Feasibility of booster pumps in a waste water transportation system: a case study

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ABSTRACT

A new waste water treatment plant will be built in the western harbour of Amsterdam, replacing two existing plants closer to the city centre. The distance from many waste water collection basins to the treatment plant will rise to about 20 kilometres (12.5 miles). The pressure rating of the pipes and the installed power of many waste water pumps in the collection basins are insufficient to meet the design flow rates. Furthermore storage space, even underground, is extremely expensive in Amsterdam. Therefore, the Water Management and Sewage Services in Amsterdam prefer to apply booster pumps in the waste water transportation system, which is an innovation in waste water system design. Two major questions arise if booster pumps are applied:

- Is the concept feasible from a hydraulic point of view? Can the booster pumps cope with the highly fluctuating supply of waste water (domestic and storm water)?
- How should the control system of the booster stations operate without violating the strict pressure criteria?

This paper addresses both questions in detail for the waste water transportation system of the city of Amsterdam.

keywords: waste water, booster station design, control strategy.

1 INTRODUCTION

A new waste water treatment plant (WWTP) will be built in the western harbour of Amsterdam, replacing two existing plants closer to the city centre. The distance from many sewage collection basins to the treatment plant will rise to about 20 kilometres (12.5 miles). The pressure rating of the pipes and the installed power of many sewage pumps in the collection basins are insufficient to meet the design flow rates. Furthermore storage space, even underground, is extremely expensive in Amsterdam. Therefore, the Water Management and Sewage Services in Amsterdam (DWR) prefer to apply booster pumps in the waste water transportation system (WWTS), which is an innovation in waste water system design. Two major questions arise if booster pumps are applied:

- Is the concept feasible from a hydraulic viewpoint? Can the booster pumps cope with the highly fluctuating supply of sewage water (from households and storm surges)?
- How should the control system operate the booster pumps without violating the strict pressure criteria?

The application of booster pumps has become standard practise for transportation of fluids over long distances. Oil, dredging slurries and chemicals are being transported since many decades with booster pumps. However, booster pumps in a large WWTS have not been applied before. Due to the highly fluctuating supply of domestic waste water and storm water, high standards must be set on the control of the booster pumps. The waste water supply may rise from 0% to 100% of the design capacity within a few minutes without any warning in advance. Especially in summer periods, heavy showers cause jumps of waste water supply.

In 2001, WL | Delft Hydraulics has conducted a project for DWR on the above-mentioned feasibility and control questions. This paper will focus on the following key issues:

- Modelling the waste water transportation system
- Design of control strategy
- Important control parameters
- Stability of the control strategy
- Feasibility of booster station concept

2 MODELLING THE WWTS

The waste water transportation system (WWTS) is the pressurised pipe system from the waste water collection basins towards the treatment plant. It consists of two independent branched pipe systems: the South-West system and the East-North system.

Both systems include many supplying sewage pumping stations and two booster stations in series. The length of both main lines is similar (19.4 km and 20 km). However other characteristics are quite different (table 1, *figure 1*).

Table 1: WWTS characteristics

	East-North	South-West
Main length [km]	20	19.4
Aggregate pipe length [km]	44.4	45.6
Booster stations	2	2
Number of supplying pumping stations	10	25
Number of supplying pumps (excl. spare)	38	48
Design flow [l/s]	2801	5309
Booster station design flow [% of total capacity]	64 ; 100	30 ; 93

In order to design the control system, it is necessary to determine whether anti-surge devices are required for the booster stations, because these devices strongly affect the dynamic response of the system to control actions. Most of the supplying pumping stations include air vessels or other devices. The design philosophy for pressure surges is that every pumping station is responsible for the transients it creates.

The most critical scenario for the supplying sewage pumping stations is pump trip at maximum flow rate with minimum flow rate from other pumping stations. Some of the anti-surge devices have to be replaced or extended, because the design working point will change considerably.

The most critical scenario for the booster stations is pump trip at the maximum flow rate. The surge analyses of the booster stations show that no anti-surge devices are required. The pressure criteria for surge —0.3 bara (-7 m) and 4 or 6 barg— are not violated, because the flow through the by-pass starts early enough to balance the up- and downstream pressures. Furthermore, the booster pumps reduce in speed slowly.

The booster station concept is feasible, if a control system can be designed that keeps pressures in the main lines within the allowable range between 0 barg and the nominal pressure of 4 barg for existing pipes and 6 barg for new pipes in the WWTS.

The fact that no anti-surge devices are required, implies that pressure waves caused by starting or stopping booster pumps are hardly dampened. In order to find out whether a feasible control system can be designed, the simulation software must have specific capabilities. The computational capabilities of the software must include the integrated behaviour and interaction of the control strategy and the dynamic hydraulics. The control strategy is expected to act on a time scale of seconds, while the characteristic time for pressure waves in the two main lines is about 40 s (20 km and a wave speed of appr 1000 m/s). Hence the control system will strongly interact with the pressure wave propagation. The computer code WANDA of WL | Delft Hydraulics provides this functionality since 1998, when the Control module was added to the Transient module.

An overview of the South-West WWTS model in WANDA is shown in *figure 2a* and *figure 2b*.

3 DESIGN OF CONTROL STRATEGY

Once the hydraulic system design is known, we can focus on the control system. The starting point for the booster station control is analogous with a supplying sewage pumping station. A supplying pumping station starts emptying its collection basin, if a specified start-level has been exceeded, and stops again if the basin level has dropped to the stop-level. Large pumping stations with a significant dry weather flow (DWF) may have a target level in the collection basin, which is controlled with variable speed pumps; generally a PI-controller. This level controller is applied to all supplying pumping stations (*figure 3 and figure 4*).

An analogous control strategy for the booster stations would be the following:

- The booster station is activated if a certain suction pressure is exceeded. This implies that the booster station will not run all the time. Dry weather flow can be delivered to the WWTP through the by-passes in the booster stations.
- Then one or more, say N, primary pumps start running at a minimum specified speed. The minimum speed is required to prevent fouling, vibrations and failure.
- The activated booster pumps aim for a target suction pressure by means of a Proportional-Integrating (PI) controller. This is the simplest feasible controller, because a P-controller cannot maintain a target pressure under various system conditions. The activated pumps may run to their maximum speed to reach the target pressure.
- If the speed of the running pumps equals the maximum speed for a specified period, then another, secondary, pump is started.
- If the suction pressure drops below the target value, the running pumps reduce speed (altogether).
- If the speed of the running pumps equals the minimum speed for a certain period, then one secondary pump is stopped. Following a pump stop, the other pumps may increase speed again. This strategy prevents hunting, because the capacity change of a speed variation from the minimum to the maximum speed (typically 500 and 1200 rpm) exceeds the capacity change of one pump stop from the minimum speed.
- If the last N primary pumps are running at minimum speed and the suction pressure has dropped below the stop level for a certain period, then these pumps are stopped simultaneously.

In order to implement and verify this control strategy, the following control parameters have to be established:

- suction pressure for booster start,
- suction pressure for booster stop,
- target suction pressure,
- time delays for starting and stopping subsequent pumps,
- control parameters of PI control; the next section details these parameters.

The above-described control strategy is easily built in WANDA using 10 basic control components for booster station West: suction pressure signal, pump PI-control and 4 components for starting and stopping of pumps 3 and 4 when the pump speed of the previous pump has remained equal to the maximum (start) or minimum (stop) speed (see *figure 5*).

The difficulty we have to cope with in the Amsterdam WWTS is the sequence of two booster stations. The choice of the suction pressure must be such that the start of the second booster station will not lead to stop of the first booster station and vice versa. The main effect of a booster station start is the upstream pressure drop (*figure 6: difference between by-pass and booster mode at maximum by-pass flow rate*). Downstream of the second booster station the pressure will remain the same, if the total discharge remains the same. Therefore the suction pressure should be chosen such that the downstream booster station (i.e. North and West, see *Figure 1*) starts first. Another advantage of starting the downstream booster station first, is the fact that all supplying sewage pumps can profit from the lower line pressure.

A second point of attention for the choice of the suction pressure for booster start is the capacity of the supplying pumping stations. Directly upstream of the booster station, the line pressure in by-pass mode is greater than the line pressure in booster mode (*figure 7* and *figure 8*). Each individual supplying pumping station should be able to supply its design flow if the booster station suction pressure equals the start pressure. This situation is realistic if a local shower occurs in a supply area of one pumping station.

The suction pressure for booster stop should be low enough to prevent immediate restart of the booster station after having stopped. A logical additional requirement is that the stop pressure is above the minimum pressure (atmospheric pressure).

The target suction pressure is the suction pressure at which the design flow rate of all pumping stations can be realised. This pressure must fall within the range of stop and start suction pressure.

The time delays for secondary pumps have been set to a value just above the characteristic time of the upstream part of the main lines to allow one pressure wave to return to the suction side of the booster station.

It is noted that this control strategy relies on pressure measurements only. The reason is twofold: flow meters have a slower response than pressure meters and the most important constraints are pressure constraints from a safety point of view.

4 IMPORTANT CONTROL PARAMETERS

Instead of a trial-and-error approach on the control parameters of the two consecutive booster stations in each sewage main, a rather simple systematic approach was elaborated, which turned out give very good initial control parameters [1].

A PI controller for a pump is defined by the following equations:

$$\begin{aligned} \varepsilon(t) &= H_z(t) - H_{z,set} \\ Y_i(t) &= Y_i(t-dt) + X_r \cdot \frac{dt}{T_i} \cdot \varepsilon(t) \\ Y(t) &= X_r \cdot \varepsilon(t) + Y_i(t) + Offset \end{aligned}$$

where

$\varepsilon(t)$	error signal [m]
$H_z(t)$	measured or calculated suction head [m]
$H_{z,\, set}$	target value of suction head [m]
X_r	gain of controller [rpm/m]
T_i	integration time constant [s]
$Y_i(t)$	integration contribution to the output, i.e. pump speed [rpm]
Offset	offset value for pump speed [rpm]
$Y(t)$	controller output, pump speed [rpm]

Two parameters per controller have to be determined: the gain and the integration time constant.

The so-called step-response-method was elaborated to find good initial values of these control parameters. The main advantage of this method is the fact that it does not require any rudimentary control. The step-response-method is based on the transient caused by a sudden increase of the booster pump speed (the step). The PI parameters are derived from the dynamic response of the suction pressure (the response). The step-response-method was originally developed for second order control systems defined by two time constants, t_1 and t_2. The sudden increase of the booster pump speed causes a suction head drop, ΔH. The first time constant is determined by the time to reach 63% of the head drop following the steepest gradient of the dynamic head response. The second time constant is derived from the time to reach 73% of the head drop, say Δt_2. Then t_2 is determined as follows:

$$t_2 = \frac{\Delta t_2}{1.3} - t_1$$

The determination of the two time constants is illustrated in *figure 9: Step-response-method*.

The gain and integration time are computed as follows:

$$X_r = \frac{t_1}{t_2} \cdot \frac{\Delta N}{\Delta H}$$

$$T_i = t_1$$

where ΔN is the step in pump speed and ΔH is the suction head drop between initial and final state.

Figure 10: Simulated response and approximation illustrates the second order approximation (solid line) of the response (marked line) on a pump speed step of 20 rpm. The method has been applied at two different working points of the booster stations (at 50% and 100% of the flow capacity) and for three different pump speed steps (10, 20 and 30 rpm). The derived values of the gain and integration time did not change considerably in the different situations. Despite the fact that the approximation is relatively rough, the resulting control parameters provide very good initial values for the PI-controller.

5 STABILITY OF THE CONTROL STRATEGY

Pressure oscillations may occur after start of a booster station or as a consequence of interactions between both booster station control systems.

Several runs have been carried out to verify whether the calculated pressures remain within the allowable range (between zero bar and the pipe rating). The most critical runs are:

- Switch from by-pass mode to booster mode
- Switch from booster mode to by-pass mode

Only the switch from by-pass mode to booster mode will be discussed in this paper. The starting point for this scenario is a DWF of 8% of the flow capacity (night flow). This DWF is supplied by a few bigger supplying stations. All small supplying stations maintain a zero flow situation during this scenario, leading to a stiffer system response; this means that pressure waves, approaching a small supplying station, reflect completely and cannot be damped partially by a running pump.

The transient scenario, discussed in this paper, consists of an increase of the two main supply stations (Rhijnspoorplein and 1st Weteringplantsoen) from their DWF to maximum capacity flow in 5 minutes. This corresponds with a system capacity increase from 10% to 55%. The 5 minute increase is modelled at the collection reservoirs of Rhijnspoorplein and 1st Weteringplantsoen, causing the pumps to start when the level in the collection reservoir has exceeded the start-level. The result is that the flow from Rhijnspoorplein rises to 100% in 4 minutes and the flow from 1st Weteringplantsoen rises in 9 minutes to 100% (*Figure 11: Supply increase in two supply stations*).

As a consequence the suction and discharge heads of both booster stations rise. Since the start pressure of booster station West (downstream) is lower than that of booster station South, booster station West is activated first. The evolution of suction and discharge head are shown in *Figure 12*. Until 600 s the flow towards booster station West rises steadily. Therefore the pump speed rises to its maximum speed and maintains this speed 30 s (delay time). Nevertheless the suction pressure does not drop to the target level of 6 m. Therefore another pump starts after 570 s, causing a moderate pressure wave in the WWTS. Now the booster station is capable of maintaining the target level at 6 m (*Figure 12* and *Figure 13*). The other critical scenario’s show similar results.

6 FEASIBILITY OF BOOSTER STATION DESIGN

Following conclusions have been drawn from the study:

- The local booster station control strategy is feasible.
- This control strategy relies on the suction pressure only.
- The booster station control system manages flow fluctuations that are faster than in reality.
- Excitation phenomena are prevented by proper choice of the start-pressures and speed ranges of the pumps in the booster stations.
- The delay times for switching booster pumps on or off proved to be essential to prevent switches caused by travelling pressure waves.
- It was found that the booster station control may get difficulties by periodic start and stop of supplying pumping stations, causing the booster station to oscillate between by-pass mode and booster mode. Existing control systems of supplying pumping stations have to be reviewed on the risk of starting twice within 5 minutes.

Acknowledgements

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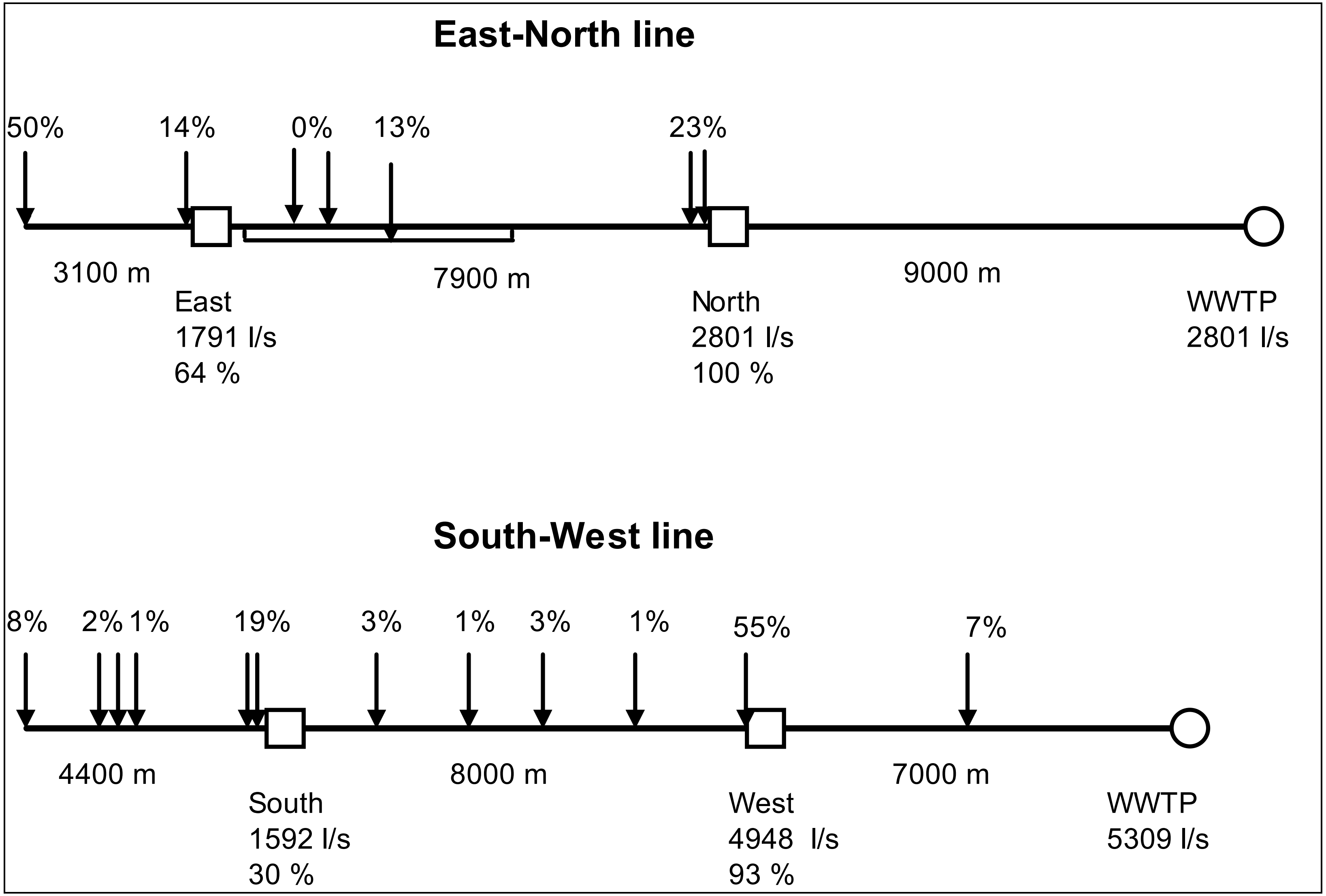


Figure 1: Flow distribution of main lines

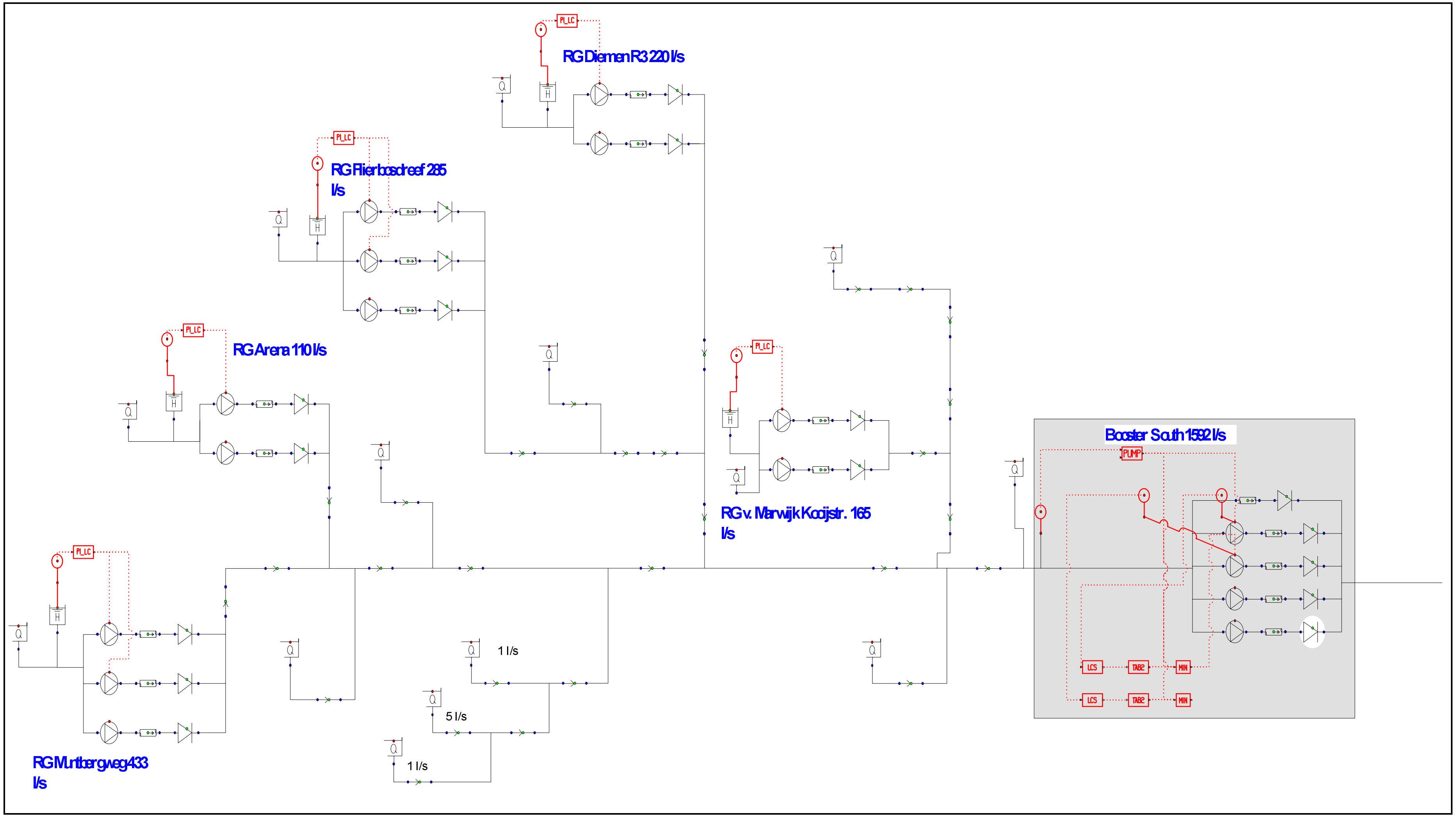


Figure 2a: Overview of WANDA model of South-West WWTS (upstream)

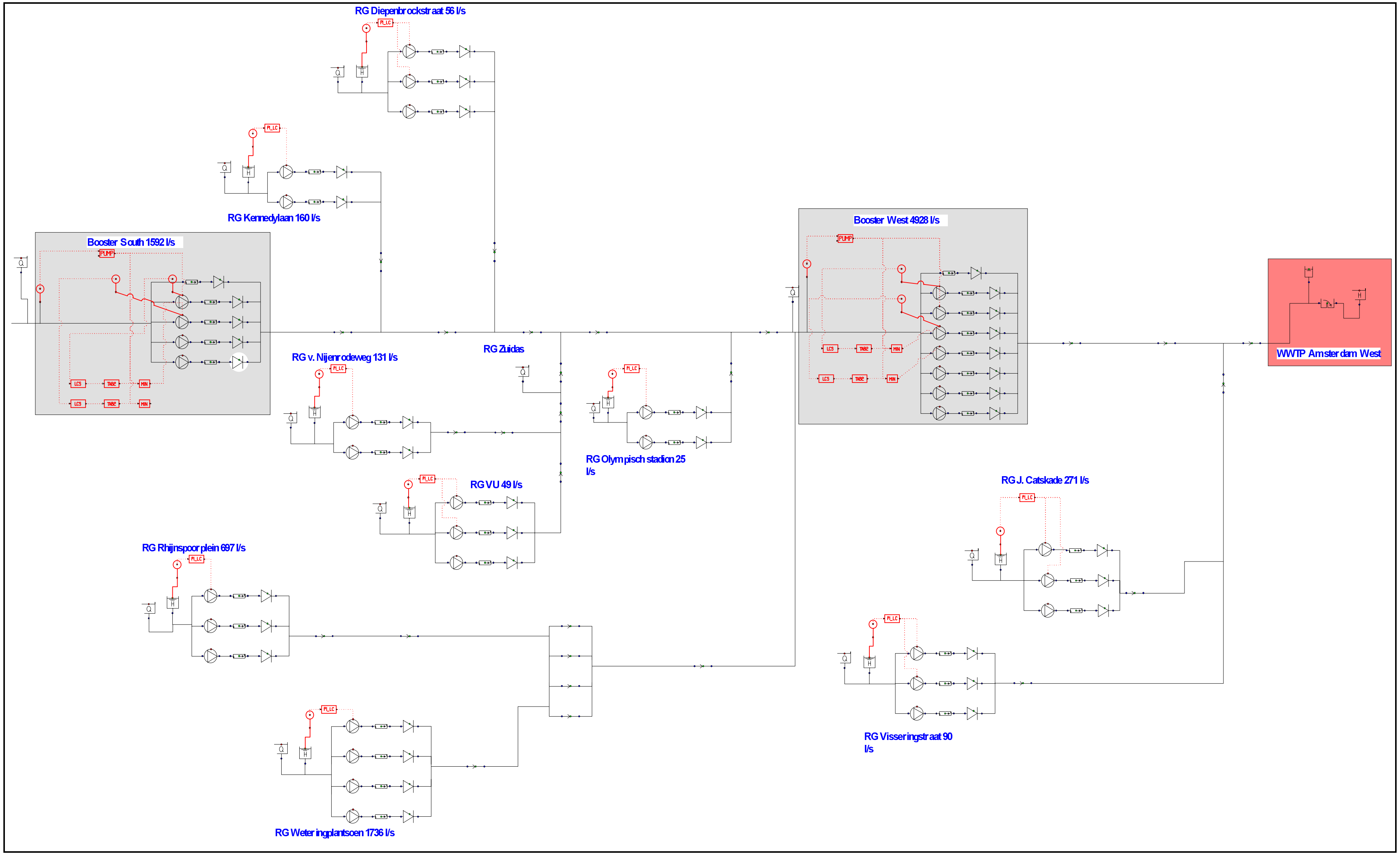


Figure 2b: Overview of WANDA model of South-West WWTS (downstream)

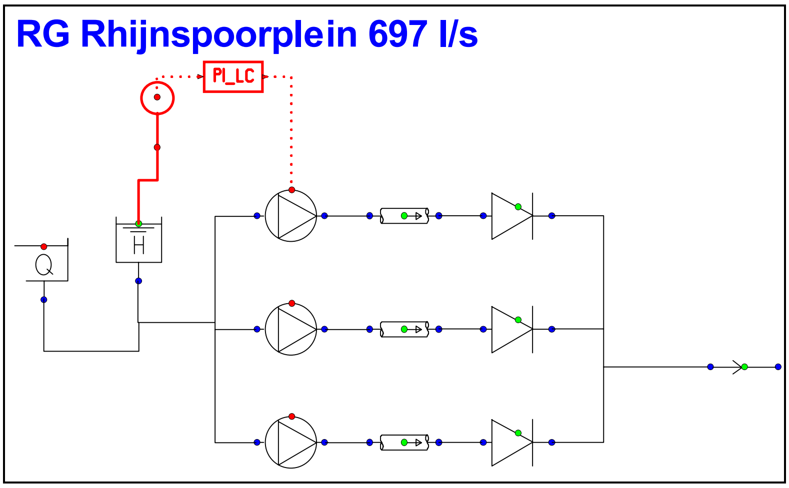
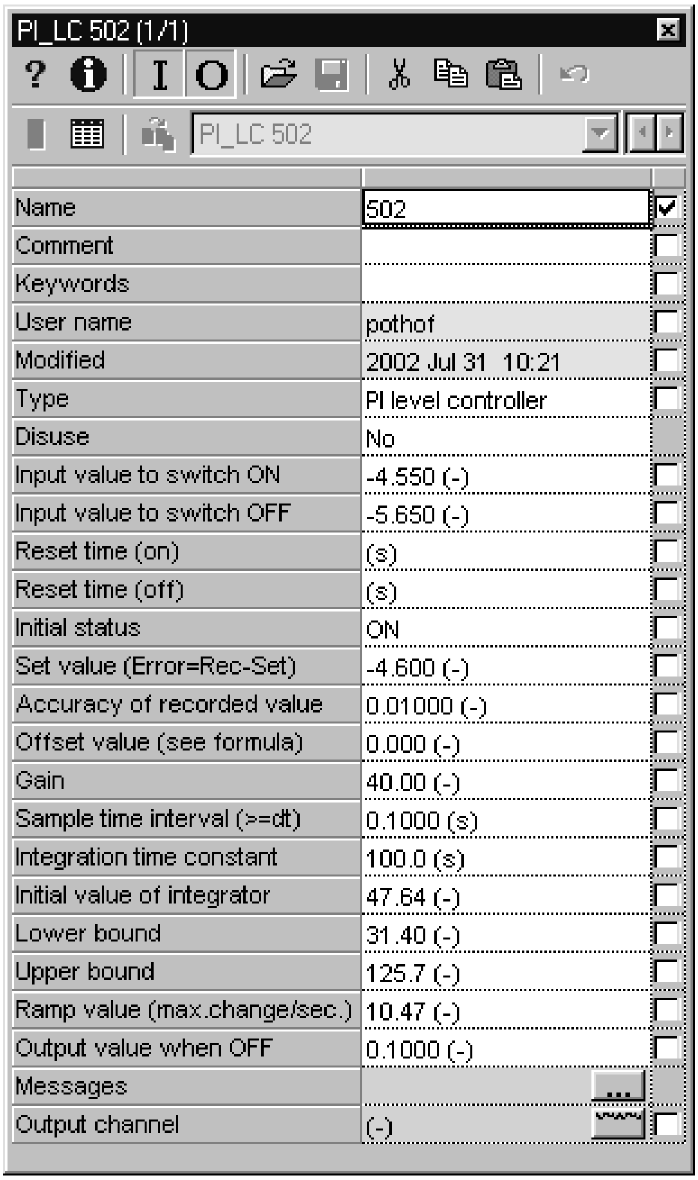


Figure 3: Control of supplying waste water pumping stations



Name	502	☑
Comment		☐
Keywords		☐
User name	pothof	☐
Modified	2002 Jul 31 10:21	☐
Type	PI level controller	☐
Disuse	No	
Input value to switch ON	-4.550 (-)	☐
Input value to switch OFF	-5.650 (-)	☐
Reset time (on)	(s)	☐
Reset time (off)	(s)	☐
Initial status	ON	☐
Set value (Error=Rec-Set)	-4.600 (-)	☐
Accuracy of recorded value	0.01000 (-)	☐
Offset value (see formula)	0.000 (-)	☐
Gain	40.00 (-)	☐
Sample time interval (>=dt)	0.1000 (s)	☐
Integration time constant	100.0 (s)	☐
Initial value of integrator	47.64 (-)	☐
Lower bound	31.40 (-)	☐
Upper bound	125.7 (-)	☐
Ramp value (max.change/sec.)	10.47 (-)	☐
Output value when OFF	0.1000 (-)	☐
Messages	...	
Output channel	(-)	☐

Figure 4: Control parameters of Rhijnspoorplein

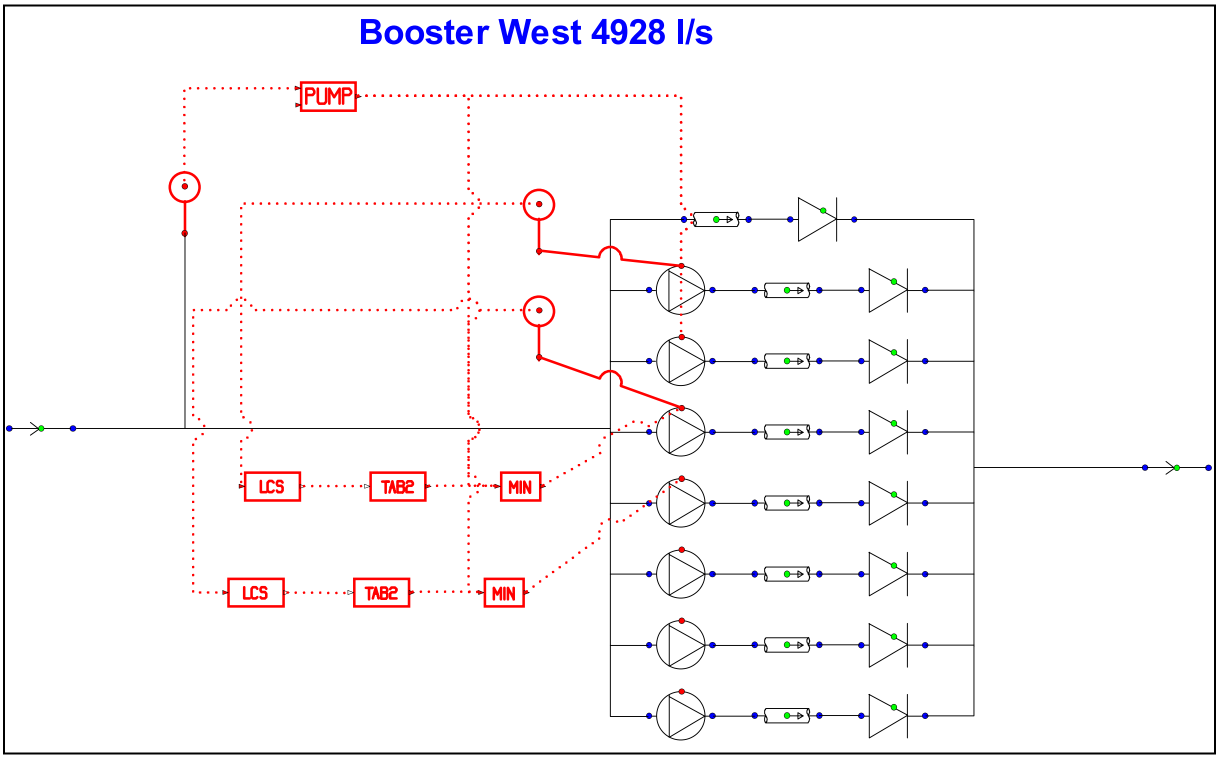


Figure 5: Control of booster station

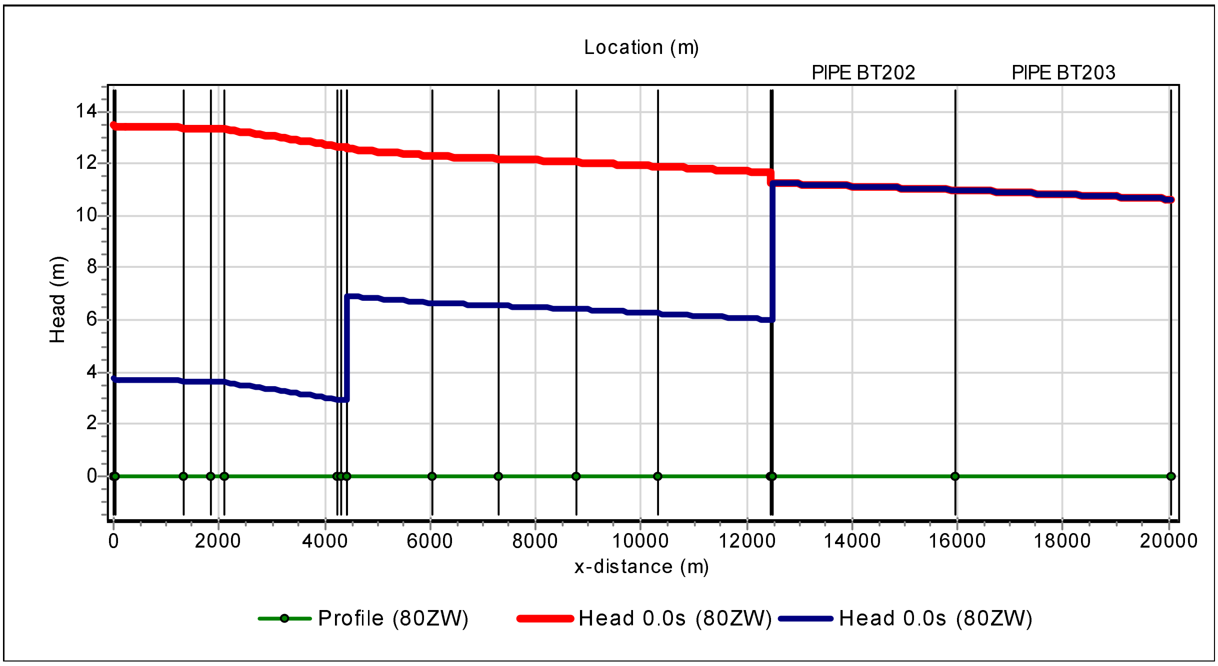


Figure 6: Head difference between by-pass mode and booster mode at maximum by-pass flow rate

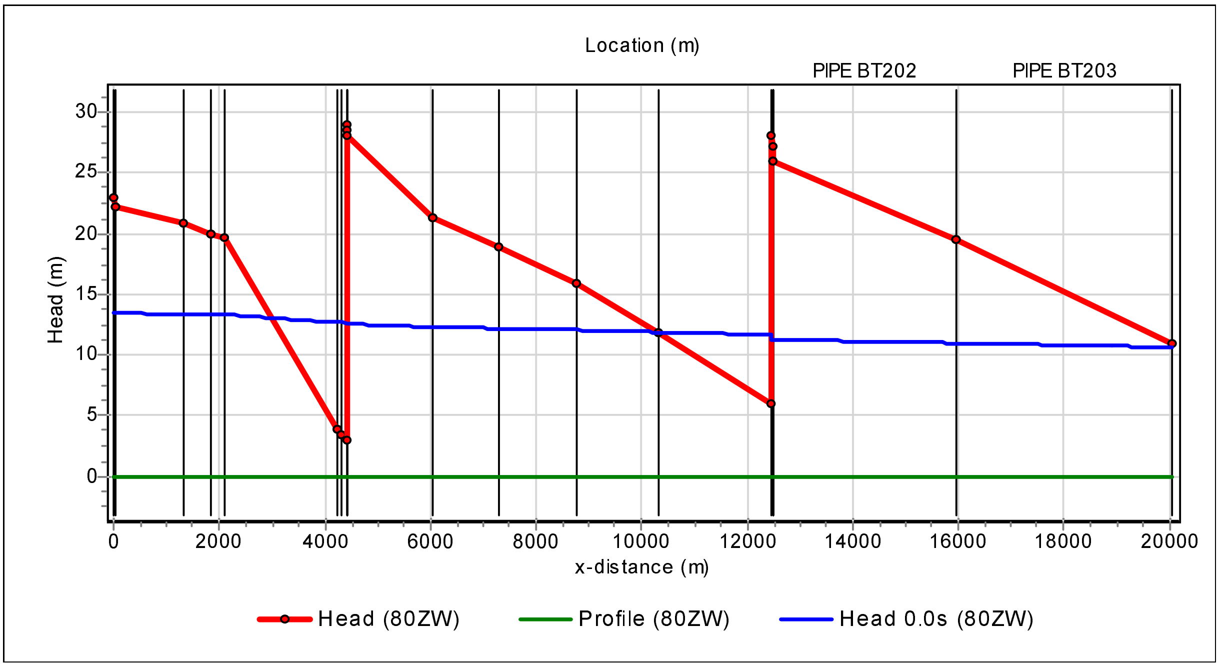


Figure 7: Hydraulic grade lines in the South-West main at maximum by-pass flow and maximum booster flow

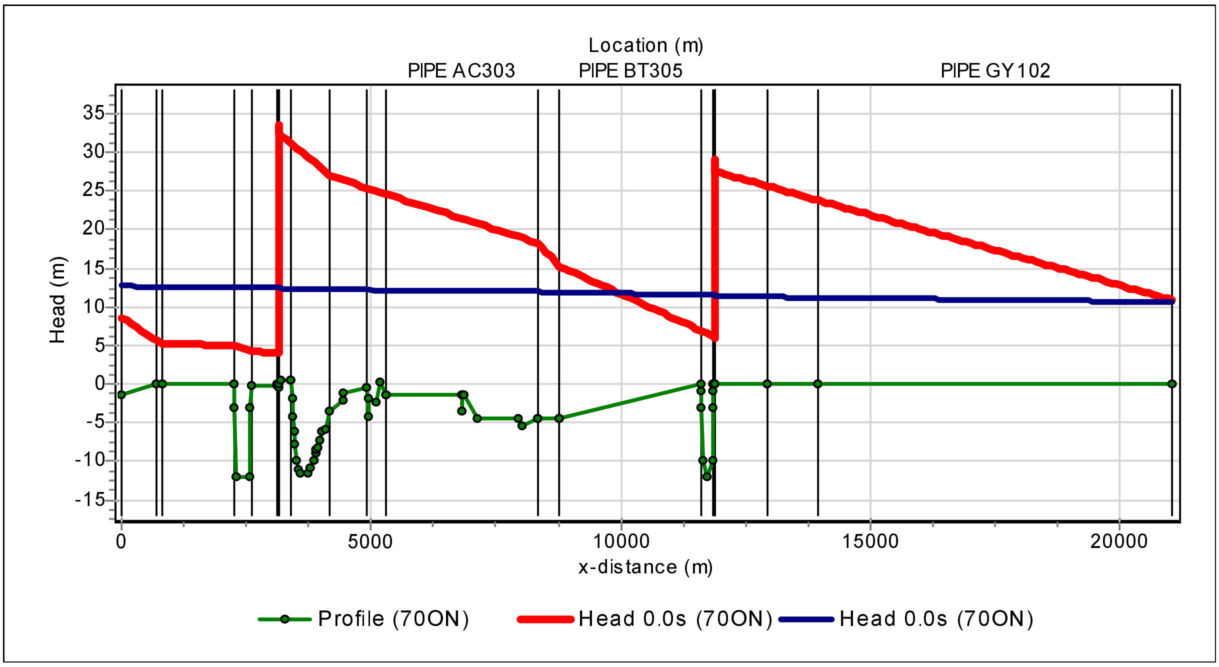


Figure 8: Hydraulic grade lines in the East-North main at maximum by-pass flow and maximum booster flow

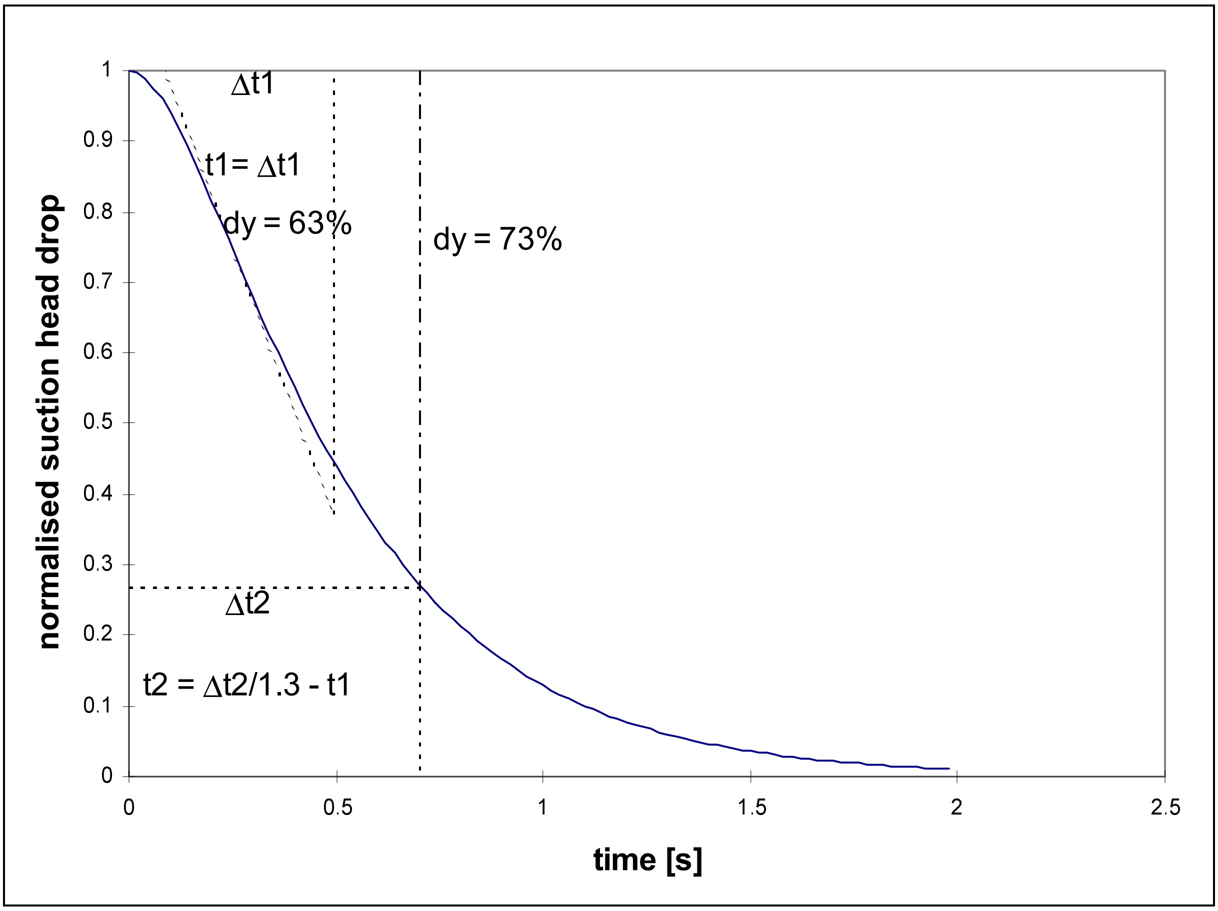


Figure 9: Step-response-method

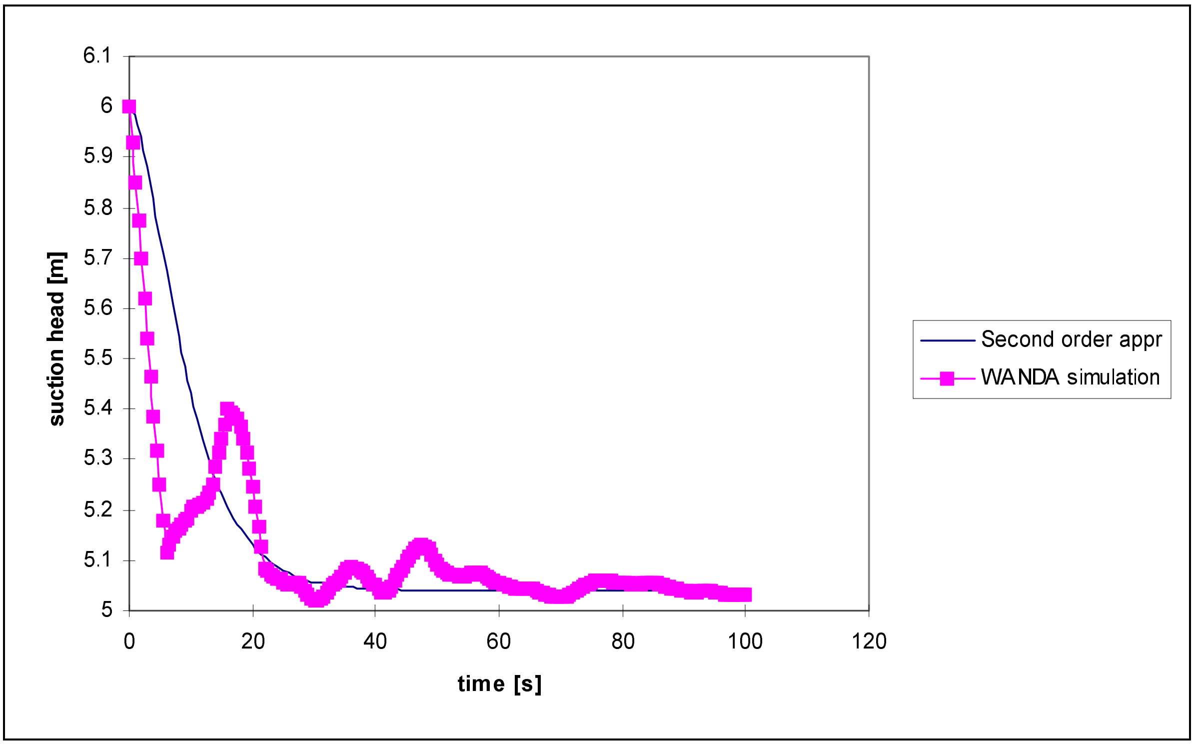


Figure 10: Simulated response and approximation

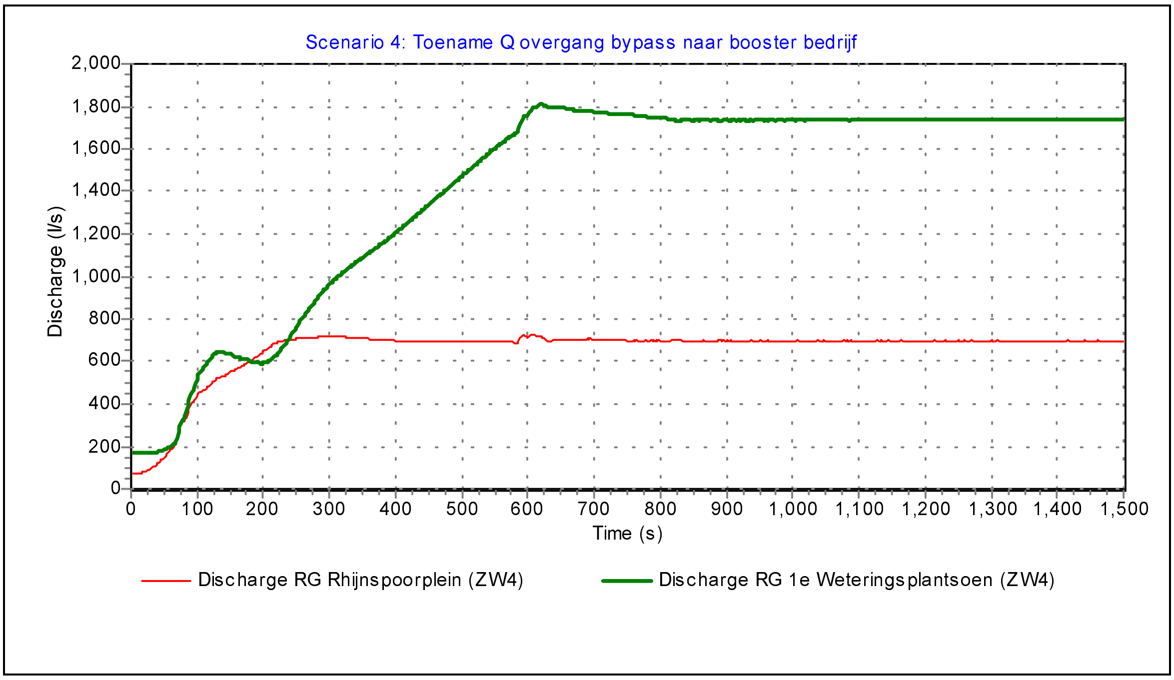


Figure 11: Supply increase in two supply stations

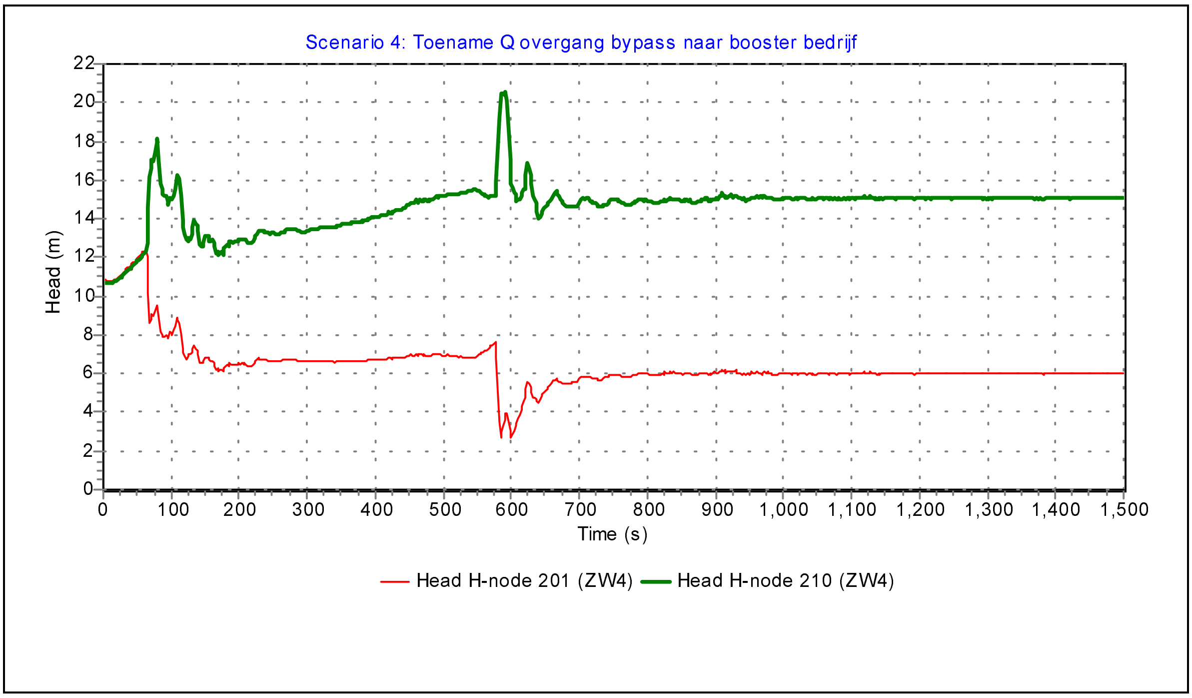


Figure 12: Time evolution of suction head and discharge head in booster station West

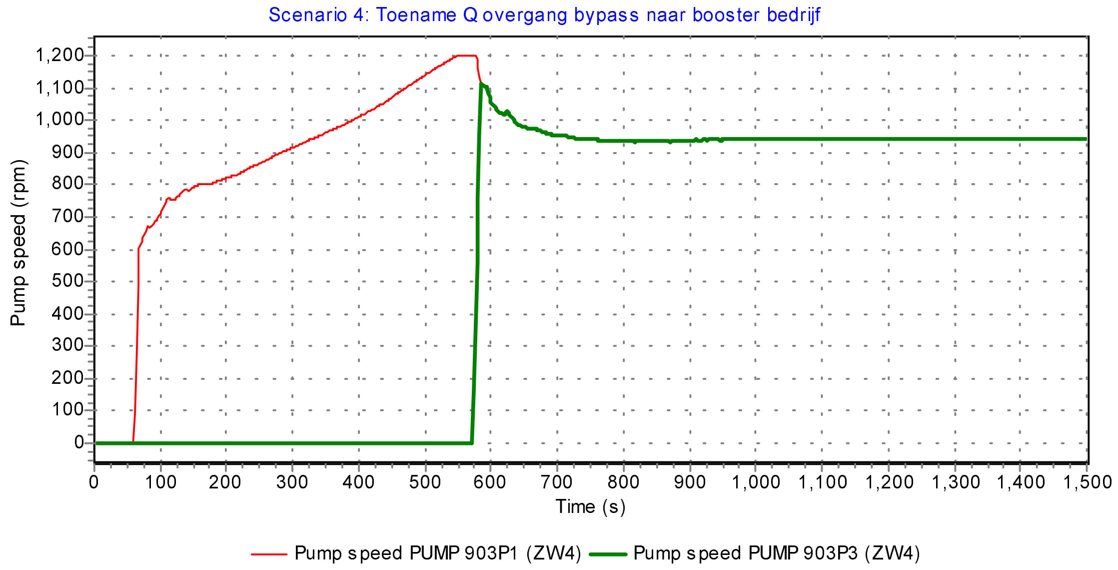


Figure 13: Pump speeds in booster station West