignin('base','PipeID_SF_F02_syphonB',             PipeID_SF_F02_syphonB);
assignin('base','ValveID_HEZ502_OA03',               ValveID_HEZ502_OA03);
assignin('base','PipeID_SF_F03_syphonA',             PipeID_SF_F03_syphonA);
assignin('base','PipeID_SF_F03_syphonB',             PipeID_SF_F03_syphonB);
assignin('base','ValveID_HEZ503_OA03',               ValveID_HEZ503_OA03);
assignin('base','PipeID_SF_F04_syphonA',             PipeID_SF_F04_syphonA);
assignin('base','PipeID_SF_F04_syphonB',             PipeID_SF_F04_syphonB);
assignin('base','ValveID_HEZ504_OA03',               ValveID_HEZ504_OA03);
assignin('base','PipeID_SF_F05_syphonA',             PipeID_SF_F05_syphonA);
assignin('base','PipeID_SF_F05_syphonB',             PipeID_SF_F05_syphonB);
assignin('base','ValveID_HEZ505_OA03',               ValveID_HEZ505_OA03);
assignin('base','PipeID_SF_F06_syphonA',             PipeID_SF_F06_syphonA);
assignin('base','PipeID_SF_F06_syphonB',             PipeID_SF_F06_syphonB);
assignin('base','ValveID_HEZ506_OA03',               ValveID_HEZ506_OA03);
```

Original results compare file



D:\Stimela\Stimela\First Month\My_projects...\PSM_PLR_Compare.m Page 1
September 23, 2009 11:14:08 AM

```
function val = ExcelCompare

%Ophalen van de variabelen
V=st_varia;

%Harde verwijzing naar bestanden
naampelsoffile = './Stimeladata/PS_R1_Dimensions.mat'; %modelblokjes, data ophalen van di ↙
mensies (ook _in.sti _out.sti zijn modelwaarden. Indien geen voorgaande zuivering is in s ↙
ti gelijk aan input ruwwaterblokje)
naamcalcfile = './StimelaData/CAS_FG1_Equi.mat'; %data ophalen na cascade tbv SI en taccp ↙
1 na cascade in blokje SI calculation
naamhfmixfile = './StimelaData/HF_ME_Equi.mat';
naamrawwaterfile = './StimelaData/Raw_water_Equi.mat';
naamexcelfile = './PSM_PLR_data/PSM_PLR_2009_1_20.mat'; %wordt alleen om te plotten
naamsieveexcelfile = './PSM_PLR_data/PSM_PLR_2009_1_3.mat';
naamnaohfile = './StimelaData/PM_THPSM_ONTHARD.mat';
naamco2file = './StimelaData/HEZ0CG_FT10.mat';

factconcmolCa   = 40;
factconcmolMg   = 24;

%Ophalen van de parameters
Pa = st_getPdata(naampelsoffile, 'pels25');

NumCel = Pa.NumCel; %aantal cellen

Co.Soda=NaN;
Co.vPel=NaN;
Co.BPFlow = NaN;
SodaFlow  = Co.Soda;
PelVel    = Co.vPel;
BPFlow    = Co.BPFlow;

%Laden bestanden met resultaten
eval(['load ' naampelsoffile(1:length(naampelsoffile)-4) '_in.sti -mat']); %creation of _ ↙
in.sti file
eval(['load ' naampelsoffile(1:length(naampelsoffile)-4) '_out.sti -mat']);
eval(['load ' naampelsoffile(1:length(naampelsoffile)-4) '_EM.sti -mat']);

%Bewerken van de uitvoer gegevens
LengteIn  = size(pels25in,2);
Q1        = pels25in(V.Flow+1,LengteIn);
T1        = pels25in(V.Temperature+1,LengteIn);

Cain      = pels25in(V.Calcium+1,:)/factconcmolCa;
Mgin      = pels25in(V.Magnesium+1,:)/factconcmolMg;
HCO3in    = pels25in(V.Bicarbonate+1,:);
pHin      = pels25in(V.pH+1,:);
Tempin    = pels25in(V.Temperature+1,:);
Turbin    = pels25in(V.Turbidity+1,:);
SSin      = pels25in(V.Suspended_solids+1,:);
EGVin     = pels25in(V.Conductivity+1,:);
THin      = Cain+Mgin;

Caout      = pels25out(V.Calcium+1,:)/factconcmolCa;
Mgout      = pels25out(V.Magnesium+1,:)/factconcmolMg;
HCO3out    = pels25out(V.Bicarbonate+1,:);
```

```
pHout      = pels25out(V.pH+1,:);
Tempout    = pels25out(V.Temperature+1,:);
Turbout    = pels25out(V.Turbidity+1,:);
SSout      = pels25out(V.Suspended_solids+1,:);
EGVout     = pels25out(V.Conductivity+1,:);
THout      = Caout+Mgout;


%Extra measurements (EM)
time = pels25EM(1,:);
dP = pels25EM(2,:);
Diam = pels25EM(4,:);
BedHeight = pels25EM(3,:);
dDiam = pels25EM(1+1*Pa.NumCel+(1:Pa.NumCel),:);
dpe   = pels25EM(1+2*Pa.NumCel+(1:Pa.NumCel),:);
dPL   = pels25EM(1+3*Pa.NumCel+(1:Pa.NumCel),:);
dPX   = pels25EM(1+5*Pa.NumCel+(1:Pa.NumCel),:);
dv    = pels25EM(1+6*Pa.NumCel+(1:Pa.NumCel),:);
dPX   = dPX./dPL;


% determine time fraction
timespan=time(end)-time(1);
dt=60;
dttxt='Minutes';
if timespan>3600
  dt=3600;
  dttxt='Hours';
end
if timespan>2*24*3600
  dt=3600*24;
  dttxt='Days';
end


% after chemical equilibrium
eval(['load ' naamcalcfile(1:length(naamcalcfile)-4) '_out.sti -mat']);
eval(['load ' naamcalcfile(1:length(naamcalcfile)-4) '_EM.sti -mat']);

Camix = calceqout(V.Calcium+1,:)/factconcmolCa;
Mgmix = calceqout(V.Magnesium+1,:)/factconcmolMg;
HCO3mix = calceqout(V.Bicarbonate+1,:);
pHmix = calceqout(V.pH+1,:);
Tempmix = calceqout(V.Temperature+1,:);
Turbmix = calceqout(V.Turbidity+1,:);
SSmix = calceqout(V.Suspended_solids+1,:);
EGVmix = calceqout(V.Conductivity+1,:);
THmix  = Camix+Mgmix;

% na reactor
TCCP = calceqEM(3,:);
SI = calceqEM(2,:);

% HF mixer
eval(['load ' naamhfmixfile(1:length(naamhfmixfile)-4) '_out.sti -mat']);
eval(['load ' naamhfmixfile(1:length(naamhfmixfile)-4) '_ES.sti -mat']);
```

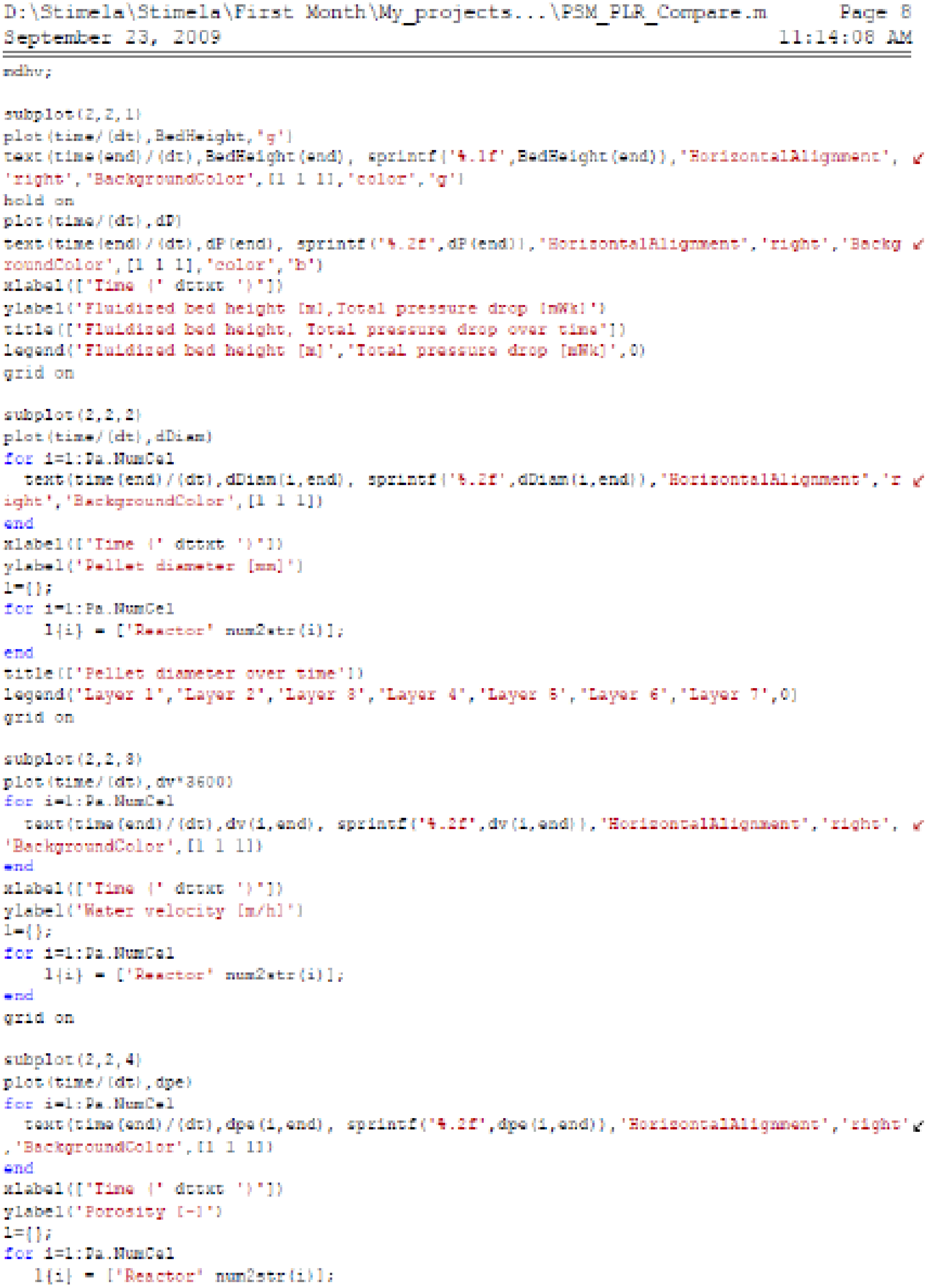
```
Cahfmix = calceqout(V.Calcium+1,:)/factconcmolCa;
Mghfmix = calceqout(V.Magnesium+1,:)/factconcmolMg;
HCO3hfmix = calceqout(V.Bicarbonate+1,:);
pHhfmix = calceqout(V.pH+1,:);
Temphfmix = calceqout(V.Temperature+1,:);
EGVhfmix = calceqout(V.Conductivity+1,:);
THhfmix = Cahfmix+Mghfmix

TCCPhfmix = calceqEM(3,:);
SIhfmix = calceqEM(2,:);

%Raw water
eval(['load ' naamrawwaterfile(1:length(naamrawwaterfile)-4) '_in.sti -mat']);
eval(['load ' naamrawwaterfile(1:length(naamrawwaterfile)-4) '_EM.sti -mat']);
Carawwater = calceqin(V.Calcium+1,:)/factconcmolCa;
Mgrawwater = calceqin(V.Magnesium+1,:)/factconcmolMg;
HCO3rawwater = calceqin(V.Bicarbonate+1,:);
pHrawwater = calceqin(V.pH+1,:);
Temprawwater = calceqin(V.Temperature+1,:);
EGVrawwater = calceqin(V.Conductivity+1,:);
THrawwater = Carawwater+Mgrawwater


SIrawwater = calceqEM(2,:);
TCCPrawwater = calceqEM(3,:);

%Laden resultaten vanuit excel
eval(['load ' naamexcelfile]);
Data=[];

%Laden resultaten vanuit sieveexcel
eval(['load ' naamsieveexcelfile]);
Data=[];

%Omzetten van getallen naar strings voor weergave
AT        = sprintf('%.1f',Pa.A);
kg0T       = sprintf('%.2f',Pa.kg0);
d0T       = sprintf('%.2f',Pa.d0);
rhogT     = sprintf('%.0f',Pa.rhog);
rhosT     = sprintf('%.0f',Pa.rhos);
NumCelT   = sprintf('%.0f',Pa.NumCel);
Q1T       = sprintf('%.1f',Q1);
T1T       = sprintf('%.1f',T1);
SodaFlowT = sprintf('%.1f',SodaFlow);
PelVelT   = sprintf('%.1f',PelVel);
BPFlowT   = sprintf('%.1f',BPFlow);


figure
mdhv;

%NaOH dosage
eval(['load ' naamnaohfile(1:length(naamnaohfile)-4) '_EM.sti -mat']);
NaOH = wssetcEM(2,:);

%CO2 dosage
eval(['load ' naamco2file(1:length(naamco2file)-4) '_EM.sti -mat']);
```

```
CO2 = wssetcEM(2,:);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% ↙
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
subplot(2,2,1)
plot(time/(dt),NaOH,'r','LineWidth',2)
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Amount of NaOH (l/h)')
title(['Dosage of NaOH'])
legend('NaOH calculated',0)
grid on

subplot(2,2,2)
plot(time/(dt),CO2*2*1.98/44.01/2400*1000,'b','LineWidth',2)
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Amount of CO2 (mmol/l)')
title(['Dosage of CO2'])
legend('CO2 calculated',0)
set(gca,'ylim',[0 0.8])
grid on

figure
mdhv;

subplot(2,2,1)
plot(time/(dt),Carawwater,'r','LineWidth',2)
hold on
plot(PLR_2009_1_20_Ca_PWM_PO_INF2670(1,:)/(dt),PLR_2009_1_20_Ca_PWM_PO_INF2670(2,:)/factc ↙
oncmolCa,'r*')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Calcium (mmol/l)')
title(['Calcium concentration'])
legend('Raw water calculated','Raw water measured',0)
set(gca,'ylim',[0 3])
grid on

subplot(2,2,2)
plot(time/(dt),Mgrawwater,'r','LineWidth',2)
hold on
plot(PLR_2009_1_20_Mg_PWM_PO_INF2700(1,:)/(dt),PLR_2009_1_20_Mg_PWM_PO_INF2700(2,:)/factc ↙
oncmolMg,'r*')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Magnesium (mmol/l)')
title(['Magnesium concentration'])
legend('Raw water calculated','Raw water measured',0)
set(gca,'ylim',[0 1])
grid on

subplot(2,2,3)
plot(time/(dt),Temprawwater,'r','LineWidth',2)
hold on
plot(PLR_2009_1_20_Temp_PWM_PO_INF1915(1,:)/(dt),PLR_2009_1_20_Temp_PWM_PO_INF1915(2,:),' ↙
r*')
```

```
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Temperature (oC)')
title(['Temperature'])
legend('Raw water calculated','Raw water measured',0)
set(gca,'ylim',[0 15])
grid on

subplot(2,2,4)
plot(time/(dt),pHrawwater,'r','LineWidth',2)
hold on
plot(PLR_2009_1_20_pH_PWM_PO_INF2210(1,:)/(dt),PLR_2009_1_20_pH_PWM_PO_INF2210(2,:),'r*')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('pH (-)')
title(['pH'])
legend('Raw water calculated','Raw water measured',0)
set(gca,'ylim',[6 10])
grid on

figure
mdhv;


subplot(2,2,1)
plot(time/(dt),EGVrawwater,'r','LineWidth',2)
hold on
plot(PLR_2009_1_20_EGV_PWM_PO_INF1685(1,:)/(dt),PLR_2009_1_20_EGV_PWM_PO_INF1685(2,:),'r*'↙
)
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('EGV (mS/m)')
title(['Conductivity'])
legend('Raw water calculated','Raw water measured',0)
set(gca,'ylim',[0 80])
grid on

subplot(2,2,2)
plot(time/(dt),HCO3rawwater,'r','LineWidth',2)
hold on
plot(PLR_2009_1_20_HCO3_PWM_PO_INF2420(1,:)/(dt),PLR_2009_1_20_HCO3_PWM_PO_INF2420(2,:),' ↙
r*')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Bicarbonate (mg/l)')
title(['Bicarbonate concentration'])
legend('Raw water calculated','Raw water measured',0)
set(gca,'ylim',[0 250])
grid on

subplot(2,2,3)
plot(time/(dt),SIrawwater,'r','LineWidth',2)
hold on
plot(PLR_2009_1_20_SI_PWM_PO_INF2310(1,:)/(dt),PLR_2009_1_20_SI_PWM_PO_INF2310(2,:),'r*')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('SI (-)')
```

```
title(['Saturation Index'])
legend('Raw water calculated','Raw water measured',0)
set(gca,'ylim',[-0.5 1.5])
grid on

subplot(2,2,4)
plot(time/(dt),THrawwater,'r','LineWidth',2)
hold on
plot(PLR_2009_1_20_TH_PWM_PO_INF2810(1,:)/(dt),PLR_2009_1_20_TH_PWM_PO_INF2810(2,:),'r*')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('TH (mmol/l)')
title(['Total Hardness'])
legend('Raw water calculated','Raw water measured',0)
set(gca,'ylim',[0 3.0])
grid on

figure
mdhv;

subplot(2,2,1)
plot(time/(dt),Camix,'LineWidth',2)
hold on
plot(PLR_2009_1_20_Ca_PWM_CASC_EFF2670(1,:)/(dt),PLR_2009_1_20_Ca_PWM_CASC_EFF2670(2,:)/f ↙
actconcmolCa,'o')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Calcium (mmol/l)')
title(['Calcium concentration'])
legend('Weir aerator effluent calculated','Weir aerator effluent measured',0)
set(gca,'ylim',[0 3])
grid on

subplot(2,2,2)
plot(time/(dt),Mgmix,'LineWidth',2)
hold on
plot(PLR_2009_1_20_Mg_PWM_CASC_EFF2700(1,:)/(dt),PLR_2009_1_20_Mg_PWM_CASC_EFF2700(2,:)/f ↙
actconcmolMg,'o')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Magnesium (mmol/l)')
title(['Magnesium concentration'])
legend('Weir aerator effluent calculated','Weir aerator effluent measured',0)
set(gca,'ylim',[0 1])
grid on

subplot(2,2,4)
plot(time/(dt),pHmix,'LineWidth',2)
hold on
plot(PLR_2009_1_20_pH_PWM_CASC_EFF2210(1,:)/(dt),PLR_2009_1_20_pH_PWM_CASC_EFF2210(2,:),' ↙
o')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('pH (-)')
title(['pH'])
legend('Weir aerator effluent calculated','Weir aerator effluent measured',0)
set(gca,'ylim',[6 10])
```

```
grid on

figure
mdhv;

subplot(2,2,1)
plot(time/(dt),EGVmix,'LineWidth',2)
hold on
plot(PLR_2009_1_20_EGV_PWM_CASC_EFF1685(1,:)/(dt),PLR_2009_1_20_EGV_PWM_CASC_EFF1685(2,:),↙
'o')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('EGV (mS/m)')
title(['Conductivity'])
legend('Weir aerator effluent calculated','Weir aerator effluent measured',0)
set(gca,'ylim',[0 80])
grid on

subplot(2,2,2)
plot(time/(dt),HCO3mix,'LineWidth',2)
hold on
plot(PLR_2009_1_20_HCO3_PWM_CASC_EFF2420(1,:)/(dt),PLR_2009_1_20_HCO3_PWM_CASC_EFF2420(2, ↙
:),'o')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Bicarbonate (mg/l)')
title(['Bicarbonate concentration'])
legend('Weir aerator effluent calculated','Weir aerator effluent measured',0)
set(gca,'ylim',[0 250])
grid on

subplot(2,2,3)
plot(time/(dt),SI,'LineWidth',2)
hold on
plot(PLR_2009_1_20_SI_PWM_CASC_EFF2310(1,:)/(dt),PLR_2009_1_20_SI_PWM_CASC_EFF2310(2,:),' ↙
o')
xlabel(['Time (' dttxt ')'])
Ylabel('SI (-)')
title(['Saturation Index'])
legend('Weir aerator effluent calculated','Weir aerator effluent measured',0)
set(gca,'ylim',[-0.5 1.5])
grid on

subplot(2,2,4)
plot(time/(dt),THmix,'LineWidth',2)
hold on
plot(PLR_2009_1_20_TH_PWM_CASC_EFF2810(1,:)/(dt),PLR_2009_1_20_TH_PWM_CASC_EFF2810(2,:),' ↙
o')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('TH (mmol/l)')
title(['Total Hardness'])
legend('Weir aerator effluent calculated','Weir aerator effluent measured',0)
set(gca,'ylim',[0 2.6])
grid on

figure
```



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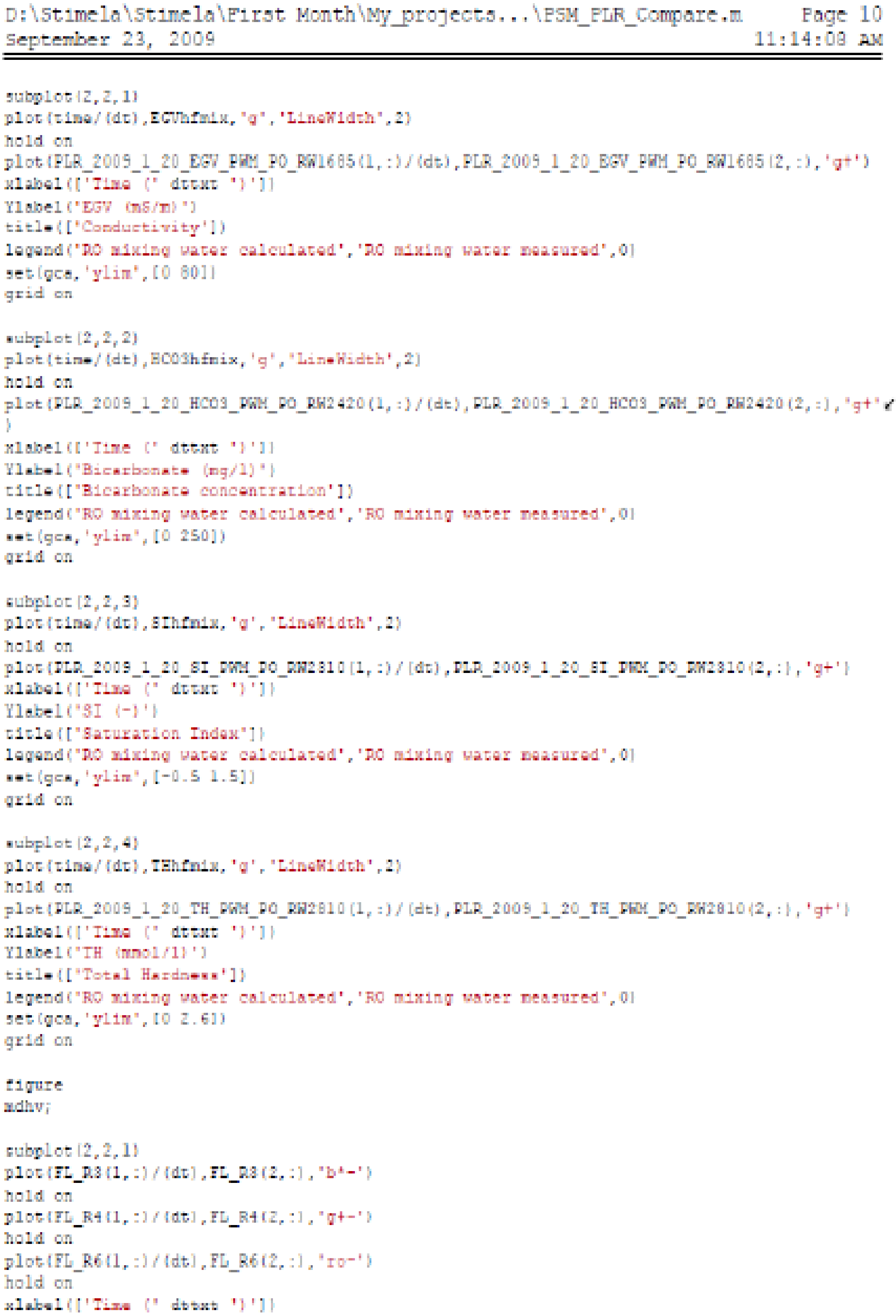
```
mdhv;

subplot(2,2,1)
plot(time/(dt),BedHeight,'g')
text(time(end)/(dt),BedHeight(end), sprintf('%.1f',BedHeight(end)),'HorizontalAlignment', ↙
'right','BackgroundColor',[1 1 1],'color','g')
hold on
plot(time/(dt),dP)
text(time(end)/(dt),dP(end), sprintf('%.2f',dP(end)),'HorizontalAlignment','right','Backg ↙
roundColor',[1 1 1],'color','b')
xlabel(['Time (' dttxt ')'])
ylabel('Fluidized bed height [m],Total pressure drop [mWk]')
title(['Fluidised bed height, Total pressure drop over time'])
legend('Fluidised bed height [m]','Total pressure drop [mWk]',0)
grid on

subplot(2,2,2)
plot(time/(dt),dDiam)
for i=1:Pa.NumCel
  text(time(end)/(dt),dDiam(i,end), sprintf('%.2f',dDiam(i,end)),'HorizontalAlignment','r ↙
ight','BackgroundColor',[1 1 1])
end
xlabel(['Time (' dttxt ')'])
ylabel('Pellet diameter [mm]')
l={};
for i=1:Pa.NumCel
    l{i} = ['Reactor' num2str(i)];
end
title(['Pellet diameter over time'])
legend('Layer 1','Layer 2','Layer 3','Layer 4','Layer 5','Layer 6','Layer 7',0)
grid on

subplot(2,2,3)
plot(time/(dt),dv*3600)
for i=1:Pa.NumCel
  text(time(end)/(dt),dv(i,end), sprintf('%.2f',dv(i,end)),'HorizontalAlignment','right', ↙
'BackgroundColor',[1 1 1])
end
xlabel(['Time (' dttxt ')'])
ylabel('Water velocity [m/h]')
l={};
for i=1:Pa.NumCel
    l{i} = ['Reactor' num2str(i)];
end
grid on

subplot(2,2,4)
plot(time/(dt),dpe)
for i=1:Pa.NumCel
  text(time(end)/(dt),dpe(i,end), sprintf('%.2f',dpe(i,end)),'HorizontalAlignment','right'↙
,'BackgroundColor',[1 1 1])
end
xlabel(['Time (' dttxt ')'])
ylabel('Porosity [-]')
l={};
for i=1:Pa.NumCel
   l{i} = ['Reactor' num2str(i)];
```

```
end
title(['Pellet porosity over time'])
legend('Layer 1','Layer 2','Layer 3','Layer 4','Layer 5','Layer 6','Layer 7',0)
grid on

figure
mdhv;

subplot(2,2,1)
plot(time/(dt),Cahfmix,'g','LineWidth',2)
hold on
plot(PLR_2009_1_20_Ca_PWM_PO_RW2670(1,:)/(dt),PLR_2009_1_20_Ca_PWM_PO_RW2670(2,:)/factcon ↙
cmolCa,'g+')
xlabel(['Time (' dttxt ')'])
Ylabel('Calcium (mmol/l)')
title(['Calcium concentration'])
legend('RO mixing water calculated','RO mixing water measured',0)
set(gca,'ylim',[0 3])
grid on

subplot(2,2,2)
plot(time/(dt),Mghfmix,'g','LineWidth',2)
hold on
plot(PLR_2009_1_20_Mg_PWM_PO_RW2700(1,:)/(dt),PLR_2009_1_20_Mg_PWM_PO_RW2700(2,:)/factcon ↙
cmolMg,'g+')
xlabel(['Time (' dttxt ')'])
Ylabel('Magnesium (mmol/l)')
title(['Magnesium concentration'])
legend('RO mixing water calculated','RO mixing water measured',0)
set(gca,'ylim',[0 1])
grid on

subplot(2,2,3)
plot(time/(dt),Temphfmix,'g','LineWidth',2)
hold on
plot(PLR_2009_1_20_Temp_PWM_PO_RW1915(1,:)/(dt),PLR_2009_1_20_Temp_PWM_PO_RW1915(2,:),'g+'↙
)
xlabel(['Time (' dttxt ')'])
Ylabel('Temperature (oC)')
title(['Temperature'])
legend('RO mixing water calculated','RO mixing water measured',0)
set(gca,'ylim',[0 15])
grid on

subplot(2,2,4)
plot(time/(dt),pHhfmix,'g','LineWidth',2)
hold on
plot(PLR_2009_1_20_pH_PWM_PO_RW2210(1,:)/(dt),PLR_2009_1_20_pH_PWM_PO_RW2210(2,:),'g+')
xlabel(['Time (' dttxt ')'])
Ylabel('pH (-)')
title(['pH'])
legend('RO mixing water calculated','RO mixing water measured',0)
set(gca,'ylim',[6 10])
grid on

figure
mdhv;
```



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```
subplot(2,2,1)
plot(time/(dt),EGVhfmix,'g','LineWidth',2)
hold on
plot(PLR_2009_1_20_EGV_PWM_PO_RW1685(1,:)/(dt),PLR_2009_1_20_EGV_PWM_PO_RW1685(2,:),'g+')
xlabel(['Time (' dttxt ')'])
Ylabel('EGV (mS/m)')
title(['Conductivity'])
legend('RO mixing water calculated','RO mixing water measured',0)
set(gca,'ylim',[0 80])
grid on

subplot(2,2,2)
plot(time/(dt),HCO3hfmix,'g','LineWidth',2)
hold on
plot(PLR_2009_1_20_HCO3_PWM_PO_RW2420(1,:)/(dt),PLR_2009_1_20_HCO3_PWM_PO_RW2420(2,:),'g+'↙
)
xlabel(['Time (' dttxt ')'])
Ylabel('Bicarbonate (mg/l)')
title(['Bicarbonate concentration'])
legend('RO mixing water calculated','RO mixing water measured',0)
set(gca,'ylim',[0 250])
grid on

subplot(2,2,3)
plot(time/(dt),SIhfmix,'g','LineWidth',2)
hold on
plot(PLR_2009_1_20_SI_PWM_PO_RW2810(1,:)/(dt),PLR_2009_1_20_SI_PWM_PO_RW2810(2,:),'g+')
xlabel(['Time (' dttxt ')'])
Ylabel('SI (-)')
title(['Saturation Index'])
legend('RO mixing water calculated','RO mixing water measured',0)
set(gca,'ylim',[-0.5 1.5])
grid on

subplot(2,2,4)
plot(time/(dt),THhfmix,'g','LineWidth',2)
hold on
plot(PLR_2009_1_20_TH_PWM_PO_RW2810(1,:)/(dt),PLR_2009_1_20_TH_PWM_PO_RW2810(2,:),'g+')
xlabel(['Time (' dttxt ')'])
Ylabel('TH (mmol/l)')
title(['Total Hardness'])
legend('RO mixing water calculated','RO mixing water measured',0)
set(gca,'ylim',[0 2.6])
grid on

figure
mdhv;

subplot(2,2,1)
plot(FL_R3(1,:)/(dt),FL_R3(2,:),'b*-')
hold on
plot(FL_R4(1,:)/(dt),FL_R4(2,:),'g+-')
hold on
plot(FL_R6(1,:)/(dt),FL_R6(2,:),'ro-')
hold on
xlabel(['Time (' dttxt ')'])
```

```
Ylabel('Measured fluidized bed height (m)')
title(['Measured fluidized bed height over time for reactors'])
legend('Reactor 3','Reactor 4','Reactor 6',0)
set(gca,'ylim',[2 4.2])
grid on

subplot(2,2,2)
plot(R3_L1(1,:)/(dt),R3_L1(2,:),'b*-')
hold on
plot(R3_L2(1,:)/(dt),R3_L2(2,:),'g+-')
hold on
plot(R3_L3(1,:)/(dt),R3_L3(2,:),'ro-')
hold on
plot(R3_L4(1,:)/(dt),R3_L4(2,:),'c^-')
hold on
plot(R3_L5(1,:)/(dt),R3_L5(2,:),'m.-')
hold on
plot(R3_L6(1,:)/(dt),R3_L6(2,:),'yp-')
hold on
plot(R3_L7(1,:)/(dt),R3_L7(2,:),'kd-')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Pellet diameter (mm)')
title(['Pellet diameter over time for reactor 3'])
legend('Layer 1','Layer 2','Layer 3','Later 4','Layer 5','Layer 6','Layer 7',0)
set(gca,'ylim',[0.3 0.9])
grid on

subplot(2,2,3)
plot(R4_L1(1,:)/(dt),R4_L1(2,:),'b*-')
hold on
plot(R4_L2(1,:)/(dt),R4_L2(2,:),'g+-')
hold on
plot(R4_L3(1,:)/(dt),R4_L3(2,:),'ro-')
hold on
plot(R4_L4(1,:)/(dt),R4_L4(2,:),'c^-')
hold on
plot(R4_L5(1,:)/(dt),R4_L5(2,:),'m.-')
hold on
plot(R4_L6(1,:)/(dt),R4_L6(2,:),'yp-')
hold on
plot(R4_L7(1,:)/(dt),R4_L7(2,:),'kd-')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Pellet diameter (mm)')
title(['Pellet diameter over time for reactor 4'])
legend('Layer 1','Layer 2','Layer 3','Later 4','Layer 5','Layer 6','Layer 7',0)
set(gca,'ylim',[0.2 1.2])
grid on

subplot(2,2,4)
plot(R6_L1(1,:)/(dt),R6_L1(2,:),'b*-')
hold on
plot(R6_L2(1,:)/(dt),R6_L2(2,:),'g+-')
hold on
plot(R6_L3(1,:)/(dt),R6_L3(2,:),'ro-')
hold on
```

```
plot(R6_L4(1,:)/(dt),R6_L4(2,:),'c^-')
hold on
plot(R6_L5(1,:)/(dt),R6_L5(2,:),'m.-')
hold on
plot(R6_L6(1,:)/(dt),R6_L6(2,:),'yp-')
hold on
plot(R6_L7(1,:)/(dt),R6_L7(2,:),'kd-')
hold on
xlabel(['Time (' dttxt ')'])
Ylabel('Pellet diameter (mm)')
title(['Pellet diameter over time for reactor 6'])
legend('Layer 1','Layer 2','Layer 3','Later 4','Layer 5','Layer 6','Layer 7',0)
set(gca,'ylim',[0 1.5])
grid on
```