Design and performance evaluation of a simplified dynamic model for combined sewer overflows in pumped sewer systems

van Daal-Rombouts, Petra; Sun, Siao; Langeveld, Jeroen; Bertrand-Krajewski, J.-L.; Clemens, Francois

DOI
10.1016/j.jhydrol.2016.04.056

Publication date
2016

Document Version
Accepted author manuscript

Published in
Journal of Hydrology

Citation (APA)
van Daal-Rombouts, P., Sun, S., Langeveld, J., Bertrand-Krajewski, J.-L., & Clemens, F. (2016). Design and performance evaluation of a simplified dynamic model for combined sewer overflows in pumped sewer systems. *Journal of Hydrology*, *538*(July), 609-624. https://doi.org/10.1016/j.jhydrol.2016.04.056

DESIGN AND PERFORMANCE EVALUATION OF A SIMPLIFIED DYNAMIC MODEL FOR COMBINED SEWER OVERFLOWS IN PUMPED SEWER SYSTEMS

Petra VAN DAAL-ROMBOUTS[1,2,*], Siao SUN[3], Jeroen LANGEVELD[1,4], Jean-Luc BERTRAND-KRAJEWSKI[5], François CLEMENS[1,6]

[1] Delft University of Technology, P.O. Box 5048, 2600 GA Delft, the Netherlands

[2] Witteveen+Bos, P.O. Box 233, 7400 AE Deventer, the Netherlands

[3] Key laboratory of Regional Sustainable Development Modeling, Institute of Geographical Sciences and Natural Resource Research, Chinese Academy of Sciences, Beijing, 100101, People's Republic of China

[4] Partners4UrbanWater, Javastraat 104A, 6524 MJ Nijmegen, the Netherlands

[5] University of Lyon, INSA Lyon, DEEP – EA 7429, F-69621 Villeurbanne Cedex, France

[6] Deltares, P.O. Box 177, 2600 MH Delft, the Netherlands

*Corresponding author's e-mail: p.m.m.vandaal-rombouts@tudelft.nl

Abstract

Optimisation or real time control (RTC) studies in wastewater systems increasingly require rapid simulations of sewer systems in extensive catchments. To reduce the simulation time calibrated simplified models are applied, with the performance generally based on the goodness of fit of the calibration. In this research the performance of three simplified and a full hydrodynamic (FH) model for two catchments are compared based on the correct determination of CSO event occurrences and of the total discharged volumes to the surface water. Simplified model M1 consists of a rainfall runoff outflow (RRO) model only. M2 combines the RRO model with a static reservoir model for the sewer behaviour. M3 comprises

the RRO model and a dynamic reservoir model. The dynamic reservoir characteristics were derived from FH model simulations. It was found that M2 and M3 are able to describe the sewer behaviour of the catchments, contrary to M1. The preferred model structure depends on the quality of the information (geometrical database and monitoring data) available for the design and calibration of the model. Finally, calibrated simplified models are shown to be preferable to uncalibrated FH models when performing optimisation or RTC studies.

Keywords

calibration, conceptual models, full hydrodynamic models, integrated modelling, monitoring, urban drainage systems

1. Introduction

Optimisation studies in wastewater management are increasingly common (Bach et al., 2014; Benedetti et al., 2013), requiring model simulations for the wastewater system as a whole, i.e. the contributing sewer systems, wastewater treatment plants (WWTP) and receiving surface waters. These model simulations are performed by coupling models for each sub system into an integrated model. In integrated modelling studies and real time control (RTC) applications two properties are of main importance: accuracy of the results and the required simulation time. Accurate results are essential for any modelling study. When working with integrated models this is especially true since faulty results from one sub model serve as input for the next sub model. As the simulation time increases with the model size, integrated model simulations take much time to perform. For example, simulating the full hydrodynamic sewer model for the Eindhoven case study (4,000 ha) as described in (Langeveld et al., 2013) for a period of 24 hours takes approximately 45 minutes on a regular laptop (4 cores of 2.8 GHz each). As optimisation studies generally consist of scenario analysis or the application of RTC, making evaluation of alternative scenarios beforehand or in real time necessary, the need for rapid simulation is evident.

To reduce the simulation time, simplified models, also commonly referred to as conceptual or surrogate models, are applied. Simplified models consist in many representations, see e.g. (Coutu et al., 2012; Mannina and Viviani, 2010; Motiee et al., 1997; Vaes et al., 1999; Wolfs and Willems, 2014), but all aim to compress the complexity of the real system in only a few characteristics and/or relationships. To ensure their representativeness, the simplified models are calibrated against field measurements. The model structure and parameter set that lead to the best overall fit with the measurements is accepted as the best simplified model. Attempts

63 to find appropriate calibration algorithms are described in e.g. (Krebs et al., 2014; Mair et al.,
64 2012; Vrugt et al., 2009; Wolfs et al., 2013).
65
66 Previous research, see e.g. (Del Giudice et al., 2015; Dotto et al., 2014; Kleidorfer et al., 2009;
67 Sun and Bertrand-Krajewski, 2013a, 2012; Vaes et al., 2001), made clear that the model input
68 can have a major impact on the simplified models performance. When constructing simplified
69 models for sewer systems in practice, however, usually only a few measurements are available
70 for model calibration. Sewer systems that are not specifically monitored for research purposes
71 will likely have water level measurements at the systems edges, at the discharges to the
72 WWTP and surface water and flow measurements if sewerage is pumped to the WWTP. No
73 flow measurements are generally available at free flow discharges to the WWTP and at
74 combined sewer overflow (CSO) locations. Simplified models are therefore, in the majority of
75 cases, calibrated based on the available water level measurements. The best performing
76 model is obtained by adjusting model parameters to reproduce the measurements based on
77 criteria such as Nash-Sutcliffe or root mean squared errors (RMSE).
78
79 The outputs of a (simplified) sewer model applied in integrated modelling are the discharges to
80 the other sub systems: the WWTP and surface water. Although the quality of the calibration is
81 a measure for the capability of the simplified sewer model to reproduce observations, it does
82 not necessarily imply a sufficiently accurate determination of the discharges. Therefore, in the
83 study presented here, simplified sewer models are calibrated with the established DREAM
84 algorithm (Vrugt et al., 2008 and 2009), while the performance is evaluated on the correct
85 determination of the occurrence of CSO events and the best estimation of the total volumes
86 discharged to the surface water.
87

Three simplified models are used in this paper to represent the processes in sewer systems: i) rainfall runoff outflow (RRO) model, ii) static reservoir model (SR) and iii) dynamic reservoir model (DR). RRO models simulate the surface runoff generation process and the discharges at the outlet of small catchments equipped with sloped sewer systems. Among RRO models, (Sun and Bertrand-Krajewski, 2013b) have demonstrated the effectiveness of the standard linear reservoir model for such cases. However, the simple linear relation between the discharge and the storage in the fictitious reservoir of the model is likely not to be effective for looped sewer systems equipped with pumping stations and CSO structures. Other process descriptions are needed in order to characterize the flow behaviour in these more complicated systems. In this study, a standard RRO model is thus complemented with either the SR model or the more elaborate DR model to represent looped, pumped, systems. For the derivation of the SR models geometrical information and pumping station settings are taken from a full hydrodynamic (FH) model, i.e. a 1D model taking into account hydrodynamic processes in the sewer system. For the DR models additional key relationships between variables are obtained through FH model simulations. In the development of SR and DR models, simplicity was constantly balanced against physical representativeness. Simplicity, and by that reproducibility and applicability in practical RTC situations, was pursued.

This paper thus presents a comparison of three simplified models: i) a single RRO model, ii) a combination RRO + SR models and iii) a combination RRO + DR models for the simulation of CSO events and volumes. Finally, the performances of the simplified and FH models are compared. This study has been conducted for two catchment areas in the Netherlands: Loenen and Waalre. Both catchments consist of pumped, combined sewer systems, but differ in size, structure and average ground level slope.

2. Materials and method

2.1. Catchment areas

Two combined sewer systems have been selected to test the simplified models: Loenen and Waalre. Loenen is located in the central east of the Netherlands in a mildly sloping area. This system has a partly looped and partly branched character. It is equipped with one pumping station and two CSOs. One CSO, referred to as primary, is located downstream in the sewer system and discharges much more and more often than the upstream, secondary, CSO. At the location of the pumping station an additional inflow from a small neighbouring sewer system is incorporated. Sewer system characteristics and layout can be found in table 1 and figure 1 (left).

Waalre is located in the south of the Netherlands. The sewer system is looped with one pumping station, a primary CSO equipped with a settling tank and a secondary CSO that rarely discharges. Additionally Waalre is connected to a neighbouring catchment in the east. Although water can flow both ways, it serves as a discharge for Waalre. Characteristics of the sewer systems are listed in table 1, while figure 1 (right) displays the sewer system layout.

2.2. Monitoring data

For Loenen monitoring data is available at a one minute interval from June 2001 to January 2002, collected as part of a dedicated research project. Flow measurements are available at the pumping station and an inflow into the pumping station from a neighbouring catchment. Level measurements are available in the pumping chamber and at the CSO locations, as displayed in figure 1 (left). Additionally, two rain gauges were installed in the catchment. Due to various reasons no continuous data set is available for the measuring period.

For Waalre monitoring data at the sewer system edges is available at a one minute interval. Flow is measured at the pumping station. Level measurements are available in the pumping chamber, inside the settling tank and at the secondary CSO location. The measuring locations are indicated in figure 1 (right). Additional one minute interval rain gauge measurements are performed at several locations approximately 10 km around Waalre. All measurements are recorded permanently. Data validation was performed applying the algorithms described in (Van Bijnen and Korving, 2008). Rain radar data with a five minute interval and pixel size of one square kilometre are available from the Royal Netherlands Meteorological Institute (KNMI). The radar data is calibrated against the rain gauge measurements using a procedure based on conditional merging as described in (De Niet et al., 2013). The rain radar calibration was performed only during wet weather days and when the rain gauges functioned in the period of April 2011 to January 2012.

Dry Weather Flow (DWF)

Daily dry weather flow (DWF) profiles have been derived from the monitoring data for both catchments. For Waalre it was based on the pump flow measurements in 2011. The mean hourly pumped discharge at DWF days was used to represent a typical daily DWF profile. DWF days are defined as having received less than 0.05 mm of precipitation after exponential smoothing (80% accounted to the current day and 20% to the following day) to prevent false detection of DWF days due to the absence of rain gauges inside the catchment. Unrealistic measurements and periods with snowfall have been manually discarded. The DWF profile for Loenen was previously derived by (Langeveld, 2004) based on the pump flow measurements using a similar strategy. The resulting profiles can be found in figure 2.

2.3. Full hydrodynamic (FH) models

FH models for both catchments are available in InfoWorks ICM (www.innovyze.com). The FH model for Loenen was calibrated by (Langeveld, 2004), following the procedure described by (Clemens, 2001). The calibration involved a detailed check of the geometrical database and tuning of several parameters to match measured and modelled water levels at up to ten locations. As the calibration resulted in very close resemblance between the modelled and measured water levels (deviations < 5 cm), it was concluded that the geometrical database was virtually without errors. The FH model for Waalre was validated following the procedure described in (Langeveld et al., 2013). It involved the comparison of measured and modelled water levels as a function of time at the three monitoring locations. No parameter optimisation was performed. As mentioned in the report (Liefting, 2012) the measured and modelled water levels resembled one another in general and it was concluded that no large errors in the geometrical database existed. Nevertheless, occasional deviations in measured and modelled water levels of up to 50 cm occurred.

The FH models are applied in this study for three purposes: i) properties of the geometrical database and pumping station settings are utilized in the design of the SR and DR models, ii) key relationships between variables are obtained by means of FH model simulations and applied in the DR model, and iii) the performance of the simplified models is compared to the performance of the FH models. For all simulations with the FH models for any of the above purposes, a standard (uncalibrated) parameter set is employed as (Korving and Clemens, 2005) showed that the portability of event specific parameter sets for FH models is low. The main distinction between the calibrated FH model for Loenen and validated FH model for Waalre lies therefore in the trustworthiness of the underlying geometrical database.

185 The simulations performed with the FH model for the second purpose, application in the
186 design of the DR model, are based on ten years (1955-1964) of 15 minute interval rainfall
187 measurements in De Bilt in the Netherlands. The simulations were executed with a one minute
188 time step, recording for every time step the volume, water level and flows in all manholes,
189 conduits, pumps, CSOs etc. The derivation of the required relationships is described in detail in
190 section 2.4.3.

191 **2.4. Model structures**

192 The general structure of the three simplified models tested in this paper is shown in figure 3.
193 Model M1 includes only a RRO model. Model M2 combines a RRO model and a SR model,
194 while model M3 combines a RRO model and a DR model. Rainfall, DWF and optional additional
195 flows are model inputs, while flows to the surface water (Q_{SW}) and to the WWTP (Q_{WWTP}) are
196 model outputs. In the following sections, all models are explained in more detail.

197 **2.4.1. Rainfall runoff outflow (RRO) model**

198 The standard linear reservoir model is a typical RRO model, see e.g. (Sun and Bertrand-
199 Krajewski, 2013b). It comprises of a rainfall loss model followed by a linear reservoir. The
200 rainfall loss model consists of initial (I_{ini} [mm]) and proportional (P_{cons} [-]) rainfall losses, i.e.
201 depression losses and ratio of contributing and total area. The resulting net rainfall (I_{net} [mm])
202 occurs with a time lag (T_{lag} [min]) and feeds the linear reservoir with a reservoir constant (K
203 [min]). The outflow of the standard linear reservoir (Q_{out}) is derived from the inputs using:
204

205 $$Q_{out}(t) = \exp\left(-\frac{\Delta t}{K}\right) Q_{out}(t-\Delta t) + \left[1-\exp\left(-\frac{\Delta t}{K}\right)\right] I_{net}(t-T_{lag})A, \qquad (1)$$

206

with A the catchment area [ha]. For more details on the standard linear reservoir model the reader is referred to (Sun and Bertrand-Krajewski, 2013b).

To determine the total inflow into the sewer models (Q_{in} in figure 3) for models M2 and M3, Q_{DWF} and $Q_{optional}$ are simply added to Q_{out}. For model M1, Q_{out} together with Q_{DWF} and $Q_{optional}$ represent both the surface runoff and the subsequent flow routing within the sewer system. It is split in the two sewer discharges Q_{SW} and Q_{WWTP} on the assumption that as much water is pumped to the WWTP as possible, i.e. all discharges up to the maximum pumping capacity is accounted to Q_{WWTP} as illustrated in figure 4 for Loenen. For Waalre, Q_{WWTP} is determined using the same method. From the remainder the discharge through the connection to the neighbouring catchment (determined from FH model simulations as it is not monitored) is subtracted before accounting it to Q_{SW}.

2.4.2. Static reservoir (SR) model

The SR model aims to represent processes within the sewer system that the basic RRO model cannot explicitly simulate. FH model properties of the geometrical database and pumping station settings are applied in its design. A schematic representation of the SR model for Loenen is shown in figure 5. It consists of a single basin for the sewer system which is filled by Q_{in} as described in the previous section. It empties through a pump resulting in Q_{WWTP}, and a single CSO resulting in Q_{SW}.

Several characteristics or relationships are applied in the SR model, numbered S SR1-SR3 in figure 5. Their representation and derivation were performed as follows:

SR1. Static storage-level curve

The static storage-level curve is used to convert the sewer volume (V_S) into the water level in the sewer (H_S). It is derived from the geometrical database of the FH model as the cumulative volume of all manholes, conduits, etc. of the sewer system under each possible water level.

SR2. Discharge through pump

The discharge through the pump ($Q_{S,P}$) is calculated through H_S and the pump characteristic. The pump characteristic is taken from the FH model. The DWF and maximum capacity are 115 and 209 m^3/h respectively. The switch on level is 15.00 m, and the switch off level 14.05 m above Normal Amsterdam Water Level (m AD).

SR3. Discharge through CSO

The discharge through the CSO (Q_{CSO}) is taken to be only caused by the primary CSO. The discharge is calculated through H_S and the standard weir equations for frontal weirs:

$$Q_{free} = c_1 h^{c_2} \quad (2)$$

for free outflow, with flow Q_{free} [m^3/s], h [m] water level above the weir crest, c_1 [m^{3-c_2}/s] taken to be 1.36 times the weir width [m] and c_2 [-] taken to be 1.5. Or

$$Q_{sub} = c_3 h_{DS} \sqrt{2g(h_{US} - h_{DS})} \quad (3)$$

for submerged outflow, with flow Q_{sub} [m^3/s], h_{US} and h_{DS} [m] the upstream and downstream water level above the weir crest, c_3 [m] taken to be 0.8 times the weir width [m] and g the standard acceleration due to gravity [9.81 m/s^2]. Submerged

outflow is assumed to occur when $2/3*h_{US} < h_{DS}$. For Loenen only free outflow is assumed.

A schematic representation of the SR model for Waalre is depicted in figure 6. It consists of a basin for the sewer system and a basin for the settling tank. The sewer basin is filled by Q_{in} and has three discharges: one through the pump resulting in Q_{WWTP}, one through the connection with the neighbouring catchment and one through a single CSO to the settling tank. The discharge through the CSO fills the settling tank that is emptied either through a pump back into the sewer basin, or through a CSO to the surface water resulting in Q_{SW}.

Again several characteristics or relationships have been applied in the model, numbered SR4-SR10 in figure 6. Their representation and derivation were performed as follows:

SR4. Static storage-level curve sewer

See SR1, and excluding the settling tank.

SR5. Discharge sewer through pump

The discharge through the pump ($Q_{S,P}$) is calculated through the water level in the sewer (H_S) and the pump characteristic. The pump characteristic is derived from analysis of the water level and flow measurements at the pumping station, and (Van Daal-Rombouts, 2012). The DWF and maximum capacity are 85 and 400 m^3/h respectively. The switch on level is 17.15 m AD, the switch off level 16.30 m AD.

SR6. Discharge sewer through connection

From simulations with the FH model it was found that water only flows from Waalre to the neighbouring catchment. The discharge through the connection (Q_{CONN}) is calculated through H_S and the standard equation for a free outflow over a V-notch weir,

$$Q = c_1 \tan(\theta/2) h^{5/2}, \quad (4)$$

as the connecting sewer is egg shaped. Here Q is the flow [m^3/s], c_1 a constant [$m^{1/2}/s$] taken to be 1.4, θ the notch angle taken to be 67°, and h [m] the water level over the weir crest. Free outflow is assumed at all times and the bottom of the notch is taken to be the highest invert of the connecting conduit.

SR7. Discharge sewer through CSO

The discharge through the CSO (Q_{CSO}) is taken to be caused only by the primary CSO and is calculated through H_S and equations 2 and 3. Both free and submerged outflow are allowed (only free outflow is displayed).

SR8. Static storage-level curve settling tank

The static storage-level curve is used to convert the settling tank volume (V_T) into the water level in the tank (H_T). It is derived from the FH model, similar to SR1.

SR9. Discharge settling tank through pump

The discharge of the settling tank through the pump ($Q_{T,P}$) is based on H_T and the pump characteristic. The pump characteristic was taken from the FH model, where the pumping capacity was adjusted to match the monitoring data.

SR10. Discharge settling tank

The discharge of the settling tank (Q_T) is calculated through H_T and equation 2.

2.4.3. Dynamic reservoir (DR) model

The DR models for the sewer systems are similar to the SR models, but contain additional relationships derived from FH model simulations to better account for the dynamic behaviour of a sewer system. A schematic representation of the DR model for Loenen is shown in figure 7

303 and can be compared to the SR model in figure 5. Differences are expressed in the storage-
304 level curve applied (SR1 - DR1) and the water level applied in the CSO discharge (DR2 - no
305 equivalent in the SR model).
306
307 The characteristics or relationships applied in the DR model are numbered DR1-DR4 in figure 7.
308 Their representation and derivation are explained bellow:
309 DR1. Hybrid storage-level curve
310 A so called hybrid storage-level curve is used to convert the sewer volume (V_S) into the
311 water level in the sewer (H_S). The hybrid curve follows the static storage-level curve
312 (see SR1) for low water levels to correctly model DWF circumstances and pumping
313 behaviour, and gradually turns to the dynamic storage-level curve for high water levels
314 (with possibly pressurised flow conditions) to take the dynamic properties of the sewer
315 system under wet weather flow (WWF) conditions and CSO discharges into account.
316 Figure 8 (left) displays the static, dynamic, and hybrid storage curves for Loenen.
317 The dynamic storage-level curve was derived from simulations performed with the FH
318 model as described in section 2.3. The resulting water volumes in the entire sewer
319 system (every minute for 10 years) were grouped in one cm intervals of the
320 corresponding water level at the pumping station. The grouped volumes were
321 averaged and smoothed to obtain the dynamic storage-level curve, as displayed in
322 figure 8 (right). Note that the dynamic storage-level curve converges towards the static
323 storage-level curve for DWF conditions or low rain intensities as the water level in the
324 sewer system levels off.
325 DR2. Level at CSO
326 H_S is converted into the water level at the primary CSO location (H_{CSO}). The relationship
327 is based on FH model simulations, where a linear relation is fitted through the

simulated water levels at the pumping station and the CSO location. Only elevated water levels (WWF conditions) are taken into account.

DR3. Discharge through pump

See SR2.

DR4. Discharge through CSO

See SR3, only now H_{CSO} is applied.

A schematic representation of the DR model for Waalre is shown in figure 9 and can be compared to the SR model in figure 6. Differences are expressed in the storage-level curve applied (DR5-SR4), the water level applied in the CSO discharge (DR6-no equivalent in the SR model) and the water level applied in and the calculation of the flow through the connection (DR7-no equivalent in SR model, DR9-SR6).

The characteristics or relationships applied in the DR for Waalre are numbered DR5-DR13 in figure 9. Their representation and derivation are explained as follows:

DR5. Hybrid storage-level curve sewer

A hybrid storage-level curve is used to convert V_S into H_S. The derivation follows DR1. The resulting curves for Waalre are displayed in Figure 10: (left) the static, dynamic, and hybrid storage curves, (right) the derivation of the dynamic storage-level curve from the FH model simulation results.

DR6. Level sewer at CSO

Similar to DR2, a relationship has been derived between H_{CSO} and H_S. As Waalre is equipped with the settling tank two linear segments that connect at the highest weir crest level of the settling tank have been applied. Only elevated water levels (WWF conditions) are taken into account.

DR7. Level sewer at connection

Similar to H_{CSO} in DR6, a relationship between the water level at the connection to the neighbouring catchment (H_{CONN}) and H_S is derived from the FH model simulations. A linear relation was fitted, taking only elevated water levels (WWF conditions) into account.

DR8. Discharge sewer through pump

See SR5.

DR9. Discharge sewer through connection

The discharge of the sewer through the connection to the neighbouring catchment (Q_{CONN}) is based on H_{CONN} and a relationship derived from the FH model simulations. The simulated water levels at the connection and the corresponding flow through the connection were fitted with a third order polynomial equation. To prevent unrealistic (negative) output a maximum value is set for H_{CONN}.

DR10. Discharge sewer through CSO

See SR7, where H_{CSO} is applied in the calculation of the discharge from the sewer.

DR11. Static storage-level curve settling tank

See SR8.

DR12. Discharge settling tank through pump

See SR9.

DR13. Discharge settling tank

See SR10.

2.5. Calibration procedure

2.5.1. DREAM algorithm

376 Calibration, which adjusts model parameters by minimizing the difference between model
377 outputs and measurements, is an important step before applying simplified models. The
378 research on calibration methods in the area of rainfall-runoff modelling is comprehensive,
379 leading to the application of automatic calibration methods instead of traditional manual
380 calibration mainly based on trial and error approaches. In this study an automatic calibration
381 method (the differential evolution adaptive metropolis (DREAM) method (Vrugt et al., 2008,
382 2009)) was applied for the calibration of the RRO models. The DREAM method is based on the
383 Bayesian theorem, which considers model parameters as probabilistic variables revealing the
384 probabilistic belief on the parameters according to observed model outputs. In DREAM the
385 probability distribution function of parameters is derived using an iterative approximation
386 method (the Markov chain Monte Carlo (MCMC) method) coupled with multiple chains in
387 parallel in order to provide a robust exploration of the search space. In addition to an optimal
388 model parameter set, DREAM also results in an evaluation of model parameter uncertainty,
389 which provides important information on model reliability. The effectiveness of DREAM in
390 water related model calibration has been demonstrated in many previous studies, e.g. (Keating
391 et al., 2010; Leonhardt et al., 2014).

392 **2.5.2. Parameter optimisation**

393 The DREAM algorithm is applied to calibrate the parameters of the RRO model to find the
394 minimal difference between the simplified model output and the measurements. Table 2
395 shows the parameters, units and the searching range for the calibration procedure.
396
397 The algorithm minimises the sum of squared errors (SSE) between the model output and
398 measurements. Water level measurements are applied in the calibration as they are the actual
399 monitoring data available, containing all information on the sewer systems behaviour. For

Loenen the water level measurement at the primary CSO location is used to calibrate M2 and M3. For Waalre the water level measurements at the pumping station and inside the settling tank are applied, by minimising the sum of the SSEs for each model output-measurement combination. Only periods with elevated water levels are considered in the calibration, as the RRO model parameters are connected to rainfall only. Since water levels do not have significance in M1, it's calibration is based on the total outflow from the sewer system, i.e. the sum of the measured pump flow and the calculated outflow at the CSO locations (determined with the measured water levels and equation 2) for Loenen and Waalre. For Waalre the outflow through the connection with the neighbouring catchment is added. As this flow is not monitored, it is based on FH model simulations for the respective rain events.

The information content on which the models are calibrated is similar, especially for the elevated water levels relevant for CSO discharges. M2 and M3 are calibrated on measured water levels at the CSO locations. The discharge to the surface water in M2 and M3 is calculated using the modelled water level and equation 2. The same equation with the measured water levels is applied to determine the outflow for the calibration of M1. Additionally, the pumped outflow supplies information during low intensity rainfall, as contained in the level measurements at the pumping station (in case of Waalre) or the primary CSO location (for Loenen) when it is not yet discharging.

The calibration is performed using 10,000 iterations in DREAM, as it was found from test runs that the cumulative density functions of the parameters do not change (within the parameter stability) after several thousand iterations. The last 5,000 iterations are used for further analysis: the optimal parameter set and model output are derived, and the model is run with

all 5,000 parameter sets to determine the 95% confidence intervals for the water levels and discharges.

2.5.3. Events

For each catchment six rain events are available for the parameter optimisation, e.g. they led to a significant rise in water level in the sewer system, with or without discharge to the surface water, no external influences were known and monitoring data was available and judged reliable after data validation. The selected events and their characteristics are summarised in table 3.

(Korving and Clemens, 2005) showed that the portability of event specific parameter sets for FH models is low. (Sun and Bertrand-Krajewski, 2012) investigated the impact of calibration data selection on the model performance of regression models. Given the limited dataset, full consideration of this aspect is considered beyond the scope of this paper. It is clear, however, that comparison of the model structures on single event calibration is insufficient. Therefore three scenarios have been explored:

1. Calibration of single rain events,
2. Calibration on all events together,
3. Calibration on any set of 3 events and verification with the remaining 3 events.

2.6. Performance evaluation

The performance of the calibrated simplified model structures should be evaluated on the capability to correctly represent the sewer systems functioning at the edges of the system. As argued in the introduction this is not obtained by comparing the best fits between the measured and modelled water levels but by comparing the discharges from the system, i.e. to

447 the WWTP and the surface water. As the RRO models are calibrated, i.e. all calibration
448 parameters are related to rainfall, the focus of the performance evaluation will be on the CSO
449 discharges to the surface water. As the discharge to the WWTP is also relevant for integrated
450 studies it will be reported for completeness.
451
452 Common sense dictates that the impact of CSO events depends foremost on the occurrence of
453 such events, with the absolute discharged flows of secondary consequence. This is supported
454 by literature stating that impact based RTC can influence the systems performance for small
455 and moderate events, contrary to large events on which it has no influence (Langeveld et al.,
456 2013), and that up to a certain point overflow frequency is a good indicator of receiving water
457 impact (Lau et al., 2002). Therefore the first evaluation criterion for the simplified sewer
458 models is the correct determination of CSO event occurrences. The second evaluation criterion
459 is the correct determination of the total discharged volume.
460
461 Based on the monitored water levels at the CSO locations in the sewer systems and settling
462 tank, for each event and catchment the discharge to the surface water (Q_{SW}) is calculated
463 through application of equation 2. Additionally the total discharge to the WWTP (Q_{WWTP}) is
464 calculated from the pump flow measurements. For each model structure and scenario the
465 modelled the total discharged volumes (V_{SW} and V_{WWTP}) are determined as the integral of the
466 model outputs Q_{SW} and Q_{WWTP}.
467
468 CSO event occurrences are analysed through false positives (FP) and false negatives (FN). A FP
469 is defined as a CSO event occurrence ($V_{SW} > 0$) in the model output but not in the
470 measurements, a FN as a CSO event occurrence in the measurements but not in the model
471 output. For the comparison of discharged volumes, differences in V_{SW} (and V_{WWTP}) between the

model output and the measurements are calculated and listed for each event and scenario. Cumulative results for each scenario are determined by taking the root mean squared errors (RMSE) over all events.

For comparison purposes the selected rain events have also been simulated using the FH models. The comparison between simplified models with calibrated inflow parameters and FH models with uncalibrated inflow parameters is relevant since the FH models simulate the sewer systems behaviour in greatest detail and hence are deemed to be most accurate (Ferreri et al., 2010; Meirlaen et al., 2001; Rubinato et al., 2013). This might hold true for calibrated FH models but not for the much more commonly applied uncalibrated models, as proper calibration of FH models is very time consuming and requires a very large monitoring data set.

Finally, the simulation time needed by different simplified model structures and the FH model will be compared.

3. Results and discussion

3.1. Calibration

As described in the previous section the performance of the simplified model structures will be evaluated based upon the correct determination of CSO occurrences and the total discharge to the surface water. The calibration results, however, provide useful insight into the models functioning. Therefore, a typical calibration result for each catchment will be presented. Nash-Sutcliffe efficiency indexes (NS) (Nash and Sutcliffe, 1970) are supplied for easy comparison of the calibration results. Optimal parameter sets will be given for all events and scenarios.

The results for the individual calibration of rain events 2001-08-27 (Loenen) and 2011-08-14 (Waalre) for all model structures are displayed in figures 11 and 12 respectively. From top to bottom the applied rainfall is shown, followed by the model results for M1 (based on the total sewer outflow), and M2 and M3 (based on the water level in the sewer system). For Waalre additional water level measurements in the settling tank were applied, the results of which have been added to the bottom of figure 12. For each model structure the optimal results are displayed together with their 95% confidence bands.

Figures 11 and 12 show that M2 and M3 are in general well able to describe the sewer systems behaviour: the measurements applied in the calibration are closely followed during the filling of the basins, once they are full and during emptying, resulting in NS values > 0.95 for Loenen and > 0.75 for Waalre. Small differences occur between these models especially during filling and in the response to temporal changes in the rainfall. M1 cannot describe the sewer systems behaviour in detail as it has only the reservoir constant K to account for surface storage and in-

sewer storage. The response to rainfall is therefore more smoothed, which is best demonstrated in figure 11. NS values < 0.4 are found.

For both catchments and all model structures the 95% confidence bands are mostly < 1%. Logically, the influence of the (inflow) calibration parameters on water levels in sewer systems is most apparent at the onset of a rain event or during temporal changes, resulting in confidence bands up to 10% for M2 and M3, while they stay < 1% for M1.

For all scenarios for Loenen NS values for M2 and M3 > 0.90. For M1, values differ strongly from -8.52 to 0.44. For Waalre for M2 and M3 in scenario 1, NS values range between 0.61 and 0.96, with one event around zero. In scenario 2 the values drop to 0.5 to 0.6. The NS values for M1 again differ strongly between events and scenarios from -9.42 to 0.82.

Figure 13 shows the optimal parameter values for Loenen (left) and Waalre (right) for all model structures. In asterisks the results for scenario 1 (calibration on single rain events) are given, the line indicates the parameter values for scenario 2 (all events together). Results for all twenty possible combinations of three calibration events in scenario 3 can be found in figure 14. The optimal parameter values reflect the results for the water levels and NS values: the parameters for M2 and M3 show much resemblance within a catchment, while M1 deviates. Especially the difference in K stands out, as the RRO model in M1 has to account for the surface and in-sewer storage, while in M2 and M3 only for the surface storage. The optimal parameter values between scenarios 2 (line in figure 13) and 3 (figure 14) are consistent, indicating that the exact split in a calibration and verification set does not have a major impact on the outcome.

3.2. Performance evaluation

3.2.1. Model discharge

As the calibration of the simplified models is performed on rainfall related parameters, the focus of the performance evaluation will be on the discharge to the surface water (Q_{SW}) while the discharge to the WWTP (Q_{WWTP}) is included for completeness.

Optimal Q_{SW} and Q_{WWTP} for all model structures for the calibration of the single events of 2001-08-27 (Loenen) and 2011-08-14 (Waalre) are displayed in figures 15 and 16 as well as the discharges determined from the measurements. The difference between M1 and M2/M3 observed in the calibration results are also clear from these figures, as Q_{SW} for M1 tends to be more smoothed because of the higher value for K.

3.2.2. Determination of CSO events

FPs and FNs for all events for each model structure and scenario, based on the optimal parameter sets, are given in table 4. For scenarios 1 and 2 the total number is reported, for scenario 3 the results have been averaged over all combinations and multiplied by two for easy comparison. Additionally, results for the FH model have been added.

Based on the FPs and FNs in table 4, M1 can be immediately discarded for these catchments. For each scenario and catchment two FPs were recorded, the exact number of rain events that did not lead to a CSO event. This is easily explained since a rain event leading to a significant rise in water level in a pumped sewer system will likely contain rain intensities higher than the pumping capacity of the sewer system reserved for WWF (design guideline in the Netherlands: 0.7 mm/h). In M1 all rainfall in excess of this capacity has to be discharged to the surface water, leading to a CSO event. The calibration algorithm unsuccessfully tries to overcome this

inadequacy in the model structure by delaying the rainfall (high T_{lag}) and smoothing the response (high K), as can be found from the optimal parameter values in figure 13.

For M2 and M3 the results are less conclusive. Single FPs or FNs occur depending on the catchment and scenario applied. The floating point values for scenario 3 for Waalre (due to averaging over all possible combinations) and the optimal parameter values in figure 13 further indicate that the inflow parameters are calibrated differently depending on the selection of calibration/verification events. Only for M3 for Loenen no FPs or FNs occur in any scenario signalling that the M3, combining the RRO and DR models, is likely the best performing model for Loenen.

3.2.3. Determination of discharged volumes

The total volumes discharged to the surface water (V_{SW}) for each model structure and scenarios 1 and 2 are displayed in figure 17 for Loenen and 18 for Waalre. V_{SW} is the integrated model output Q_{SW}, for which the optimal values and 95% confidence bands are determined as described in section 2.5.2. The calculation of the 95% confidence intervals for the measurements is based on an uncertainty in the standard weir equation of 25%. This percentage is estimated on previous work by (Van Daal-Rombouts et al., 2014) on scale models and (Fach et al., 2009) on computational fluid dynamics. Both studies indicate deviations between the actual (measured or calculated) CSO discharge and the discharge determined with the standard weir equation of up to 50%. They also indicate that this strongly depends on the water level over the weir crest leading to under and over estimations of the flow. Therefore an intermediate value was chosen. For the FH model an uncertainty of 50% was applied based on the possibility to calibrate FH models up to 5 cm difference in water levels and equation 2.

582

583 The cumulative results for V_{SW} and V_{WWTP}, given in table 5, were determined by taking the
584 RMSE of the results from the optimal parameter sets over all events. The RMSE for scenario 3
585 have been averaged over all possible combinations and values for the FH model have been
586 added.

587

588 The results for V_{SW} in figures 17 and 18 and table 5 support the preliminary conclusion that M3
589 outperforms M2 for Loenen. For all scenarios the RMSE and the uncertainty bands for M3 are
590 smaller than for M2. Despite the inability of M1 to correctly determine CSO event occurrences,
591 it outperforms M2 based on V_{WS}. For Waalre the performance of M2 and M3 are similar,
592 corresponding to the determination of the CSO events. Nevertheless, M2 consistently
593 performs better than M3. Similar to Loenen, M1 generally performs well based on V_{SW}. The
594 difference in the performance of M2 and M3 between the catchments is also reflected in the
595 optimal parameter values (figure 13). The parameter values for Waalre are close resulting in
596 similar RMSE values in table 5, while for Loenen there is more variety between the model
597 structures especially for I_{ini} and K.

598

599 These results can be explained by the information available for the simplified model design
600 and calibration as described in sections 2.2 and 2.3. All information is better known or of
601 higher quality for Loenen: i) The monitoring data for Loenen was gathered for research
602 purposes, while the monitoring campaign for Waalre received less dedicated attention. ii) For
603 Loenen two rain gauges were installed in the catchment itself, while for Waalre no local rain
604 gauges were available. iii) The geometrical database underlying the FH model for Loenen is
605 better known than for Waalre. The results for the RMSE of V_{SW} indicate that the more detailed
606 model M3, i.e. RRO model for the runoff combined with the DR model for the sewer system, is

607 favoured when high quality information is available (in this case Loenen), while the less
608 detailed model M2, RRO with SR, suffices when the information is of lower quality (Waalre).
609
610 One main source of uncertainty for Waalre likely stems from the calibrated rain radar input.
611 The rainfall in general seems reasonable with NS values for M2 or M3 > 0.6. In detail the
612 rainfall seems off in intensities and/or timing, an example of which can be found in figure 16.
613 Judging from the rainfall, the models responses in Q_{SW} are in accordance (main peak in the
614 outflow after main peak in the rainfall). However, in the measurements the main peak in the
615 outflow occurs right at the beginning of the rain event. The other events display a similar
616 mismatch between the rainfall and the outflow. This may also explain the very low values for
617 the parameters T_{lag} and K, see figure 13, as the calibration procedure tries to correct the
618 mismatch in the input data.
619
620 For V_{WWTP} the RMSE values in table 5 show that model M1 consistently performs worse than
621 M2 and M3 for all scenarios and both catchments. M2 and M3 generally perform on a similar
622 level, which is to be expected as the pumping regime in the SR and DR model structures is the
623 same.
624
625 The NS values reported in section 3.1 are based on the calibration parameters for each time
626 step, and the FP/FN in table 4 and RMSE in table 5 on V_{SW}. Each presents information on the
627 performance of the model structure. NS indicates the quality of the description of the sewer
628 systems behaviour in general, while the others are specific for CSO discharges. The difference
629 between the best performing model structure based on these criterions, especially for Loenen,
630 is striking. Model M2 and M3 have similar NS values > 0.9, but M3 is much more accurate
631 based on FP/FN and RMSE. Simplified sewer models are calibrated on measurements,

generally only water levels, but used to determine CSO discharges. These results show that care should be taken in choosing performance indicators suitable to the purpose of the model, likely leading to multiple indicators.

3.2.4. Uncalibrated FH models

Finally the performance of the FH models is compared to the performance of the calibrated simplified models. The comparison is made for scenario 2, calibration for all events together, since there a single parameter set is derived for each model structure, similar to the single standard parameter set for the FH model.

Based on the determination of CSO event occurrences (table 4) the FH model performs at a similar level as M2 and M3. For Loenen one FP is noted for the FH model, while none for M2 and M3. For Waalre it is reversed.

Taking the RMSE for V_{SW} (table 5) into account, the FH model is easily outperformed by both M2 and M3, while V_{WWTP} is worse for Loenen and better for Waalre. The results for the simplified models for V_{SW} (scenario 3) imply little loss of accuracy when the available data is split into a calibration and verification set. This suggests that, if a sufficiently large data set were available, the optimal parameter set should be applicable to other events without much loss of accuracy.

The simulation time for the FH models takes 1,000-5,000 times longer than for M2/M3 or 250,000-475,000 times longer than for M1.

From the perspective of both the simulation time and accuracy of results it is concluded that it is better to apply simplified calibrated models in optimisation or RTC studies than uncalibrated FH models.

4. Conclusions and future research

The research described dealt with the design and performance evaluation of a so called dynamic simplified sewer model for the accurate and rapid calculation of sewer system discharges for optimisation and RTC studies. The dynamic simplified sewer model (M3) consists of a calibrated rainfall runoff outflow (RRO) model and a dynamic reservoir (DR) model for the sewer behaviour. It contains characteristics derived from full hydrodynamic (FH) model simulations to account for the dynamic properties of the sewer system behaviour.

The performance of M3 was tested for two combined, pumped catchments and compared against two other simplified models, M2 (calibrated RRO model with a static reservoir (SR)) and M1 (calibrated RRO model only), and uncalibrated FH models. The performance was not solely based on the goodness of fit of the calibration but primarily on the correct determination of CSO event occurrences, and secondly on the correct determination of the total discharged volumes to the surface water.

From this research the following conclusions can be drawn:

- Model M1 simulates > 100,000 times faster than the FH model; models M2/M3 are > 1,000 times faster than the FH model.
- M1 is unsuitable to correctly predict CSO occurrences for pumped catchments. The model structure is unable to retain rain intensities higher than the pumping capacity reserved for WWF, resulting in too many CSO discharges.
- M2 and M3 are able to describe the behaviour of pumped sewer systems.
- Performance indicators for the selection of the most appropriate model structure should be chosen carefully in relation to the modelling objectives, likely leading to

multiple indicators, each one providing a specific approach of the models' performances.

- In case of detailed and trustworthy information available for the design and calibration of the model (Loenen), M3 outperforms M2 for all scenarios. If the available information is of lower quality (Waalre), M2 consistently performs slightly better indicating that the derivation of the more detailed DR model is not useful.
- For rainfall driven modelling trustworthy and local rain measurements remain necessary despite the availability of rain radar data, to either apply as direct input or the correction of radar data.
- M2 and M3 outperform the uncalibrated FH models based on the total discharge to the surface water. In optimisation or RTC studies the application of suitable calibrated simplified models is preferred over uncalibrated FH models.

Future research is recommended in the area of statistical substantiation of the results as the available data sets were too limited to allow a statistical analysis of the results themselves. Also the use of continuous data sets instead of the current intermittent ones would be interesting because more information on the initial conditions prior to events would be included.

Following the above, future research will focus on retrieving more reliable monitoring data (especially rainfall). For the catchment of Waalre, the impact of more reliable rainfall data on the performance of the detailed M3 model will be focussed on. Calibrated simplified sewer models will be derived for the catchments in the case study area of Eindhoven for application in an integrated model to research the possibilities for quality based RTC.

Acknowledgements

The authors would like to acknowledge Innovyze (www.innovyze.com) for kindly supplying a research licence for the use of the software program InfoWorks ICM. Also the authors would like to thank the Van Gogh Programme for supplying a Travel Grant to cover the travel expenses for the cooperation between TU Delft and INSA Lyon.

The research is performed within the Dutch 'Kennisprogramma Urban Drainage' (Knowledge Programme Urban Drainage). The involved parties are: ARCADIS, Deltares, Evides, Gemeente Almere, Gemeente Arnhem, Gemeente Breda, Gemeente 's-Gravenhage, Gemeentewerken Rotterdam, Gemeente Utrecht, GMB Rioleringstechniek, Grontmij, KWR Watercycle Research Institute, Royal HaskoningDHV, Stichting RIONED, STOWA, Tauw, vandervalk + degroot, Waterboard De Dommel, Waternet and Witteveen+Bos.

References

Bach, P.M., Rauch, W., Mikkelsen, P.S., McCarthy, D.T., Deletic, A., 2014. A critical review of integrated urban water modelling - Urban drainage and beyond. Environ. Model. Softw. 54, 88–107.

Benedetti, L., Langeveld, J.G., Comeau, A., Corominas, L., Daigger, G., Martin, C., Mikkelsen, P.S., Vezzaro, L., Weijers, S.R., Vanrolleghem, P.A., 2013. Modelling and monitoring of integrated urban wastewater systems: review on status and perspectives. Water Sci. Technol. 68, 1203–1215.

Clemens, F.H.L.R., 2001. Hydrodynamic models in urban drainage: application and calibration. TU Delft.

Coutu, S., Del Giudice, D., Rossi, L., Barry, D.A., 2012. Parsimonious hydrological modeling of

732 urban sewer and river catchments. J. Hydrol. 464-465, 477–484.

733 De Niet, A.C., De Jonge, J., Korving, H., Langeveld, J.G., Van Nieuwenhuijzen, A., 2013. Het
734 beste van twee werelden, correctie van neerslagradar op basis van grondstations voor
735 toepassing in stedelijk gebied. H2O online 1–5.

736 Del Giudice, D., Reichert, P., Bareš, V., Albert, C., Rieckermann, J., 2015. Model bias and
737 complexity – Understanding the effects of structural deficits and input errors on runoff
738 predictions. Environ. Model. Softw. 64, 205–214.

739 Dotto, C.B.S., Kleidorfer, M., Deletic, A., Rauch, W., McCarthy, D.T., 2014. Impacts of measured
740 data uncertainty on urban stormwater models. J. Hydrol. 508, 28–42.

741 Fach, S., Sitzenfrei, R., Rauch, W., 2009. Determining the spill flow discharge of combined
742 sewer overflows using rating curves based on computational fluid dynamics instead of
743 the standard weir equation. Water Sci. Technol. 60, 3035–43.

744 Ferreri, G.F., Freni, G., Tomaselli, P., 2010. Ability of Preissmann slot scheme to simulate
745 smooth pressurisation transient in sewers. Water Sci. Technol. 62, 1848–1858.

746 Keating, E.H., Doherty, J., Vrugt, J.A., Kang, Q., 2010. Optimization and uncertainty assessment
747 of strongly nonlinear groundwater models with high parameter dimensionality. Water
748 Resour. Res. 46, 1–18.

749 Kleidorfer, M., Möderl, M., Fach, S., Rauch, W., 2009. Optimization of measurement campaigns
750 for calibration of a conceptual sewer model. Water Sci. Technol. 59, 1523–30.

751 Korving, H., Clemens, F.H.L.R., 2005. Impact of dimension uncertainty and model calibration on
752 sewer system assessment. Water Sci. Technol. 52, 35–42.

753 Krebs, G., Kokkonen, T., Valtanen, M., Setälä, H., Koivusalo, H., 2014. Spatial resolution
754 considerations for urban hydrological modelling. J. Hydrol. 512, 482–497.

Langeveld, J.G., 2004. Interactions within wastewater systems. TU Delft.

Langeveld, J.G., Benedetti, L., De Klein, J., Nopens, I., Amerlinck, Y., Van Nieuwenhuijzen, A., Flameling, T., Van Zanten, O., Weijers, S.R., 2013. Impact-based integrated real-time control for improvement of the Dommel River water quality. Urban Water J. 10, 312–329.

Lau, J., Butler, D., Schütze, M., 2002. Is combined sewer overflow spill frequency/volume a good indicator of receiving water quality impact? Urban Water 4, 181–189.

Leonhardt, G., Sun, S., Rauch, W., Bertrand-Krajewski, J.-L., 2014. Comparison of two model based approaches for areal rainfall estimation in urban hydrology. J. Hydrol. 511, 880–890.

Liefting, H.J., 2012. Toetsing rioolmodel Waalre.

Mair, M., Kleidorfer, M., Rauch, W., 2012. Performance of auto-calibration algorithms in the field of urban drainage modelling, in: Proceedings of UDM9. Belgrade, pp. 1–10.

Mannina, G., Viviani, G., 2010. An urban drainage stormwater quality model: Model development and uncertainty quantification. J. Hydrol. 381, 248–265.

Meirlaen, J., Huyghebaert, B., Sforzi, F., Benedetti, L., Vanrolleghem, P.A., 2001. Fast, simultaneous simulation of the integrated urban wastewater system using mechanistic surrogate models. Water Sci. Technol. 43, 301–309.

Motiee, H., Chocat, B., Blanpain, O., 1997. A storage model for the simulation of the hydraulic behaviour of drainage networks. Water Sci. Technol. 36, 57–63.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models: Part I - A discussion of principles. J. Hydrol. 10, 282–290.

Rubinato, M., Shucksmith, J., Saul, A.J., Shepherd, W., 2013. Comparison between InfoWorks

hydraulic results and a physical model of an Urban drainage system. Water Sci. Technol. 68, 372–379.

Sun, S., Bertrand-Krajewski, J.-L., 2013a. Input variable selection and calibration data selection for storm water quality regression models. Water Sci. Technol. 68, 50–58.

Sun, S., Bertrand-Krajewski, J.-L., 2013b. Separately accounting for uncertainties in rainfall and runoff: Calibration of event based conceptual hydrological models in small urban catchments using Bayesian method. Water Resour. Res. 49, 1–14.

Sun, S., Bertrand-Krajewski, J.-L., 2012. On calibration data selection: The case of stormwater quality regression models. Environ. Model. Softw. 35, 61–73.

Vaes, G., Berlamont, J., Bermont, J., 1999. Emission predictions with a multi-linear reservoir model. Water Sci. Technol. 39, 9–16.

Vaes, G., Willems, P., Berlamont, J., 2001. Rainfall input requirements for hydrological calculations. Urban Water 3, 107–112.

Van Bijnen, M., Korving, H., 2008. Application and results of automatic validation of sewer monitoring data, in: Proceedings of ICUD11. Edinburgh, pp. 1–10.

Van Daal-Rombouts, P.M.M., 2012. Personal communication.

Van Daal-Rombouts, P.M.M., Tralli, A., Verhaart, F., Langeveld, J.G., Clemens, F.H.L.R., 2014. Applicability of CFD modelling in determining accurate weir discharge - water level relationships, in: Proceedings of ICUD13. Sarawak, pp. 1–8.

Vrugt, J.A., Ter Braak, C.J.F., Clark, M.P., Hyman, J.M., Robinson, B.A., 2008. Treatment of input uncertainty in hydrologic modeling: Doing hydrology backward with Markov chain Monte Carlo simulation. Water Resour. Res. 44, 1–15.

799 Vrugt, J.A., Ter Braak, C.J.F., Gupta, H.V., Robinson, B.A., 2009. Equifinality of formal (DREAM)
800 and informal (GLUE) Bayesian approaches in hydrologic modeling? Stoch. Environ. Res.
801 Risk Assess. 23, 1011–1026.

802 Wolfs, V., Villazon, M.F., Willems, P., 2013. Development of a semi-automated model
803 identification and calibration tool for conceptual modelling of sewer systems. Water Sci.
804 Technol. 68, 167–175.

805 Wolfs, V., Willems, P., 2014. Development of discharge-stage curves affected by hysteresis
806 using time varying models, model trees and neural networks. Environ. Model. Softw. 55,
807 107–119.

DESIGN AND PERFORMANCE EVALUATION OF A SIMPLIFIED DYNAMIC MODEL FOR COMBINED SEWER OVERFLOWS IN PUMPED SEWER SYSTEMS

Petra VAN DAAL-ROMBOUTS[1,2,*], Siao SUN[3], Jeroen LANGEVELD[1,4], Jean-Luc BERTRAND-KRAJEWSKI[5], François CLEMENS[1,6]

[1] Delft University of Technology, P.O. Box 5048, 2600 GA Delft, the Netherlands

[2] Witteveen+Bos, P.O. Box 233, 7400 AE Deventer, the Netherlands

[3] Key laboratory of Regional Sustainable Development Modeling, Institute of Geographical Sciences and Natural Resource Research, Chinese Academy of Sciences, Beijing, 100101, People's Republic of China

[4] Partners4UrbanWater, Javastraat 104A, 6524 MJ Nijmegen, the Netherlands

[5] University of Lyon, INSA Lyon, DEEP – EA 7429, F-69621 Villeurbanne Cedex, France

[6] Deltares, P.O. Box 177, 2600 MH Delft, the Netherlands

*Corresponding author's e-mail: p.m.m.vandaal-rombouts@tudelft.nl

Abstract

Optimisation or real time control (RTC) studies in wastewater systems increasingly require rapid simulations of sewer systems in extensive catchments. To reduce the simulation time calibrated simplified models are applied, with the performance generally based on the goodness of fit of the calibration. In this research the performance of three simplified and a full hydrodynamic (FH) model for two catchments are compared based on the correct determination of CSO event occurrences and of the total discharged volumes to the surface water. Simplified model M1 consists of a rainfall runoff outflow (RRO) model only. M2 combines the RRO model with a static reservoir model for the sewer behaviour. M3 comprises

the RRO model and a dynamic reservoir model. The dynamic reservoir characteristics were derived from FH model simulations. It was found that M2 and M3 are able to describe the sewer behaviour of the catchments, contrary to M1. The preferred model structure depends on the quality of the information (geometrical database and monitoring data) available for the design and calibration of the model. Finally, calibrated simplified models are shown to be preferable to uncalibrated FH models when performing optimisation or RTC studies.

Keywords

calibration, conceptual models, full hydrodynamic models, integrated modelling, monitoring, urban drainage systems

1. Introduction

Optimisation studies in wastewater management are increasingly common (Bach et al., 2014; Benedetti et al., 2013), requiring model simulations for the wastewater system as a whole, i.e. the contributing sewer systems, wastewater treatment plants (WWTP) and receiving surface waters. These model simulations are performed by coupling models for each sub system into an integrated model. In integrated modelling studies and real time control (RTC) applications two properties are of main importance: accuracy of the results and the required simulation time. Accurate results are essential for any modelling study. When working with integrated models this is especially true since faulty results from one sub model serve as input for the next sub model. As the simulation time increases with the model size, integrated model simulations take much time to perform. For example, simulating the full hydrodynamic sewer model for the Eindhoven case study (4,000 ha) as described in (Langeveld et al., 2013) for a period of 24 hours takes approximately 45 minutes on a regular laptop (4 cores of 2.8 GHz each). As optimisation studies generally consist of scenario analysis or the application of RTC, making evaluation of alternative scenarios beforehand or in real time necessary, the need for rapid simulation is evident.

To reduce the simulation time, simplified models, also commonly referred to as conceptual or surrogate models, are applied. Simplified models consist in many representations, see e.g. (Coutu et al., 2012; Mannina and Viviani, 2010; Motiee et al., 1997; Vaes et al., 1999; Wolfs and Willems, 2014), but all aim to compress the complexity of the real system in only a few characteristics and/or relationships. To ensure their representativeness, the simplified models are calibrated against field measurements. The model structure and parameter set that lead to the best overall fit with the measurements is accepted as the best simplified model. Attempts

63 to find appropriate calibration algorithms are described in e.g. (Krebs et al., 2014; Mair et al.,
64 2012; Vrugt et al., 2009; Wolfs et al., 2013).
65
66 Previous research, see e.g. (Del Giudice et al., 2015; Dotto et al., 2014; Kleidorfer et al., 2009;
67 Sun and Bertrand-Krajewski, 2013a, 2012; Vaes et al., 2001), made clear that the model input
68 can have a major impact on the simplified models performance. When constructing simplified
69 models for sewer systems in practice, however, usually only a few measurements are available
70 for model calibration. Sewer systems that are not specifically monitored for research purposes
71 will likely have water level measurements at the systems edges, at the discharges to the
72 WWTP and surface water and flow measurements if sewerage is pumped to the WWTP. No
73 flow measurements are generally available at free flow discharges to the WWTP and at
74 combined sewer overflow (CSO) locations. Simplified models are therefore, in the majority of
75 cases, calibrated based on the available water level measurements. The best performing
76 model is obtained by adjusting model parameters to reproduce the measurements based on
77 criteria such as Nash-Sutcliffe or root mean squared errors (RMSE).
78
79 The outputs of a (simplified) sewer model applied in integrated modelling are the discharges to
80 the other sub systems: the WWTP and surface water. Although the quality of the calibration is
81 a measure for the capability of the simplified sewer model to reproduce observations, it does
82 not necessarily imply a sufficiently accurate determination of the discharges. Therefore, in the
83 study presented here, simplified sewer models are calibrated with the established DREAM
84 algorithm (Vrugt et al., 2008 and 2009), while the performance is evaluated on the correct
85 determination of the occurrence of CSO events and the best estimation of the total volumes
86 discharged to the surface water.
87

Three simplified models are used in this paper to represent the processes in sewer systems: i) rainfall runoff outflow (RRO) model, ii) static reservoir model (SR) and iii) dynamic reservoir model (DR). RRO models simulate the surface runoff generation process and the discharges at the outlet of small catchments equipped with sloped sewer systems. Among RRO models, (Sun and Bertrand-Krajewski, 2013b) have demonstrated the effectiveness of the standard linear reservoir model for such cases. However, the simple linear relation between the discharge and the storage in the fictitious reservoir of the model is likely not to be effective for looped sewer systems equipped with pumping stations and CSO structures. Other process descriptions are needed in order to characterize the flow behaviour in these more complicated systems. In this study, a standard RRO model is thus complemented with either the SR model or the more elaborate DR model to represent looped, pumped, systems. For the derivation of the SR models geometrical information and pumping station settings are taken from a full hydrodynamic (FH) model, i.e. a 1D model taking into account hydrodynamic processes in the sewer system. For the DR models additional key relationships between variables are obtained through FH model simulations. In the development of SR and DR models, simplicity was constantly balanced against physical representativeness. Simplicity, and by that reproducibility and applicability in practical RTC situations, was pursued.

This paper thus presents a comparison of three simplified models: i) a single RRO model, ii) a combination RRO + SR models and iii) a combination RRO + DR models for the simulation of CSO events and volumes. Finally, the performances of the simplified and FH models are compared. This study has been conducted for two catchment areas in the Netherlands: Loenen and Waalre. Both catchments consist of pumped, combined sewer systems, but differ in size, structure and average ground level slope.

2. Materials and method

2.1. Catchment areas

Two combined sewer systems have been selected to test the simplified models: Loenen and Waalre. Loenen is located in the central east of the Netherlands in a mildly sloping area. This system has a partly looped and partly branched character. It is equipped with one pumping station and two CSOs. One CSO, referred to as primary, is located downstream in the sewer system and discharges much more and more often than the upstream, secondary, CSO. At the location of the pumping station an additional inflow from a small neighbouring sewer system is incorporated. Sewer system characteristics and layout can be found in table 1 and figure 1 (left).

Waalre is located in the south of the Netherlands. The sewer system is looped with one pumping station, a primary CSO equipped with a settling tank and a secondary CSO that rarely discharges. Additionally Waalre is connected to a neighbouring catchment in the east. Although water can flow both ways, it serves as a discharge for Waalre. Characteristics of the sewer systems are listed in table 1, while figure 1 (right) displays the sewer system layout.

2.2. Monitoring data

For Loenen monitoring data is available at a one minute interval from June 2001 to January 2002, collected as part of a dedicated research project. Flow measurements are available at the pumping station and an inflow into the pumping station from a neighbouring catchment. Level measurements are available in the pumping chamber and at the CSO locations, as displayed in figure 1 (left). Additionally, two rain gauges were installed in the catchment. Due to various reasons no continuous data set is available for the measuring period.

For Waalre monitoring data at the sewer system edges is available at a one minute interval. Flow is measured at the pumping station. Level measurements are available in the pumping chamber, inside the settling tank and at the secondary CSO location. The measuring locations are indicated in figure 1 (right). Additional one minute interval rain gauge measurements are performed at several locations approximately 10 km around Waalre. All measurements are recorded permanently. Data validation was performed applying the algorithms described in (Van Bijnen and Korving, 2008). Rain radar data with a five minute interval and pixel size of one square kilometre are available from the Royal Netherlands Meteorological Institute (KNMI). The radar data is calibrated against the rain gauge measurements using a procedure based on conditional merging as described in (De Niet et al., 2013). The rain radar calibration was performed only during wet weather days and when the rain gauges functioned in the period of April 2011 to January 2012.

Dry Weather Flow (DWF)

Daily dry weather flow (DWF) profiles have been derived from the monitoring data for both catchments. For Waalre it was based on the pump flow measurements in 2011. The mean hourly pumped discharge at DWF days was used to represent a typical daily DWF profile. DWF days are defined as having received less than 0.05 mm of precipitation after exponential smoothing (80% accounted to the current day and 20% to the following day) to prevent false detection of DWF days due to the absence of rain gauges inside the catchment. Unrealistic measurements and periods with snowfall have been manually discarded. The DWF profile for Loenen was previously derived by (Langeveld, 2004) based on the pump flow measurements using a similar strategy. The resulting profiles can be found in figure 2.

2.3. Full hydrodynamic (FH) models

FH models for both catchments are available in InfoWorks ICM (www.innovyze.com). The FH model for Loenen was calibrated by (Langeveld, 2004), following the procedure described by (Clemens, 2001). The calibration involved a detailed check of the geometrical database and tuning of several parameters to match measured and modelled water levels at up to ten locations. As the calibration resulted in very close resemblance between the modelled and measured water levels (deviations < 5 cm), it was concluded that the geometrical database was virtually without errors. The FH model for Waalre was validated following the procedure described in (Langeveld et al., 2013). It involved the comparison of measured and modelled water levels as a function of time at the three monitoring locations. No parameter optimisation was performed. As mentioned in the report (Liefting, 2012) the measured and modelled water levels resembled one another in general and it was concluded that no large errors in the geometrical database existed. Nevertheless, occasional deviations in measured and modelled water levels of up to 50 cm occurred.

The FH models are applied in this study for three purposes: i) properties of the geometrical database and pumping station settings are utilized in the design of the SR and DR models, ii) key relationships between variables are obtained by means of FH model simulations and applied in the DR model, and iii) the performance of the simplified models is compared to the performance of the FH models. For all simulations with the FH models for any of the above purposes, a standard (uncalibrated) parameter set is employed as (Korving and Clemens, 2005) showed that the portability of event specific parameter sets for FH models is low. The main distinction between the calibrated FH model for Loenen and validated FH model for Waalre lies therefore in the trustworthiness of the underlying geometrical database.

The simulations performed with the FH model for the second purpose, application in the design of the DR model, are based on ten years (1955-1964) of 15 minute interval rainfall measurements in De Bilt in the Netherlands. The simulations were executed with a one minute time step, recording for every time step the volume, water level and flows in all manholes, conduits, pumps, CSOs etc. The derivation of the required relationships is described in detail in section 2.4.3.

2.4. Model structures

The general structure of the three simplified models tested in this paper is shown in figure 3. Model M1 includes only a RRO model. Model M2 combines a RRO model and a SR model, while model M3 combines a RRO model and a DR model. Rainfall, DWF and optional additional flows are model inputs, while flows to the surface water (Q_{SW}) and to the WWTP (Q_{WWTP}) are model outputs. In the following sections, all models are explained in more detail.

2.4.1. Rainfall runoff outflow (RRO) model

The standard linear reservoir model is a typical RRO model, see e.g. (Sun and Bertrand-Krajewski, 2013b). It comprises of a rainfall loss model followed by a linear reservoir. The rainfall loss model consists of initial (I_{ini} [mm]) and proportional (P_{cons} [-]) rainfall losses, i.e. depression losses and ratio of contributing and total area. The resulting net rainfall (I_{net} [mm]) occurs with a time lag (T_{lag} [min]) and feeds the linear reservoir with a reservoir constant (K [min]). The outflow of the standard linear reservoir (Q_{out}) is derived from the inputs using:

$$Q_{out}(t) = \exp\left(-\frac{\Delta t}{K}\right) Q_{out}(t-\Delta t) + \left[1-\exp\left(-\frac{\Delta t}{K}\right)\right] I_{net}(t-T_{lag})A, \qquad (1)$$

with A the catchment area [ha]. For more details on the standard linear reservoir model the reader is referred to (Sun and Bertrand-Krajewski, 2013b).

To determine the total inflow into the sewer models (Q_{in} in figure 3) for models M2 and M3, Q_{DWF} and $Q_{optional}$ are simply added to Q_{out}. For model M1, Q_{out} together with Q_{DWF} and $Q_{optional}$ represent both the surface runoff and the subsequent flow routing within the sewer system. It is split in the two sewer discharges Q_{SW} and Q_{WWTP} on the assumption that as much water is pumped to the WWTP as possible, i.e. all discharges up to the maximum pumping capacity is accounted to Q_{WWTP} as illustrated in figure 4 for Loenen. For Waalre, Q_{WWTP} is determined using the same method. From the remainder the discharge through the connection to the neighbouring catchment (determined from FH model simulations as it is not monitored) is subtracted before accounting it to Q_{SW}.

2.4.2. Static reservoir (SR) model

The SR model aims to represent processes within the sewer system that the basic RRO model cannot explicitly simulate. FH model properties of the geometrical database and pumping station settings are applied in its design. A schematic representation of the SR model for Loenen is shown in figure 5. It consists of a single basin for the sewer system which is filled by Q_{in} as described in the previous section. It empties through a pump resulting in Q_{WWTP}, and a single CSO resulting in Q_{SW}.

Several characteristics or relationships are applied in the SR model, numbered S SR1-SR3 in figure 5. Their representation and derivation were performed as follows:

SR1. Static storage-level curve

The static storage-level curve is used to convert the sewer volume (V_S) into the water level in the sewer (H_S). It is derived from the geometrical database of the FH model as the cumulative volume of all manholes, conduits, etc. of the sewer system under each possible water level.

SR2. Discharge through pump

The discharge through the pump ($Q_{S,P}$) is calculated through H_S and the pump characteristic. The pump characteristic is taken from the FH model. The DWF and maximum capacity are 115 and 209 m^3/h respectively. The switch on level is 15.00 m, and the switch off level 14.05 m above Normal Amsterdam Water Level (m AD).

SR3. Discharge through CSO

The discharge through the CSO (Q_{CSO}) is taken to be only caused by the primary CSO. The discharge is calculated through H_S and the standard weir equations for frontal weirs:

$$Q_{free} = c_1 h^{c_2} \quad (2)$$

for free outflow, with flow Q_{free} [m^3/s], h [m] water level above the weir crest, c_1 [m^{3-c_2}/s] taken to be 1.36 times the weir width [m] and c_2 [-] taken to be 1.5. Or

$$Q_{sub} = c_3 \mathrm{h}_{DS} \sqrt{2g(h_{US} - h_{DS})} \quad (3)$$

for submerged outflow, with flow Q_{sub} [m^3/s], h_{US} and h_{DS} [m] the upstream and downstream water level above the weir crest, c_3 [m] taken to be 0.8 times the weir width [m] and g the standard acceleration due to gravity [9.81 m/s^2]. Submerged

outflow is assumed to occur when $2/3*h_{US} < h_{DS}$. For Loenen only free outflow is assumed.

A schematic representation of the SR model for Waalre is depicted in figure 6. It consists of a basin for the sewer system and a basin for the settling tank. The sewer basin is filled by Q_{in} and has three discharges: one through the pump resulting in Q_{WWTP}, one through the connection with the neighbouring catchment and one through a single CSO to the settling tank. The discharge through the CSO fills the settling tank that is emptied either through a pump back into the sewer basin, or through a CSO to the surface water resulting in Q_{SW}.

Again several characteristics or relationships have been applied in the model, numbered SR4-SR10 in figure 6. Their representation and derivation were performed as follows:

SR4. Static storage-level curve sewer

See SR1, and excluding the settling tank.

SR5. Discharge sewer through pump

The discharge through the pump ($Q_{S,P}$) is calculated through the water level in the sewer (H_S) and the pump characteristic. The pump characteristic is derived from analysis of the water level and flow measurements at the pumping station, and (Van Daal-Rombouts, 2012). The DWF and maximum capacity are 85 and 400 m^3/h respectively. The switch on level is 17.15 m AD, the switch off level 16.30 m AD.

SR6. Discharge sewer through connection

From simulations with the FH model it was found that water only flows from Waalre to the neighbouring catchment. The discharge through the connection (Q_{CONN}) is calculated through H_S and the standard equation for a free outflow over a V-notch weir,

$$Q = c_1 \tan(\theta/2) h^{5/2}, \quad (4)$$

as the connecting sewer is egg shaped. Here Q is the flow [m^3/s], c_1 a constant [$m^{1/2}/s$] taken to be 1.4, θ the notch angle taken to be 67°, and h [m] the water level over the weir crest. Free outflow is assumed at all times and the bottom of the notch is taken to be the highest invert of the connecting conduit.

SR7. Discharge sewer through CSO

The discharge through the CSO (Q_{CSO}) is taken to be caused only by the primary CSO and is calculated through H_S and equations 2 and 3. Both free and submerged outflow are allowed (only free outflow is displayed).

SR8. Static storage-level curve settling tank

The static storage-level curve is used to convert the settling tank volume (V_T) into the water level in the tank (H_T). It is derived from the FH model, similar to SR1.

SR9. Discharge settling tank through pump

The discharge of the settling tank through the pump ($Q_{T,P}$) is based on H_T and the pump characteristic. The pump characteristic was taken from the FH model, where the pumping capacity was adjusted to match the monitoring data.

SR10. Discharge settling tank

The discharge of the settling tank (Q_T) is calculated through H_T and equation 2.

2.4.3. Dynamic reservoir (DR) model

The DR models for the sewer systems are similar to the SR models, but contain additional relationships derived from FH model simulations to better account for the dynamic behaviour of a sewer system. A schematic representation of the DR model for Loenen is shown in figure 7

303 and can be compared to the SR model in figure 5. Differences are expressed in the storage-
304 level curve applied (SR1 - DR1) and the water level applied in the CSO discharge (DR2 - no
305 equivalent in the SR model).
306
307 The characteristics or relationships applied in the DR model are numbered DR1-DR4 in figure 7.
308 Their representation and derivation are explained bellow:
309 DR1. Hybrid storage-level curve
310 A so called hybrid storage-level curve is used to convert the sewer volume (V_S) into the
311 water level in the sewer (H_S). The hybrid curve follows the static storage-level curve
312 (see SR1) for low water levels to correctly model DWF circumstances and pumping
313 behaviour, and gradually turns to the dynamic storage-level curve for high water levels
314 (with possibly pressurised flow conditions) to take the dynamic properties of the sewer
315 system under wet weather flow (WWF) conditions and CSO discharges into account.
316 Figure 8 (left) displays the static, dynamic, and hybrid storage curves for Loenen.
317 The dynamic storage-level curve was derived from simulations performed with the FH
318 model as described in section 2.3. The resulting water volumes in the entire sewer
319 system (every minute for 10 years) were grouped in one cm intervals of the
320 corresponding water level at the pumping station. The grouped volumes were
321 averaged and smoothed to obtain the dynamic storage-level curve, as displayed in
322 figure 8 (right). Note that the dynamic storage-level curve converges towards the static
323 storage-level curve for DWF conditions or low rain intensities as the water level in the
324 sewer system levels off.
325 DR2. Level at CSO
326 H_S is converted into the water level at the primary CSO location (H_{CSO}). The relationship
327 is based on FH model simulations, where a linear relation is fitted through the

simulated water levels at the pumping station and the CSO location. Only elevated water levels (WWF conditions) are taken into account.

DR3. Discharge through pump

See SR2.

DR4. Discharge through CSO

See SR3, only now H_{CSO} is applied.

A schematic representation of the DR model for Waalre is shown in figure 9 and can be compared to the SR model in figure 6. Differences are expressed in the storage-level curve applied (DR5-SR4), the water level applied in the CSO discharge (DR6-no equivalent in the SR model) and the water level applied in and the calculation of the flow through the connection (DR7-no equivalent in SR model, DR9-SR6).

The characteristics or relationships applied in the DR for Waalre are numbered DR5-DR13 in figure 9. Their representation and derivation are explained as follows:

DR5. Hybrid storage-level curve sewer

A hybrid storage-level curve is used to convert V_S into H_S. The derivation follows DR1. The resulting curves for Waalre are displayed in Figure 10: (left) the static, dynamic, and hybrid storage curves, (right) the derivation of the dynamic storage-level curve from the FH model simulation results.

DR6. Level sewer at CSO

Similar to DR2, a relationship has been derived between H_{CSO} and H_S. As Waalre is equipped with the settling tank two linear segments that connect at the highest weir crest level of the settling tank have been applied. Only elevated water levels (WWF conditions) are taken into account.

DR7. Level sewer at connection

Similar to H_{CSO} in DR6, a relationship between the water level at the connection to the neighbouring catchment (H_{CONN}) and H_S is derived from the FH model simulations. A linear relation was fitted, taking only elevated water levels (WWF conditions) into account.

DR8. Discharge sewer through pump

See SR5.

DR9. Discharge sewer through connection

The discharge of the sewer through the connection to the neighbouring catchment (Q_{CONN}) is based on H_{CONN} and a relationship derived from the FH model simulations. The simulated water levels at the connection and the corresponding flow through the connection were fitted with a third order polynomial equation. To prevent unrealistic (negative) output a maximum value is set for H_{CONN}.

DR10. Discharge sewer through CSO

See SR7, where H_{CSO} is applied in the calculation of the discharge from the sewer.

DR11. Static storage-level curve settling tank

See SR8.

DR12. Discharge settling tank through pump

See SR9.

DR13. Discharge settling tank

See SR10.

2.5. Calibration procedure

2.5.1. DREAM algorithm

376 Calibration, which adjusts model parameters by minimizing the difference between model
377 outputs and measurements, is an important step before applying simplified models. The
378 research on calibration methods in the area of rainfall-runoff modelling is comprehensive,
379 leading to the application of automatic calibration methods instead of traditional manual
380 calibration mainly based on trial and error approaches. In this study an automatic calibration
381 method (the differential evolution adaptive metropolis (DREAM) method (Vrugt et al., 2008,
382 2009)) was applied for the calibration of the RRO models. The DREAM method is based on the
383 Bayesian theorem, which considers model parameters as probabilistic variables revealing the
384 probabilistic belief on the parameters according to observed model outputs. In DREAM the
385 probability distribution function of parameters is derived using an iterative approximation
386 method (the Markov chain Monte Carlo (MCMC) method) coupled with multiple chains in
387 parallel in order to provide a robust exploration of the search space. In addition to an optimal
388 model parameter set, DREAM also results in an evaluation of model parameter uncertainty,
389 which provides important information on model reliability. The effectiveness of DREAM in
390 water related model calibration has been demonstrated in many previous studies, e.g. (Keating
391 et al., 2010; Leonhardt et al., 2014).

392 **2.5.2. Parameter optimisation**

393 The DREAM algorithm is applied to calibrate the parameters of the RRO model to find the
394 minimal difference between the simplified model output and the measurements. Table 2
395 shows the parameters, units and the searching range for the calibration procedure.
396
397 The algorithm minimises the sum of squared errors (SSE) between the model output and
398 measurements. Water level measurements are applied in the calibration as they are the actual
399 monitoring data available, containing all information on the sewer systems behaviour. For

Loenen the water level measurement at the primary CSO location is used to calibrate M2 and M3. For Waalre the water level measurements at the pumping station and inside the settling tank are applied, by minimising the sum of the SSEs for each model output-measurement combination. Only periods with elevated water levels are considered in the calibration, as the RRO model parameters are connected to rainfall only. Since water levels do not have significance in M1, it's calibration is based on the total outflow from the sewer system, i.e. the sum of the measured pump flow and the calculated outflow at the CSO locations (determined with the measured water levels and equation 2) for Loenen and Waalre. For Waalre the outflow through the connection with the neighbouring catchment is added. As this flow is not monitored, it is based on FH model simulations for the respective rain events.

The information content on which the models are calibrated is similar, especially for the elevated water levels relevant for CSO discharges. M2 and M3 are calibrated on measured water levels at the CSO locations. The discharge to the surface water in M2 and M3 is calculated using the modelled water level and equation 2. The same equation with the measured water levels is applied to determine the outflow for the calibration of M1. Additionally, the pumped outflow supplies information during low intensity rainfall, as contained in the level measurements at the pumping station (in case of Waalre) or the primary CSO location (for Loenen) when it is not yet discharging.

The calibration is performed using 10,000 iterations in DREAM, as it was found from test runs that the cumulative density functions of the parameters do not change (within the parameter stability) after several thousand iterations. The last 5,000 iterations are used for further analysis: the optimal parameter set and model output are derived, and the model is run with

all 5,000 parameter sets to determine the 95% confidence intervals for the water levels and discharges.

2.5.3. Events

For each catchment six rain events are available for the parameter optimisation, e.g. they led to a significant rise in water level in the sewer system, with or without discharge to the surface water, no external influences were known and monitoring data was available and judged reliable after data validation. The selected events and their characteristics are summarised in table 3.

(Korving and Clemens, 2005) showed that the portability of event specific parameter sets for FH models is low. (Sun and Bertrand-Krajewski, 2012) investigated the impact of calibration data selection on the model performance of regression models. Given the limited dataset, full consideration of this aspect is considered beyond the scope of this paper. It is clear, however, that comparison of the model structures on single event calibration is insufficient. Therefore three scenarios have been explored:

1. Calibration of single rain events,
2. Calibration on all events together,
3. Calibration on any set of 3 events and verification with the remaining 3 events.

2.6. Performance evaluation

The performance of the calibrated simplified model structures should be evaluated on the capability to correctly represent the sewer systems functioning at the edges of the system. As argued in the introduction this is not obtained by comparing the best fits between the measured and modelled water levels but by comparing the discharges from the system, i.e. to

447 the WWTP and the surface water. As the RRO models are calibrated, i.e. all calibration
448 parameters are related to rainfall, the focus of the performance evaluation will be on the CSO
449 discharges to the surface water. As the discharge to the WWTP is also relevant for integrated
450 studies it will be reported for completeness.
451
452 Common sense dictates that the impact of CSO events depends foremost on the occurrence of
453 such events, with the absolute discharged flows of secondary consequence. This is supported
454 by literature stating that impact based RTC can influence the systems performance for small
455 and moderate events, contrary to large events on which it has no influence (Langeveld et al.,
456 2013), and that up to a certain point overflow frequency is a good indicator of receiving water
457 impact (Lau et al., 2002). Therefore the first evaluation criterion for the simplified sewer
458 models is the correct determination of CSO event occurrences. The second evaluation criterion
459 is the correct determination of the total discharged volume.
460
461 Based on the monitored water levels at the CSO locations in the sewer systems and settling
462 tank, for each event and catchment the discharge to the surface water (Q_{SW}) is calculated
463 through application of equation 2. Additionally the total discharge to the WWTP (Q_{WWTP}) is
464 calculated from the pump flow measurements. For each model structure and scenario the
465 modelled the total discharged volumes (V_{SW} and V_{WWTP}) are determined as the integral of the
466 model outputs Q_{SW} and Q_{WWTP}.
467
468 CSO event occurrences are analysed through false positives (FP) and false negatives (FN). A FP
469 is defined as a CSO event occurrence ($V_{SW} > 0$) in the model output but not in the
470 measurements, a FN as a CSO event occurrence in the measurements but not in the model
471 output. For the comparison of discharged volumes, differences in V_{SW} (and V_{WWTP}) between the

model output and the measurements are calculated and listed for each event and scenario. Cumulative results for each scenario are determined by taking the root mean squared errors (RMSE) over all events.

For comparison purposes the selected rain events have also been simulated using the FH models. The comparison between simplified models with calibrated inflow parameters and FH models with uncalibrated inflow parameters is relevant since the FH models simulate the sewer systems behaviour in greatest detail and hence are deemed to be most accurate (Ferreri et al., 2010; Meirlaen et al., 2001; Rubinato et al., 2013). This might hold true for calibrated FH models but not for the much more commonly applied uncalibrated models, as proper calibration of FH models is very time consuming and requires a very large monitoring data set.

Finally, the simulation time needed by different simplified model structures and the FH model will be compared.

3. Results and discussion

3.1. Calibration

As described in the previous section the performance of the simplified model structures will be evaluated based upon the correct determination of CSO occurrences and the total discharge to the surface water. The calibration results, however, provide useful insight into the models functioning. Therefore, a typical calibration result for each catchment will be presented. Nash-Sutcliffe efficiency indexes (NS) (Nash and Sutcliffe, 1970) are supplied for easy comparison of the calibration results. Optimal parameter sets will be given for all events and scenarios.

The results for the individual calibration of rain events 2001-08-27 (Loenen) and 2011-08-14 (Waalre) for all model structures are displayed in figures 11 and 12 respectively. From top to bottom the applied rainfall is shown, followed by the model results for M1 (based on the total sewer outflow), and M2 and M3 (based on the water level in the sewer system). For Waalre additional water level measurements in the settling tank were applied, the results of which have been added to the bottom of figure 12. For each model structure the optimal results are displayed together with their 95% confidence bands.

Figures 11 and 12 show that M2 and M3 are in general well able to describe the sewer systems behaviour: the measurements applied in the calibration are closely followed during the filling of the basins, once they are full and during emptying, resulting in NS values > 0.95 for Loenen and > 0.75 for Waalre. Small differences occur between these models especially during filling and in the response to temporal changes in the rainfall. M1 cannot describe the sewer systems behaviour in detail as it has only the reservoir constant K to account for surface storage and in-

sewer storage. The response to rainfall is therefore more smoothed, which is best demonstrated in figure 11. NS values < 0.4 are found.

For both catchments and all model structures the 95% confidence bands are mostly < 1%. Logically, the influence of the (inflow) calibration parameters on water levels in sewer systems is most apparent at the onset of a rain event or during temporal changes, resulting in confidence bands up to 10% for M2 and M3, while they stay < 1% for M1.

For all scenarios for Loenen NS values for M2 and M3 > 0.90. For M1, values differ strongly from -8.52 to 0.44. For Waalre for M2 and M3 in scenario 1, NS values range between 0.61 and 0.96, with one event around zero. In scenario 2 the values drop to 0.5 to 0.6. The NS values for M1 again differ strongly between events and scenarios from -9.42 to 0.82.

Figure 13 shows the optimal parameter values for Loenen (left) and Waalre (right) for all model structures. In asterisks the results for scenario 1 (calibration on single rain events) are given, the line indicates the parameter values for scenario 2 (all events together). Results for all twenty possible combinations of three calibration events in scenario 3 can be found in figure 14. The optimal parameter values reflect the results for the water levels and NS values: the parameters for M2 and M3 show much resemblance within a catchment, while M1 deviates. Especially the difference in K stands out, as the RRO model in M1 has to account for the surface and in-sewer storage, while in M2 and M3 only for the surface storage. The optimal parameter values between scenarios 2 (line in figure 13) and 3 (figure 14) are consistent, indicating that the exact split in a calibration and verification set does not have a major impact on the outcome.

3.2. Performance evaluation

3.2.1. Model discharge

As the calibration of the simplified models is performed on rainfall related parameters, the focus of the performance evaluation will be on the discharge to the surface water (Q_{SW}) while the discharge to the WWTP (Q_{WWTP}) is included for completeness.

Optimal Q_{SW} and Q_{WWTP} for all model structures for the calibration of the single events of 2001-08-27 (Loenen) and 2011-08-14 (Waalre) are displayed in figures 15 and 16 as well as the discharges determined from the measurements. The difference between M1 and M2/M3 observed in the calibration results are also clear from these figures, as Q_{SW} for M1 tends to be more smoothed because of the higher value for K.

3.2.2. Determination of CSO events

FPs and FNs for all events for each model structure and scenario, based on the optimal parameter sets, are given in table 4. For scenarios 1 and 2 the total number is reported, for scenario 3 the results have been averaged over all combinations and multiplied by two for easy comparison. Additionally, results for the FH model have been added.

Based on the FPs and FNs in table 4, M1 can be immediately discarded for these catchments. For each scenario and catchment two FPs were recorded, the exact number of rain events that did not lead to a CSO event. This is easily explained since a rain event leading to a significant rise in water level in a pumped sewer system will likely contain rain intensities higher than the pumping capacity of the sewer system reserved for WWF (design guideline in the Netherlands: 0.7 mm/h). In M1 all rainfall in excess of this capacity has to be discharged to the surface water, leading to a CSO event. The calibration algorithm unsuccessfully tries to overcome this

inadequacy in the model structure by delaying the rainfall (high T_{lag}) and smoothing the response (high K), as can be found from the optimal parameter values in figure 13.

For M2 and M3 the results are less conclusive. Single FPs or FNs occur depending on the catchment and scenario applied. The floating point values for scenario 3 for Waalre (due to averaging over all possible combinations) and the optimal parameter values in figure 13 further indicate that the inflow parameters are calibrated differently depending on the selection of calibration/verification events. Only for M3 for Loenen no FPs or FNs occur in any scenario signalling that the M3, combining the RRO and DR models, is likely the best performing model for Loenen.

3.2.3. Determination of discharged volumes

The total volumes discharged to the surface water (V_{SW}) for each model structure and scenarios 1 and 2 are displayed in figure 17 for Loenen and 18 for Waalre. V_{SW} is the integrated model output Q_{SW}, for which the optimal values and 95% confidence bands are determined as described in section 2.5.2. The calculation of the 95% confidence intervals for the measurements is based on an uncertainty in the standard weir equation of 25%. This percentage is estimated on previous work by (Van Daal-Rombouts et al., 2014) on scale models and (Fach et al., 2009) on computational fluid dynamics. Both studies indicate deviations between the actual (measured or calculated) CSO discharge and the discharge determined with the standard weir equation of up to 50%. They also indicate that this strongly depends on the water level over the weir crest leading to under and over estimations of the flow. Therefore an intermediate value was chosen. For the FH model an uncertainty of 50% was applied based on the possibility to calibrate FH models up to 5 cm difference in water levels and equation 2.

582

583 The cumulative results for V_{SW} and V_{WWTP}, given in table 5, were determined by taking the
584 RMSE of the results from the optimal parameter sets over all events. The RMSE for scenario 3
585 have been averaged over all possible combinations and values for the FH model have been
586 added.

587

588 The results for V_{SW} in figures 17 and 18 and table 5 support the preliminary conclusion that M3
589 outperforms M2 for Loenen. For all scenarios the RMSE and the uncertainty bands for M3 are
590 smaller than for M2. Despite the inability of M1 to correctly determine CSO event occurrences,
591 it outperforms M2 based on V_{WS}. For Waalre the performance of M2 and M3 are similar,
592 corresponding to the determination of the CSO events. Nevertheless, M2 consistently
593 performs better than M3. Similar to Loenen, M1 generally performs well based on V_{SW}. The
594 difference in the performance of M2 and M3 between the catchments is also reflected in the
595 optimal parameter values (figure 13). The parameter values for Waalre are close resulting in
596 similar RMSE values in table 5, while for Loenen there is more variety between the model
597 structures especially for I_{ini} and K.

598

599 These results can be explained by the information available for the simplified model design
600 and calibration as described in sections 2.2 and 2.3. All information is better known or of
601 higher quality for Loenen: i) The monitoring data for Loenen was gathered for research
602 purposes, while the monitoring campaign for Waalre received less dedicated attention. ii) For
603 Loenen two rain gauges were installed in the catchment itself, while for Waalre no local rain
604 gauges were available. iii) The geometrical database underlying the FH model for Loenen is
605 better known than for Waalre. The results for the RMSE of V_{SW} indicate that the more detailed
606 model M3, i.e. RRO model for the runoff combined with the DR model for the sewer system, is

607 favoured when high quality information is available (in this case Loenen), while the less
608 detailed model M2, RRO with SR, suffices when the information is of lower quality (Waalre).
609
610 One main source of uncertainty for Waalre likely stems from the calibrated rain radar input.
611 The rainfall in general seems reasonable with NS values for M2 or M3 > 0.6. In detail the
612 rainfall seems off in intensities and/or timing, an example of which can be found in figure 16.
613 Judging from the rainfall, the models responses in Q_{SW} are in accordance (main peak in the
614 outflow after main peak in the rainfall). However, in the measurements the main peak in the
615 outflow occurs right at the beginning of the rain event. The other events display a similar
616 mismatch between the rainfall and the outflow. This may also explain the very low values for
617 the parameters T_{lag} and K, see figure 13, as the calibration procedure tries to correct the
618 mismatch in the input data.
619
620 For V_{WWTP} the RMSE values in table 5 show that model M1 consistently performs worse than
621 M2 and M3 for all scenarios and both catchments. M2 and M3 generally perform on a similar
622 level, which is to be expected as the pumping regime in the SR and DR model structures is the
623 same.
624
625 The NS values reported in section 3.1 are based on the calibration parameters for each time
626 step, and the FP/FN in table 4 and RMSE in table 5 on V_{SW}. Each presents information on the
627 performance of the model structure. NS indicates the quality of the description of the sewer
628 systems behaviour in general, while the others are specific for CSO discharges. The difference
629 between the best performing model structure based on these criterions, especially for Loenen,
630 is striking. Model M2 and M3 have similar NS values > 0.9, but M3 is much more accurate
631 based on FP/FN and RMSE. Simplified sewer models are calibrated on measurements,

generally only water levels, but used to determine CSO discharges. These results show that care should be taken in choosing performance indicators suitable to the purpose of the model, likely leading to multiple indicators.

3.2.4. Uncalibrated FH models

Finally the performance of the FH models is compared to the performance of the calibrated simplified models. The comparison is made for scenario 2, calibration for all events together, since there a single parameter set is derived for each model structure, similar to the single standard parameter set for the FH model.

Based on the determination of CSO event occurrences (table 4) the FH model performs at a similar level as M2 and M3. For Loenen one FP is noted for the FH model, while none for M2 and M3. For Waalre it is reversed.

Taking the RMSE for V_{SW} (table 5) into account, the FH model is easily outperformed by both M2 and M3, while V_{WWTP} is worse for Loenen and better for Waalre. The results for the simplified models for V_{SW} (scenario 3) imply little loss of accuracy when the available data is split into a calibration and verification set. This suggests that, if a sufficiently large data set were available, the optimal parameter set should be applicable to other events without much loss of accuracy.

The simulation time for the FH models takes 1,000-5,000 times longer than for M2/M3 or 250,000-475,000 times longer than for M1.

From the perspective of both the simulation time and accuracy of results it is concluded that it is better to apply simplified calibrated models in optimisation or RTC studies than uncalibrated FH models.

4. Conclusions and future research

The research described dealt with the design and performance evaluation of a so called dynamic simplified sewer model for the accurate and rapid calculation of sewer system discharges for optimisation and RTC studies. The dynamic simplified sewer model (M3) consists of a calibrated rainfall runoff outflow (RRO) model and a dynamic reservoir (DR) model for the sewer behaviour. It contains characteristics derived from full hydrodynamic (FH) model simulations to account for the dynamic properties of the sewer system behaviour.

The performance of M3 was tested for two combined, pumped catchments and compared against two other simplified models, M2 (calibrated RRO model with a static reservoir (SR)) and M1 (calibrated RRO model only), and uncalibrated FH models. The performance was not solely based on the goodness of fit of the calibration but primarily on the correct determination of CSO event occurrences, and secondly on the correct determination of the total discharged volumes to the surface water.

From this research the following conclusions can be drawn:

- Model M1 simulates > 100,000 times faster than the FH model; models M2/M3 are > 1,000 times faster than the FH model.
- M1 is unsuitable to correctly predict CSO occurrences for pumped catchments. The model structure is unable to retain rain intensities higher than the pumping capacity reserved for WWF, resulting in too many CSO discharges.
- M2 and M3 are able to describe the behaviour of pumped sewer systems.
- Performance indicators for the selection of the most appropriate model structure should be chosen carefully in relation to the modelling objectives, likely leading to

multiple indicators, each one providing a specific approach of the models' performances.

- In case of detailed and trustworthy information available for the design and calibration of the model (Loenen), M3 outperforms M2 for all scenarios. If the available information is of lower quality (Waalre), M2 consistently performs slightly better indicating that the derivation of the more detailed DR model is not useful.
- For rainfall driven modelling trustworthy and local rain measurements remain necessary despite the availability of rain radar data, to either apply as direct input or the correction of radar data.
- M2 and M3 outperform the uncalibrated FH models based on the total discharge to the surface water. In optimisation or RTC studies the application of suitable calibrated simplified models is preferred over uncalibrated FH models.

Future research is recommended in the area of statistical substantiation of the results as the available data sets were too limited to allow a statistical analysis of the results themselves. Also the use of continuous data sets instead of the current intermittent ones would be interesting because more information on the initial conditions prior to events would be included.

Following the above, future research will focus on retrieving more reliable monitoring data (especially rainfall). For the catchment of Waalre, the impact of more reliable rainfall data on the performance of the detailed M3 model will be focussed on. Calibrated simplified sewer models will be derived for the catchments in the case study area of Eindhoven for application in an integrated model to research the possibilities for quality based RTC.

Acknowledgements

The authors would like to acknowledge Innovyze (www.innovyze.com) for kindly supplying a research licence for the use of the software program InfoWorks ICM. Also the authors would like to thank the Van Gogh Programme for supplying a Travel Grant to cover the travel expenses for the cooperation between TU Delft and INSA Lyon.

The research is performed within the Dutch 'Kennisprogramma Urban Drainage' (Knowledge Programme Urban Drainage). The involved parties are: ARCADIS, Deltares, Evides, Gemeente Almere, Gemeente Arnhem, Gemeente Breda, Gemeente 's-Gravenhage, Gemeentewerken Rotterdam, Gemeente Utrecht, GMB Rioleringstechniek, Grontmij, KWR Watercycle Research Institute, Royal HaskoningDHV, Stichting RIONED, STOWA, Tauw, vandervalk + degroot, Waterboard De Dommel, Waternet and Witteveen+Bos.

References

Bach, P.M., Rauch, W., Mikkelsen, P.S., McCarthy, D.T., Deletic, A., 2014. A critical review of integrated urban water modelling - Urban drainage and beyond. Environ. Model. Softw. 54, 88–107.

Benedetti, L., Langeveld, J.G., Comeau, A., Corominas, L., Daigger, G., Martin, C., Mikkelsen, P.S., Vezzaro, L., Weijers, S.R., Vanrolleghem, P.A., 2013. Modelling and monitoring of integrated urban wastewater systems: review on status and perspectives. Water Sci. Technol. 68, 1203–1215.

Clemens, F.H.L.R., 2001. Hydrodynamic models in urban drainage: application and calibration. TU Delft.

Coutu, S., Del Giudice, D., Rossi, L., Barry, D.A., 2012. Parsimonious hydrological modeling of

732 urban sewer and river catchments. J. Hydrol. 464-465, 477–484.

733 De Niet, A.C., De Jonge, J., Korving, H., Langeveld, J.G., Van Nieuwenhuijzen, A., 2013. Het
734 beste van twee werelden, correctie van neerslagradar op basis van grondstations voor
735 toepassing in stedelijk gebied. H2O online 1–5.

736 Del Giudice, D., Reichert, P., Bareš, V., Albert, C., Rieckermann, J., 2015. Model bias and
737 complexity – Understanding the effects of structural deficits and input errors on runoff
738 predictions. Environ. Model. Softw. 64, 205–214.

739 Dotto, C.B.S., Kleidorfer, M., Deletic, A., Rauch, W., McCarthy, D.T., 2014. Impacts of measured
740 data uncertainty on urban stormwater models. J. Hydrol. 508, 28–42.

741 Fach, S., Sitzenfrei, R., Rauch, W., 2009. Determining the spill flow discharge of combined
742 sewer overflows using rating curves based on computational fluid dynamics instead of
743 the standard weir equation. Water Sci. Technol. 60, 3035–43.

744 Ferreri, G.F., Freni, G., Tomaselli, P., 2010. Ability of Preissmann slot scheme to simulate
745 smooth pressurisation transient in sewers. Water Sci. Technol. 62, 1848–1858.

746 Keating, E.H., Doherty, J., Vrugt, J.A., Kang, Q., 2010. Optimization and uncertainty assessment
747 of strongly nonlinear groundwater models with high parameter dimensionality. Water
748 Resour. Res. 46, 1–18.

749 Kleidorfer, M., Möderl, M., Fach, S., Rauch, W., 2009. Optimization of measurement campaigns
750 for calibration of a conceptual sewer model. Water Sci. Technol. 59, 1523–30.

751 Korving, H., Clemens, F.H.L.R., 2005. Impact of dimension uncertainty and model calibration on
752 sewer system assessment. Water Sci. Technol. 52, 35–42.

753 Krebs, G., Kokkonen, T., Valtanen, M., Setälä, H., Koivusalo, H., 2014. Spatial resolution
754 considerations for urban hydrological modelling. J. Hydrol. 512, 482–497.

Langeveld, J.G., 2004. Interactions within wastewater systems. TU Delft.

Langeveld, J.G., Benedetti, L., De Klein, J., Nopens, I., Amerlinck, Y., Van Nieuwenhuijzen, A., Flameling, T., Van Zanten, O., Weijers, S.R., 2013. Impact-based integrated real-time control for improvement of the Dommel River water quality. Urban Water J. 10, 312–329.

Lau, J., Butler, D., Schütze, M., 2002. Is combined sewer overflow spill frequency/volume a good indicator of receiving water quality impact? Urban Water 4, 181–189.

Leonhardt, G., Sun, S., Rauch, W., Bertrand-Krajewski, J.-L., 2014. Comparison of two model based approaches for areal rainfall estimation in urban hydrology. J. Hydrol. 511, 880–890.

Liefting, H.J., 2012. Toetsing rioolmodel Waalre.

Mair, M., Kleidorfer, M., Rauch, W., 2012. Performance of auto-calibration algorithms in the field of urban drainage modelling, in: Proceedings of UDM9. Belgrade, pp. 1–10.

Mannina, G., Viviani, G., 2010. An urban drainage stormwater quality model: Model development and uncertainty quantification. J. Hydrol. 381, 248–265.

Meirlaen, J., Huyghebaert, B., Sforzi, F., Benedetti, L., Vanrolleghem, P.A., 2001. Fast, simultaneous simulation of the integrated urban wastewater system using mechanistic surrogate models. Water Sci. Technol. 43, 301–309.

Motiee, H., Chocat, B., Blanpain, O., 1997. A storage model for the simulation of the hydraulic behaviour of drainage networks. Water Sci. Technol. 36, 57–63.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models: Part I - A discussion of principles. J. Hydrol. 10, 282–290.

Rubinato, M., Shucksmith, J., Saul, A.J., Shepherd, W., 2013. Comparison between InfoWorks

777 hydraulic results and a physical model of an Urban drainage system. Water Sci. Technol.
778 68, 372–379.

779 Sun, S., Bertrand-Krajewski, J.-L., 2013a. Input variable selection and calibration data selection
780 for storm water quality regression models. Water Sci. Technol. 68, 50–58.

781 Sun, S., Bertrand-Krajewski, J.-L., 2013b. Separately accounting for uncertainties in rainfall and
782 runoff: Calibration of event based conceptual hydrological models in small urban
783 catchments using Bayesian method. Water Resour. Res. 49, 1–14.

784 Sun, S., Bertrand-Krajewski, J.-L., 2012. On calibration data selection: The case of stormwater
785 quality regression models. Environ. Model. Softw. 35, 61–73.

786 Vaes, G., Berlamont, J., Bermont, J., 1999. Emission predictions with a multi-linear reservoir
787 model. Water Sci. Technol. 39, 9–16.

788 Vaes, G., Willems, P., Berlamont, J., 2001. Rainfall input requirements for hydrological
789 calculations. Urban Water 3, 107–112.

790 Van Bijnen, M., Korving, H., 2008. Application and results of automatic validation of sewer
791 monitoring data, in: Proceedings of ICUD11. Edinburgh, pp. 1–10.

792 Van Daal-Rombouts, P.M.M., 2012. Personal communication.

793 Van Daal-Rombouts, P.M.M., Tralli, A., Verhaart, F., Langeveld, J.G., Clemens, F.H.L.R., 2014.
794 Applicability of CFD modelling in determining accurate weir discharge - water level
795 relationships, in: Proceedings of ICUD13. Sarawak, pp. 1–8.

796 Vrugt, J.A., Ter Braak, C.J.F., Clark, M.P., Hyman, J.M., Robinson, B.A., 2008. Treatment of input
797 uncertainty in hydrologic modeling: Doing hydrology backward with Markov chain Monte
798 Carlo simulation. Water Resour. Res. 44, 1–15.

799 Vrugt, J.A., Ter Braak, C.J.F., Gupta, H.V., Robinson, B.A., 2009. Equifinality of formal (DREAM)
800 and informal (GLUE) Bayesian approaches in hydrologic modeling? Stoch. Environ. Res.
801 Risk Assess. 23, 1011–1026.

802 Wolfs, V., Villazon, M.F., Willems, P., 2013. Development of a semi-automated model
803 identification and calibration tool for conceptual modelling of sewer systems. Water Sci.
804 Technol. 68, 167–175.

805 Wolfs, V., Willems, P., 2014. Development of discharge-stage curves affected by hysteresis
806 using time varying models, model trees and neural networks. Environ. Model. Softw. 55,
807 107–119.

Table 1. Sewer system characteristics for Loenen and Waalre.

property	unit	Loenen	Waalre
number of inhabitants	-	2,100	6,200
contributing area	ha	23.4	52.3
average slope ground level	%	0.91	0.14
static storage volume	m^3 - mm	947 - 4.0	2,704 - 5.2
WWF pumping capacity	m^3/h	209	400
number of CSO structures	-	2	2 (incl. 1 SST)
length of conduits	km	12.3	27.6

Table 2. Calibration parameters with searching range.

parameter	abbreviation	unit	searching range
initial rainfall loss	I_{ini}	mm	0 - 4
proportional rainfall loss	P_{cons}	-	0 - 1
lag time	T_{lag}	min	0 - 120
reservoir constant	K	min	0 - 240

Table 3. Selected rain events with key characteristics.

catchment area	event [dd-mm-yyyyy]	rainfall depth [mm]	max rain intensity [mm/h]	duration [hh:mm]	discharge to surface water [y/n]
Loenen	30-06-2001	9.9	24.8	6:12	y
	18-07-2001	13.9	25.4	14:36	y
	19-07-2001	12.2	34.0	12:15	n
	23-07-2001	12.3	19.4	7:48	y
	27-08-2001	17.0	24.0	7:45	y
	23-10-2001	7.4	6.0	7:39	n
Waalre	29-04-2011	6.5	5.2	6:20	n
	14-08-2011	27.0	23.4	10:35	y
	18-08-2011	12.0	14.9	7:20	n
	22-08-2011	39.2	68.8	23:04	y
	14-12-2011	15.4	11.9	23:31	y
	16-12-2011	33.4	8.5	22:15	y

Table 4. FPs and FNs for all 6 events for each model structure and scenario based on the optimal parameter sets. The results for scenario 3 have been averaged over all combinations and multiplied by two for easy comparison.

scenario	1: individual events		2: all events together		3: 3 events calibration, 3 verification			
					calibration		verification	
catchment / model structure	total FP	total FN	total FP	total FN	mean FP	mean FN	mean FP	mean FN
Loenen								
M1	2	0	2	0	2.0	0.0	2.0	0.0
M2	1	0	0	0	1.0	0.0	1.0	0.0
M3	0	0	0	0	0.0	0.0	0.0	0.0
FH			1	0				
Waalre								
M1	2	0	2	0	2.0	0.0	1.9	0.0
M2	0	1	1	0	0.4	0.2	0.6	0.1
M3	0	1	1	0	0.4	0.2	0.6	0.1
FH			0	0				

Table 5. RMSE for V_{SW} and V_{WWTP} for all 6 events for each model structure and scenario (1: individual events, 2: all events together, 3: calibrate and verify on 3 events each) based on the optimal parameters sets.

	RMSE [m^3]							
	V_{SW}				V_{WWTP}			
catchment / model structure	1	2	3 calibra-tion	3 verifica-tion	1	2	3 calibra-tion	3 verifica-tion
Loenen								
M1	112	150	147	178	445	242	248	255
M2	416	197	346	364	67	150	135	158
M3	57	145	94	125	124	143	133	132
FH		661				399		
Waalre								
M1	3,470	2,469	2,448	2,157	3,072	2,075	2,307	2,240
M2	5,202	967	2,593	2,212	422	1,331	995	1,330
M3	5,398	1,480	2,788	2,487	556	1,346	1,027	1,354
FH		2,658				619		

Figure captions

Figure 1. Sewer system layout for Loenen (left) and Waalre (right). Monitoring locations and locations of pumping stations and CSOs are indicated. Line colour and width indicate pipe diameter ranges: >= 1500 mm (thick black), >= 1000 (black), >= 600 (thick grey), >= 400 (grey) and < 400 mm (light grey).

Figure 2. Daily DWF profiles per person for Loenen and Waalre.

Figure 3. The three simplified models M1-M3 convert the three inputs to two discharges to the surface water (Q_{SW}) and the WWTP (Q_{WWTP}). RRO: rainfall runoff outflow, SR: static reservoir, DR: dynamic reservoir.

Figure 4. The output of the RRO model is split into Q_{SW} and Q_{WWTP} based on the maximum pumping capacity of the catchment (209 m^3/h for Loenen).

Figure 5. Schematic representation of the SR model for Loenen. Applied characteristics or relationships as displayed in graphs SR1-SR3 are elaborated upon in the main text.

Figure 6. Schematic representation of the SR model for Waalre. Applied characteristics or relationships as displayed in graphs SR4-SR10 are elaborated upon in the main text.

Figure 7. Schematic representation of the DR model for Loenen. Applied characteristics or relationships as displayed in graphs DR1-DR4 are elaborated upon in the main text.

Figure 8. Hybrid storage-level curve (left) and derivation of the dynamic storage-level curve from the FH model simulation results (right) for Loenen.

Figure 9. Schematic representation of the DR model for Waalre. Applied characteristics or relationships as displayed in graphs DR5-DR13 are elaborated upon in the main text.

Figure 10. Hybrid storage-level curve (left) and derivation of the dynamic storage-level curve from the FH model simulation results (right) for Waalre.

Figure 11. Results for the individual calibration of rain event 2001-08-27 for all model structures for Loenen.

Figure 12. Results for the individual calibration of rain event 2011-08-14 for all model structures for Waalre.

Figure 13. Optimal parameter values for scenarios 1 (individual calibrated events (asterisks)) and scenario 2 (all events together (line)) for Loenen (left) and Waalre (right). The horizontal axis presents event numbers. Please note the changing scale for T_{lag} and K.

Figure 14. Optimal parameter values for scenario 3 for Loenen (left) and Waalre (right). The horizontal axis presents the 20 possible combinations to take 3 events from 6. Please note the changing scale for T_{lag} and K.

Figure 15. Q_{SW} and Q_{WWTP} for the individually calibrated event of 2001-08-27 for Loenen.

Figure 16. Q_{SW} and Q_{WWTP} for the individually calibrated event of 2011-08-14 for Waalre.

Figure 17. V_{SW} with 95% confidence bands for all events and each model structure for Loenen. For scenarios 1 (individual events, top) and 2 (all events together, bottom). The horizontal axis presents event numbers.

Figure 18. V_{SW} with 95% confidence bands for all events and each model structure for Waalre. For scenarios 1 (individual events, top) and 2 (all events together, bottom). The horizontal axis presents event numbers.

Figure 1 - left

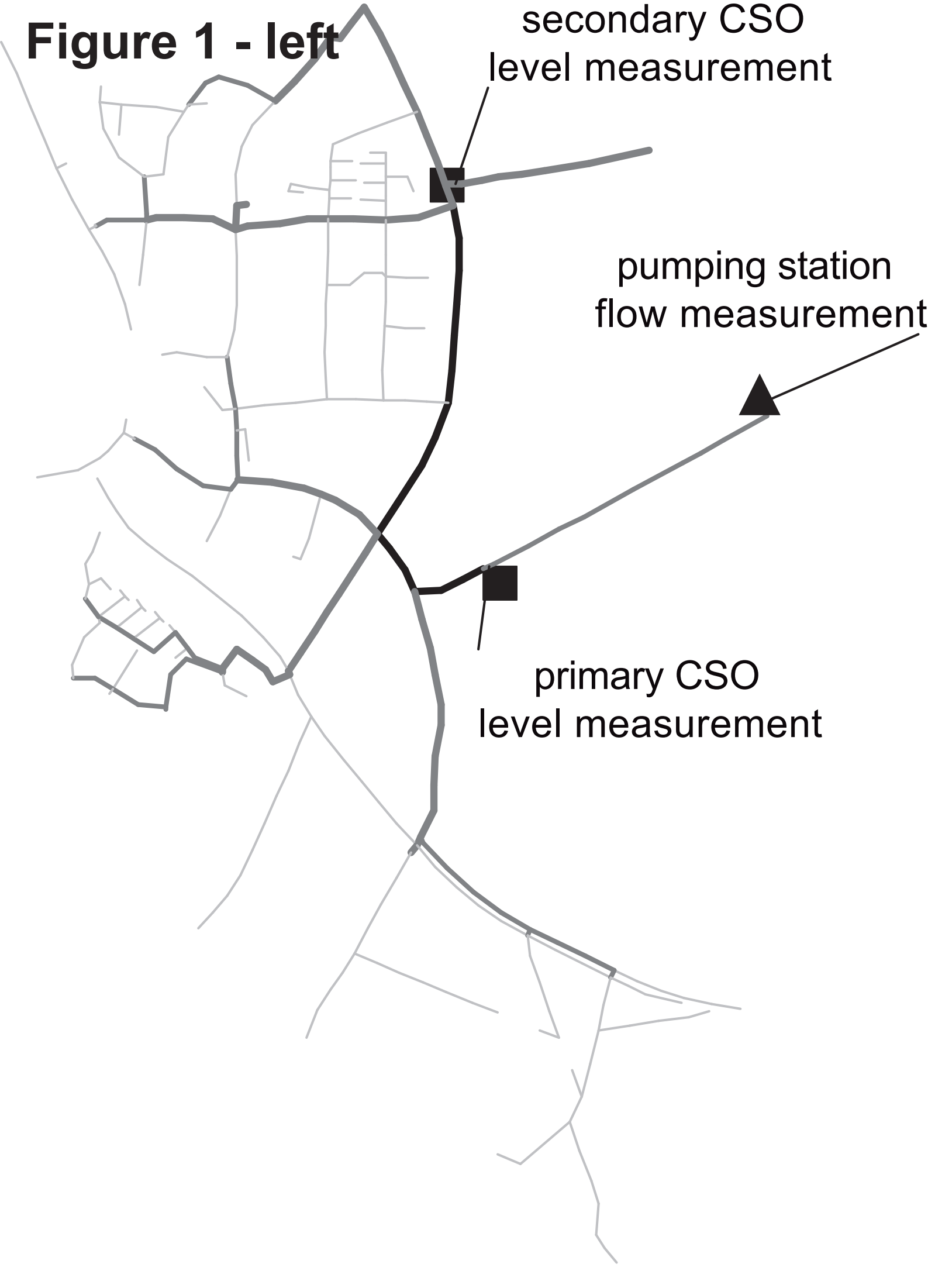


Figure 1 - right

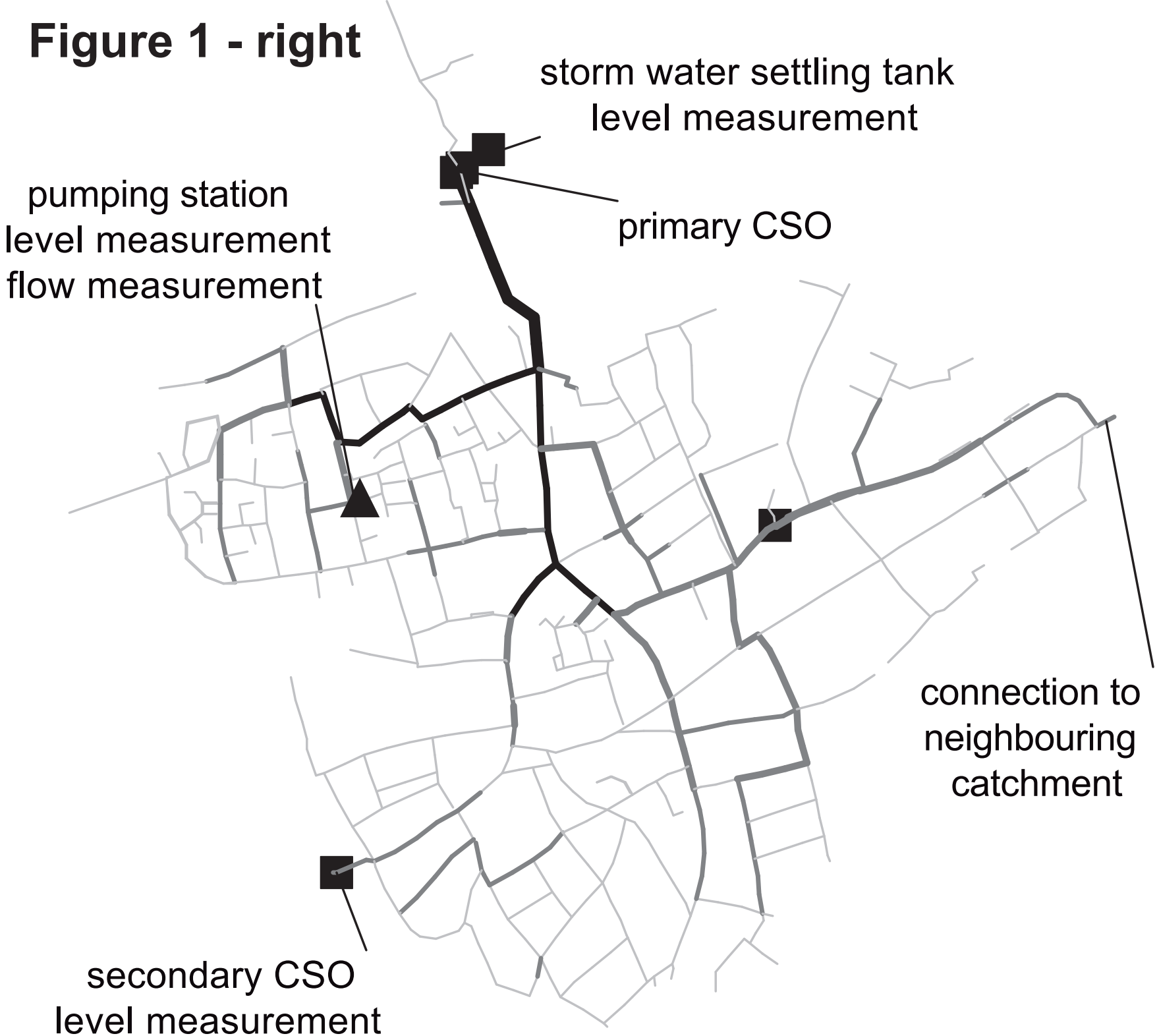


Figure 2

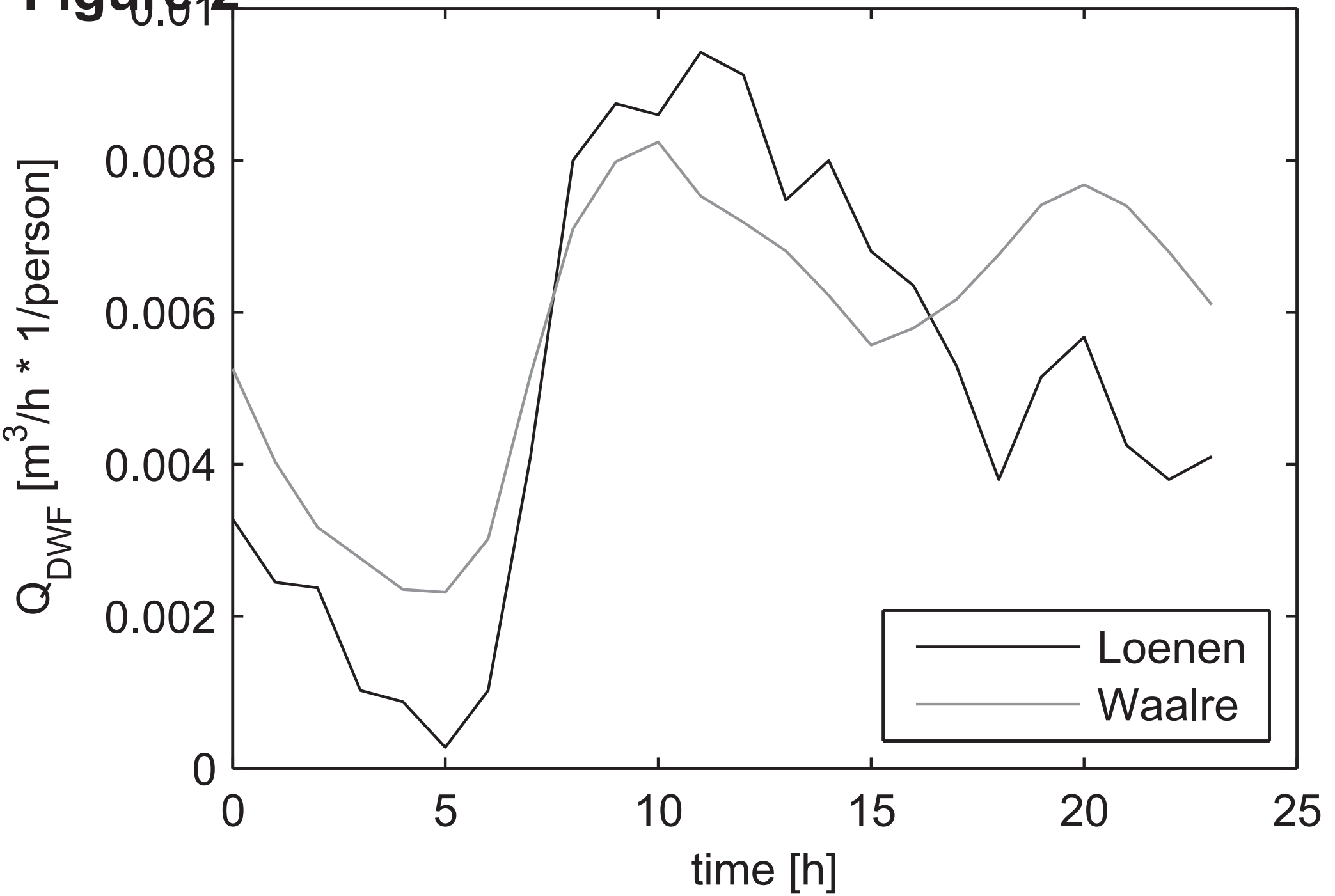

0.01
0.008
0.006
0.004
0.002
0
Q_{DWF} [m^3/h * 1/person]
0
5
10
15
20
25
time [h]
Loenen
Waalre

Figure 3

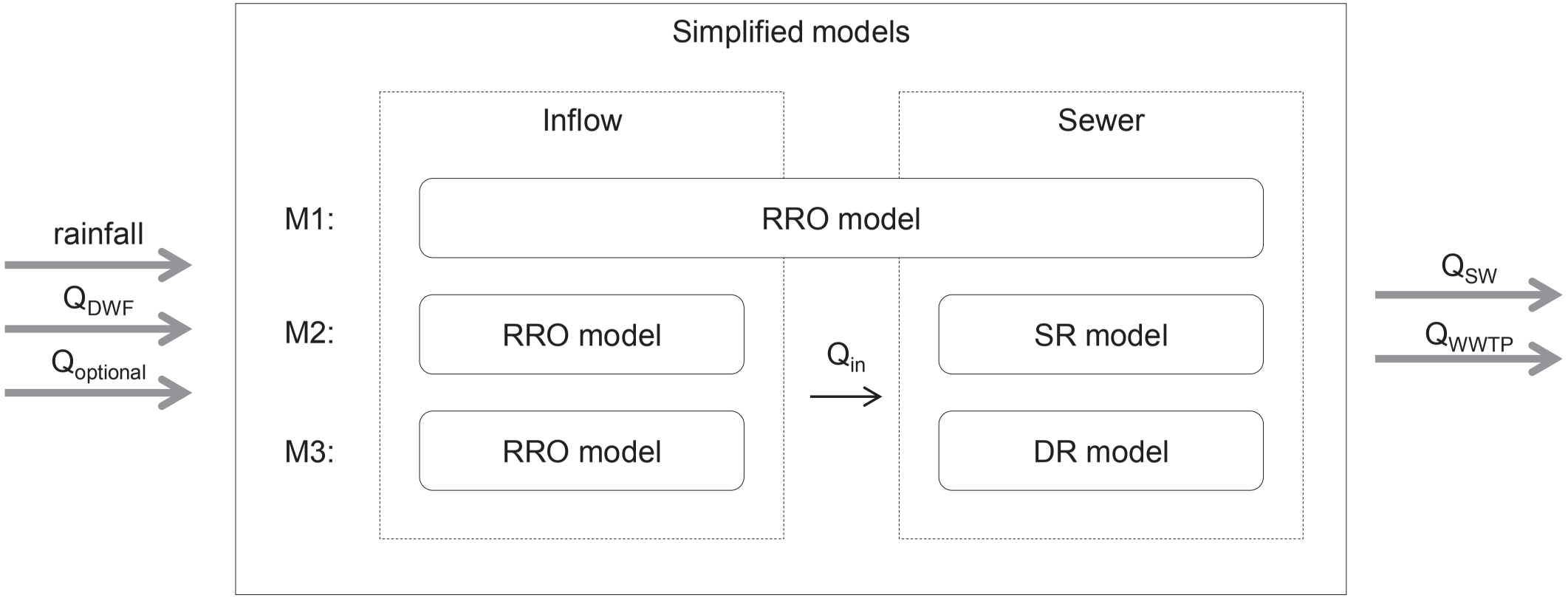

Simplified models
Inflow
Sewer
M1:
RRO model
M2:
RRO model
SR model
M3:
RRO model
DR model
Q_{in}
rainfall
Q_{DWF}
$Q_{optional}$
Q_{SW}
Q_{WWTP}

Figure 4

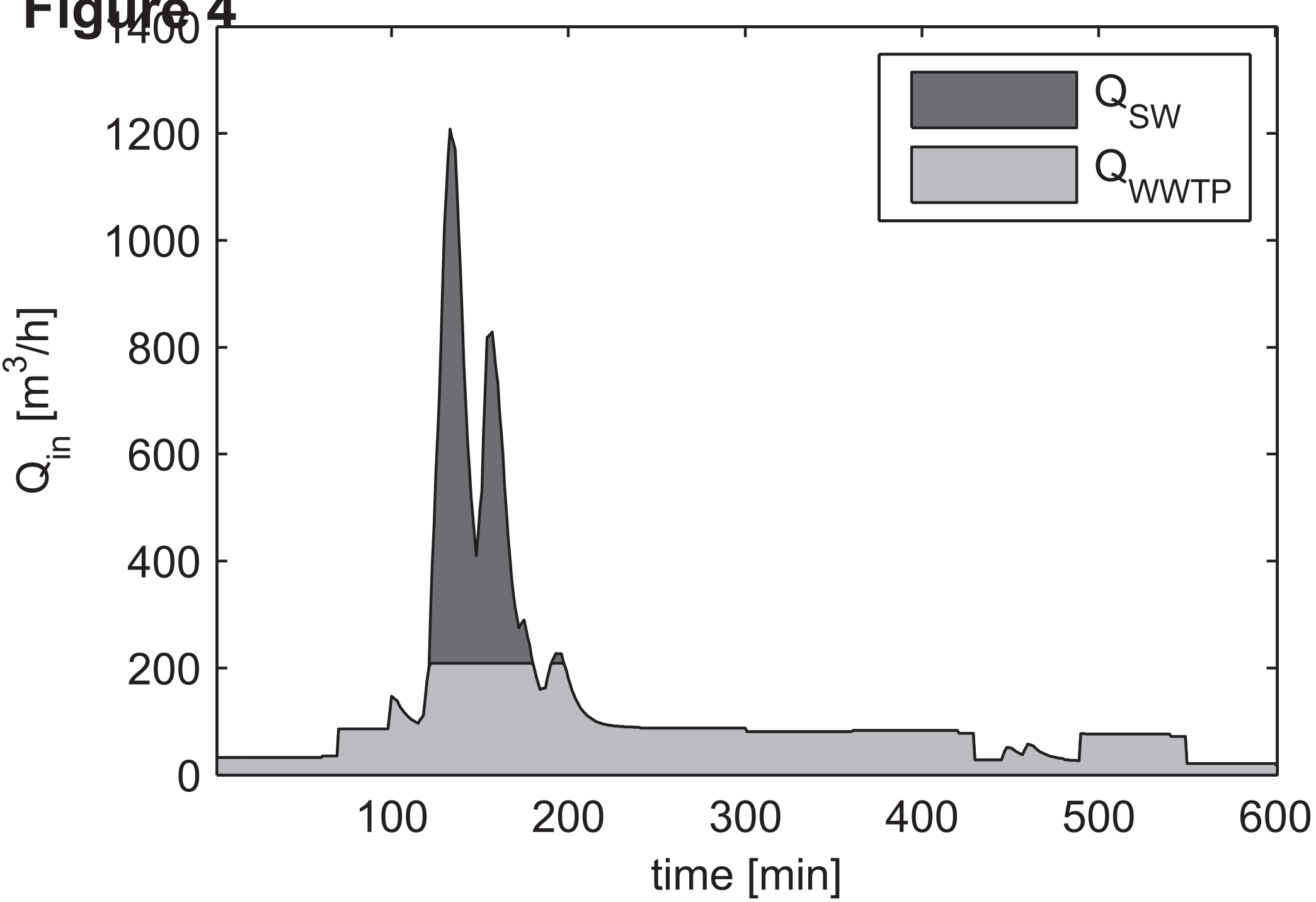

1400
1200
1000
800
600
400
200
0
Q_{in} [m^3/h]
100
200
300
400
500
600
time [min]
Q_{SW}
Q_{WWTP}

Figure 5 - total SR model Loenen with graphs SR1-SR3

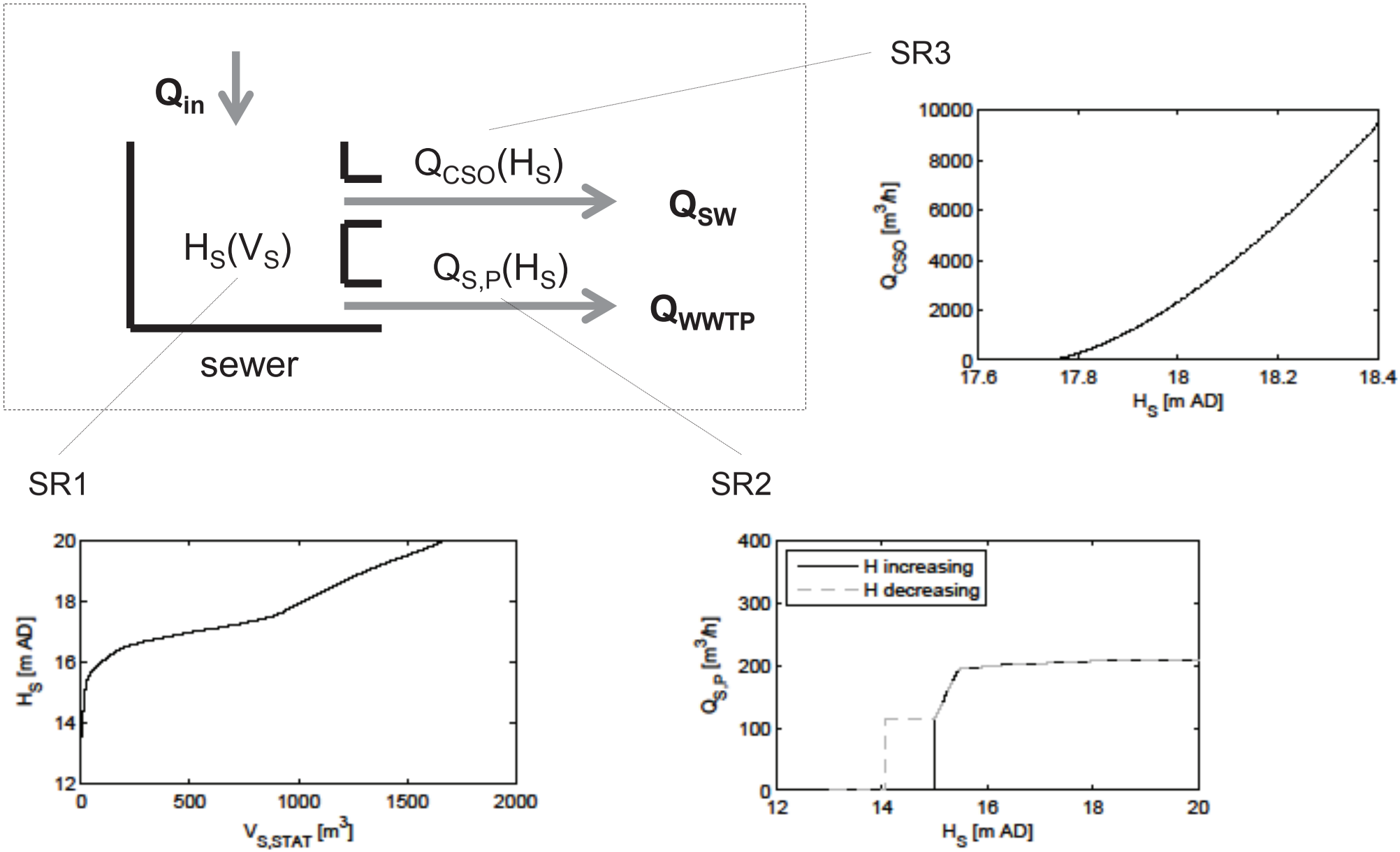


Figure 5 - high res SR1

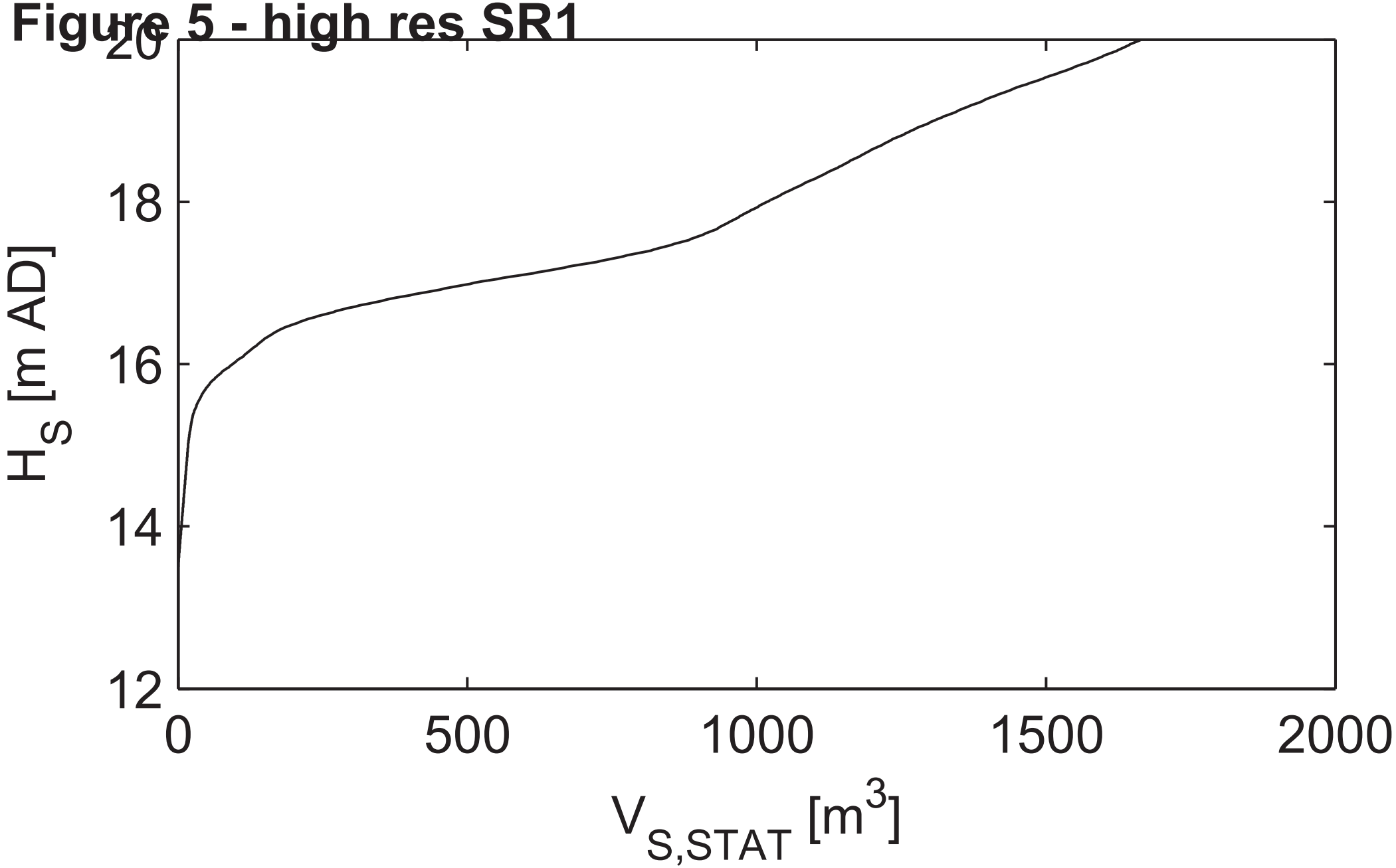


Figure 5 - high res SR2

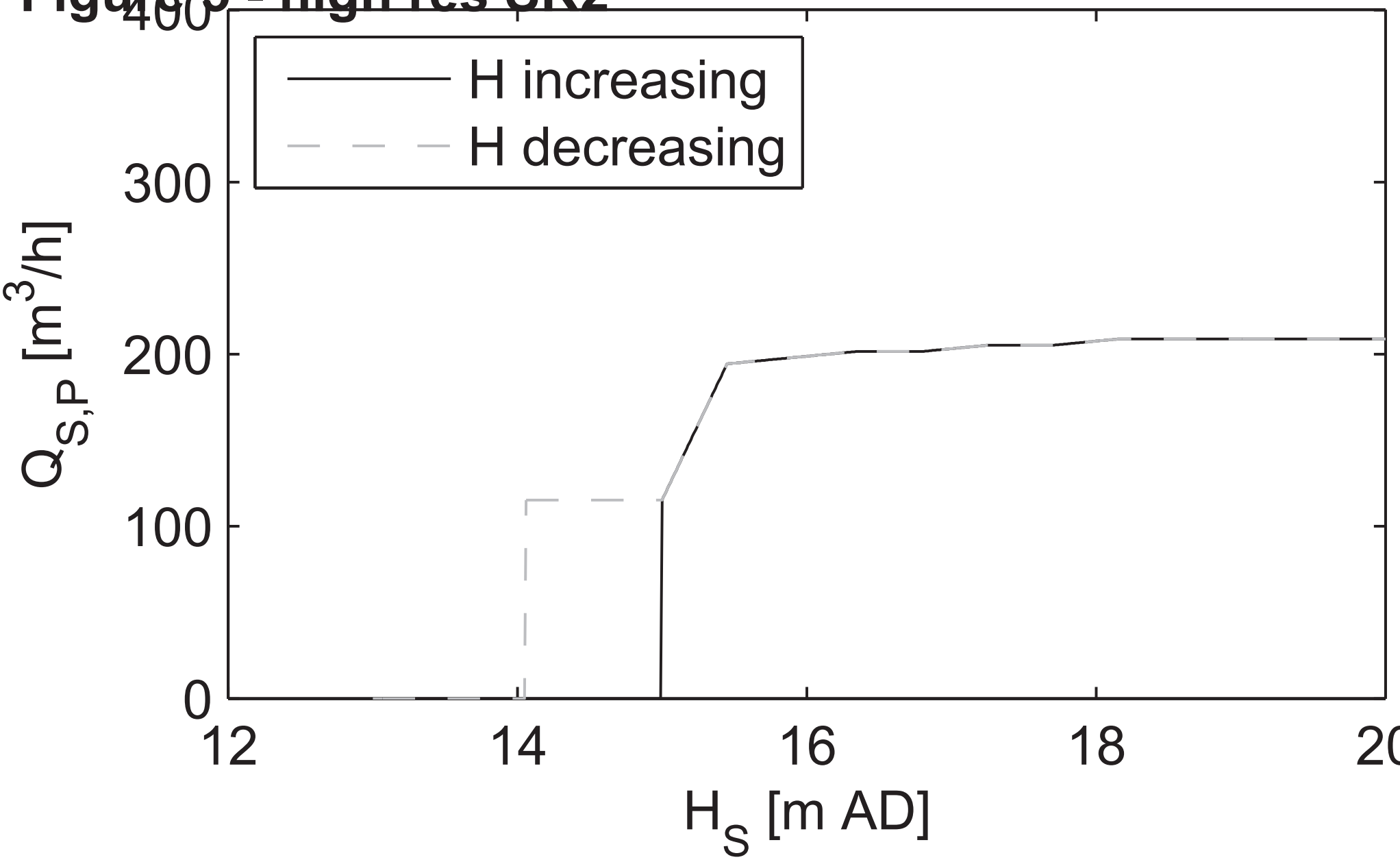


Figure 5 - high res SR3

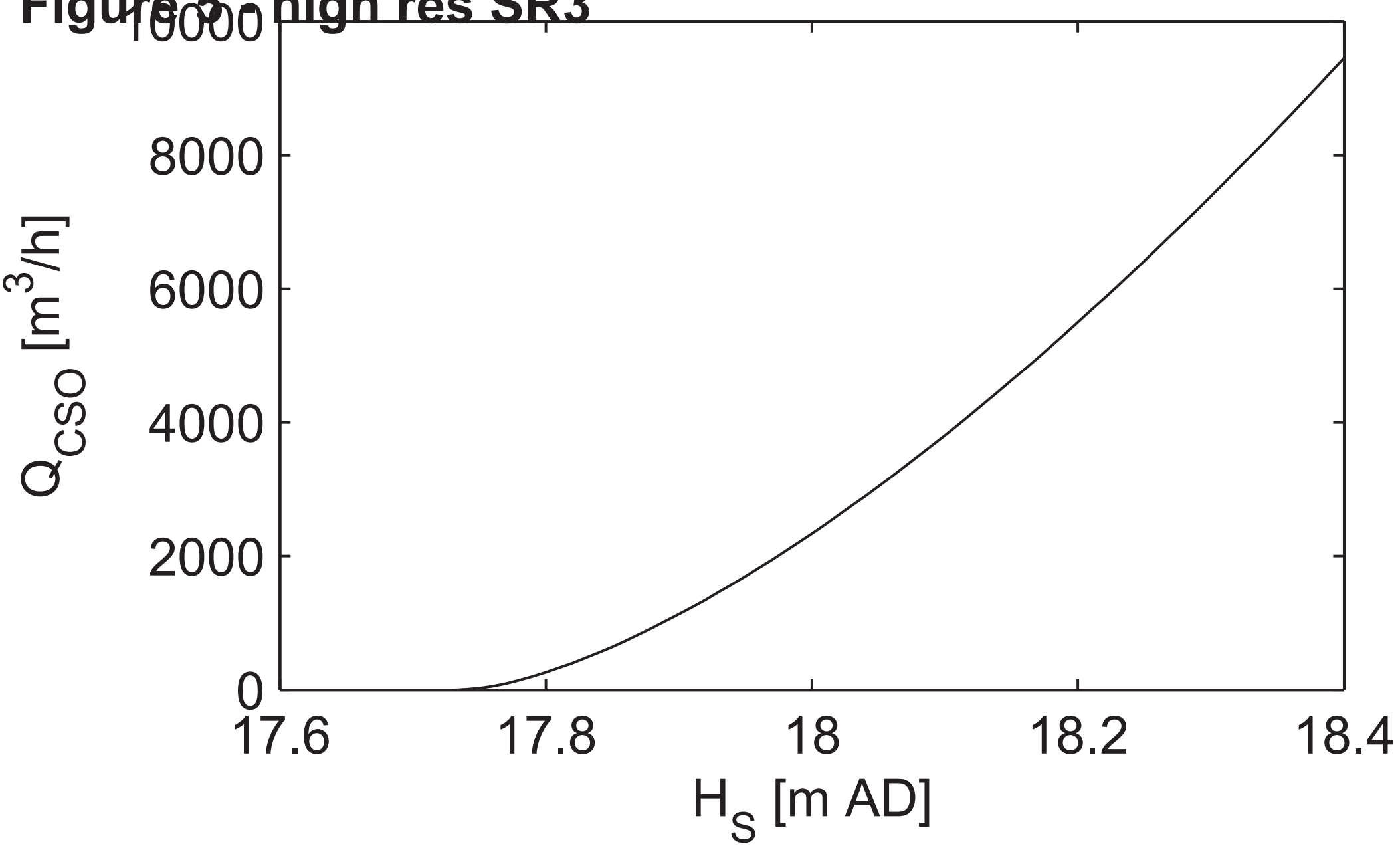


Figure 6 - total SR model Waalre with graphs SR4-SR10

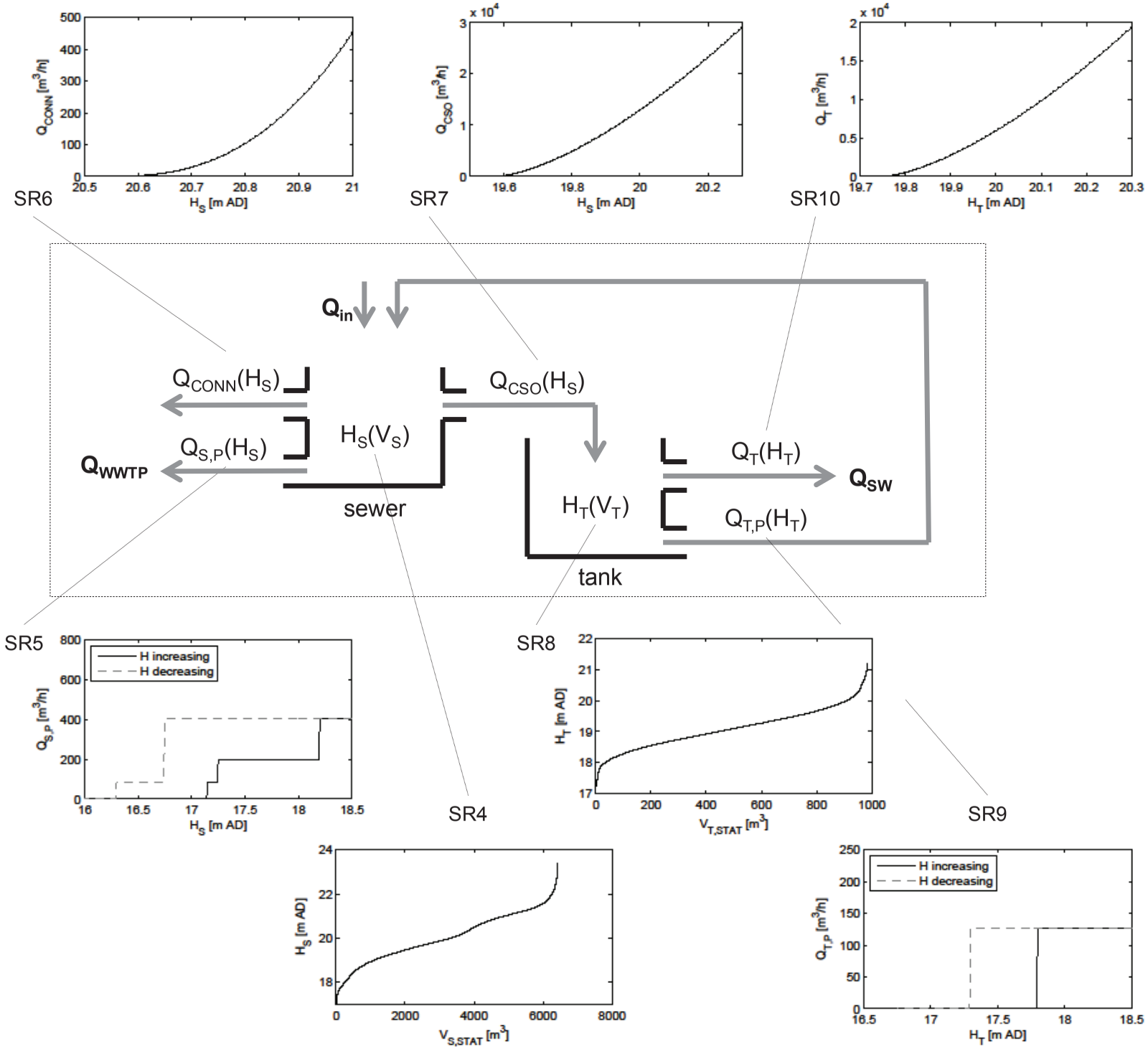


Figure 6 - high res SR4

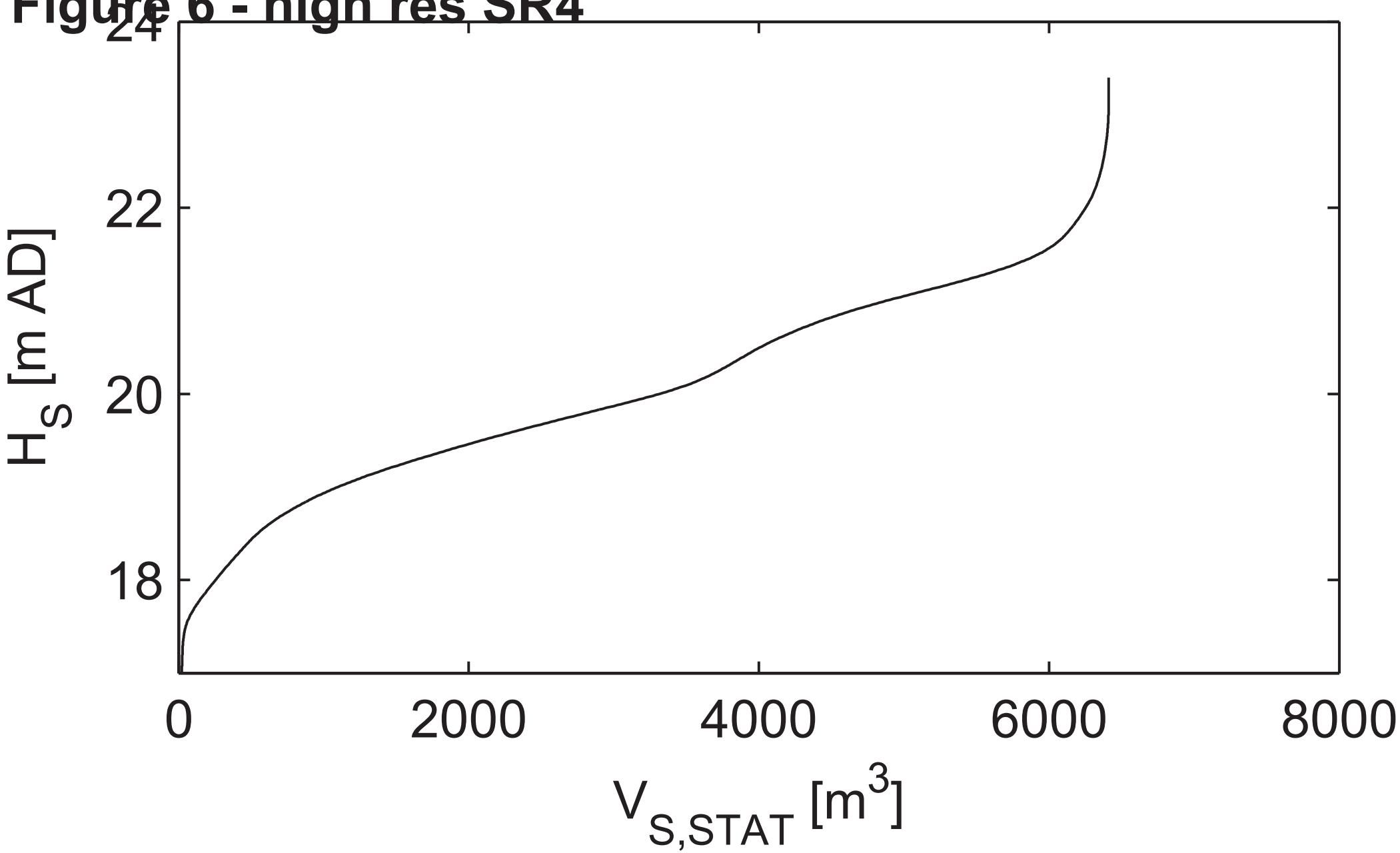


Figure 6 - high res SR5

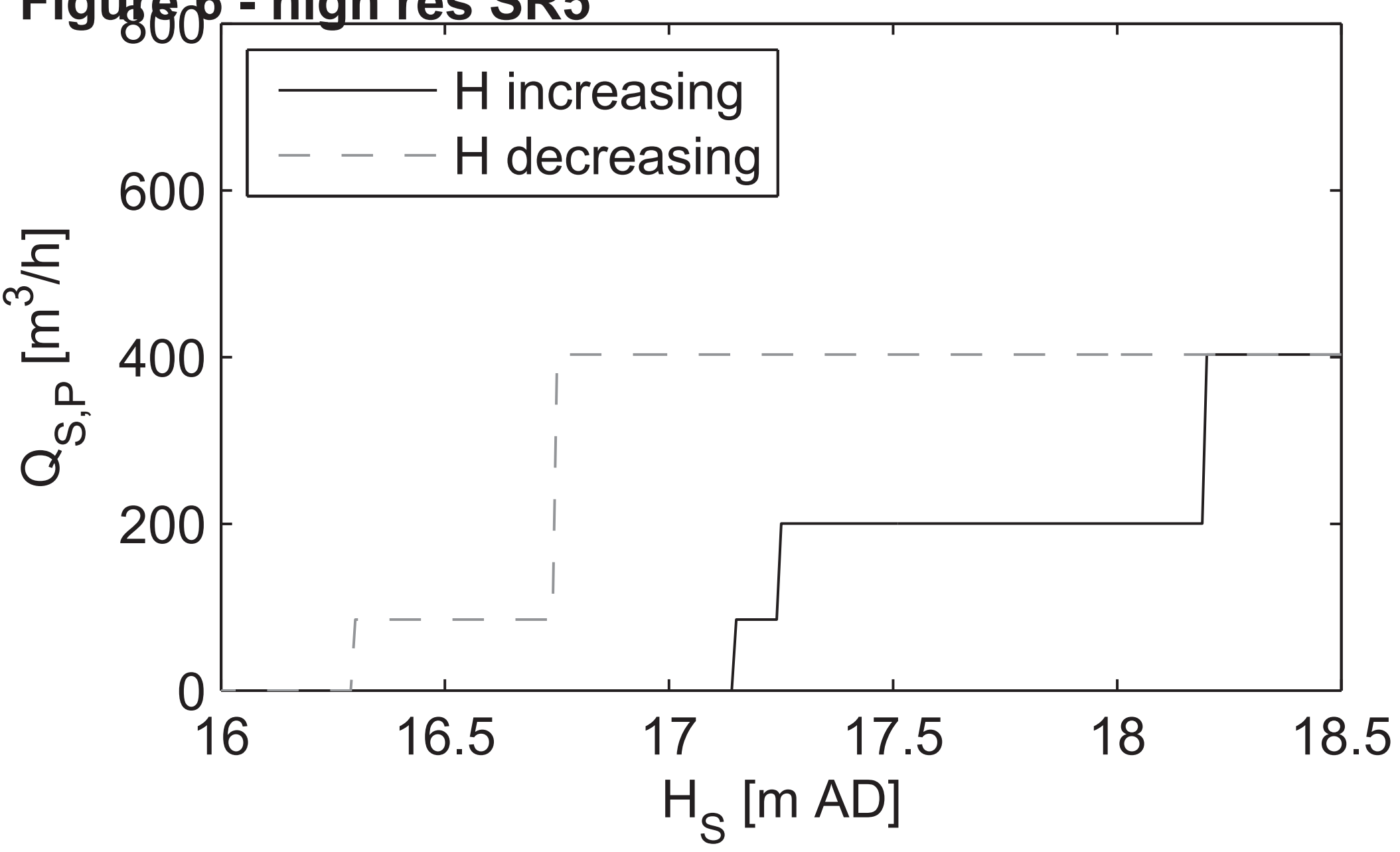


Figure 6 - high res SR6

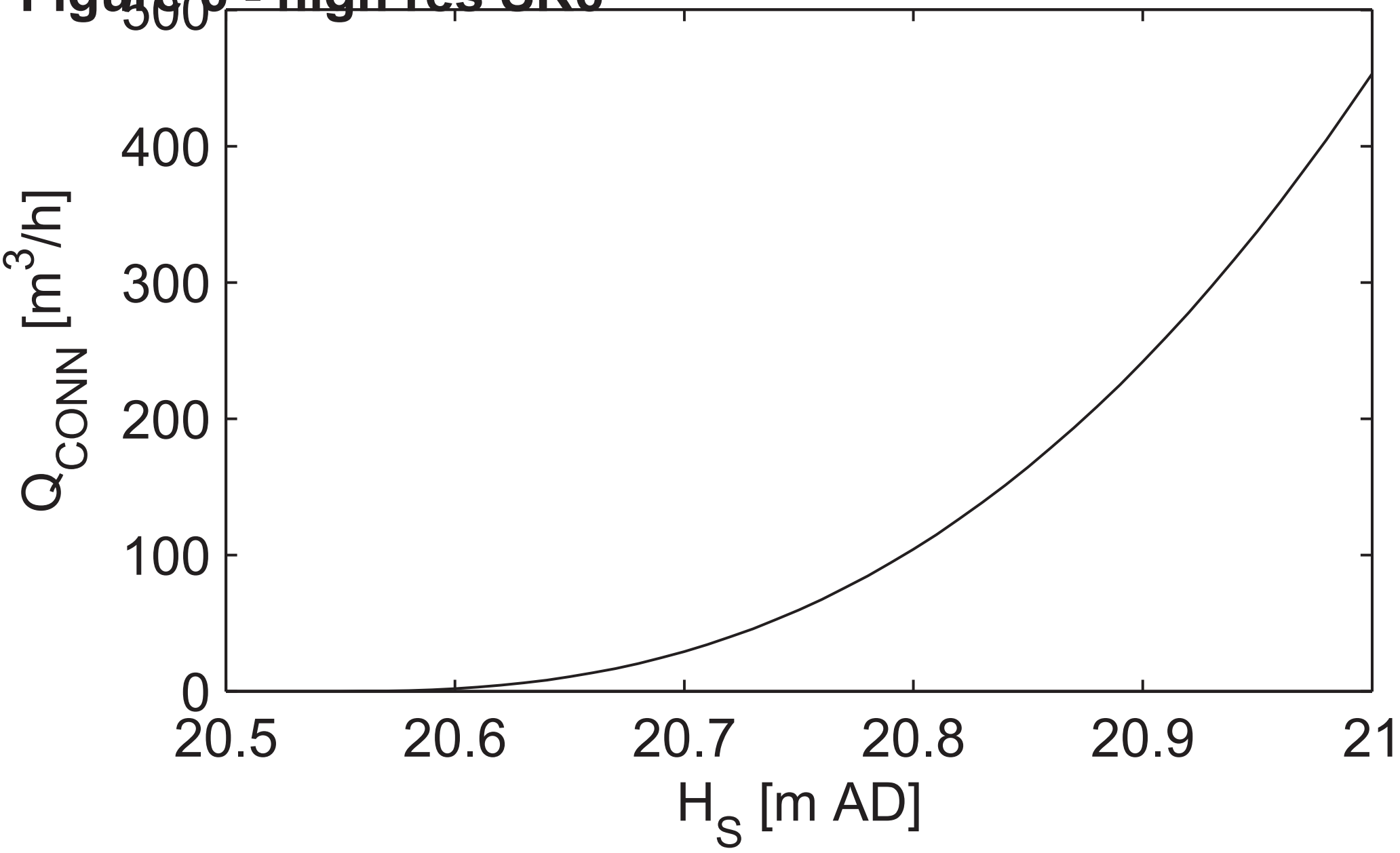


Figure 6 - High res SR7

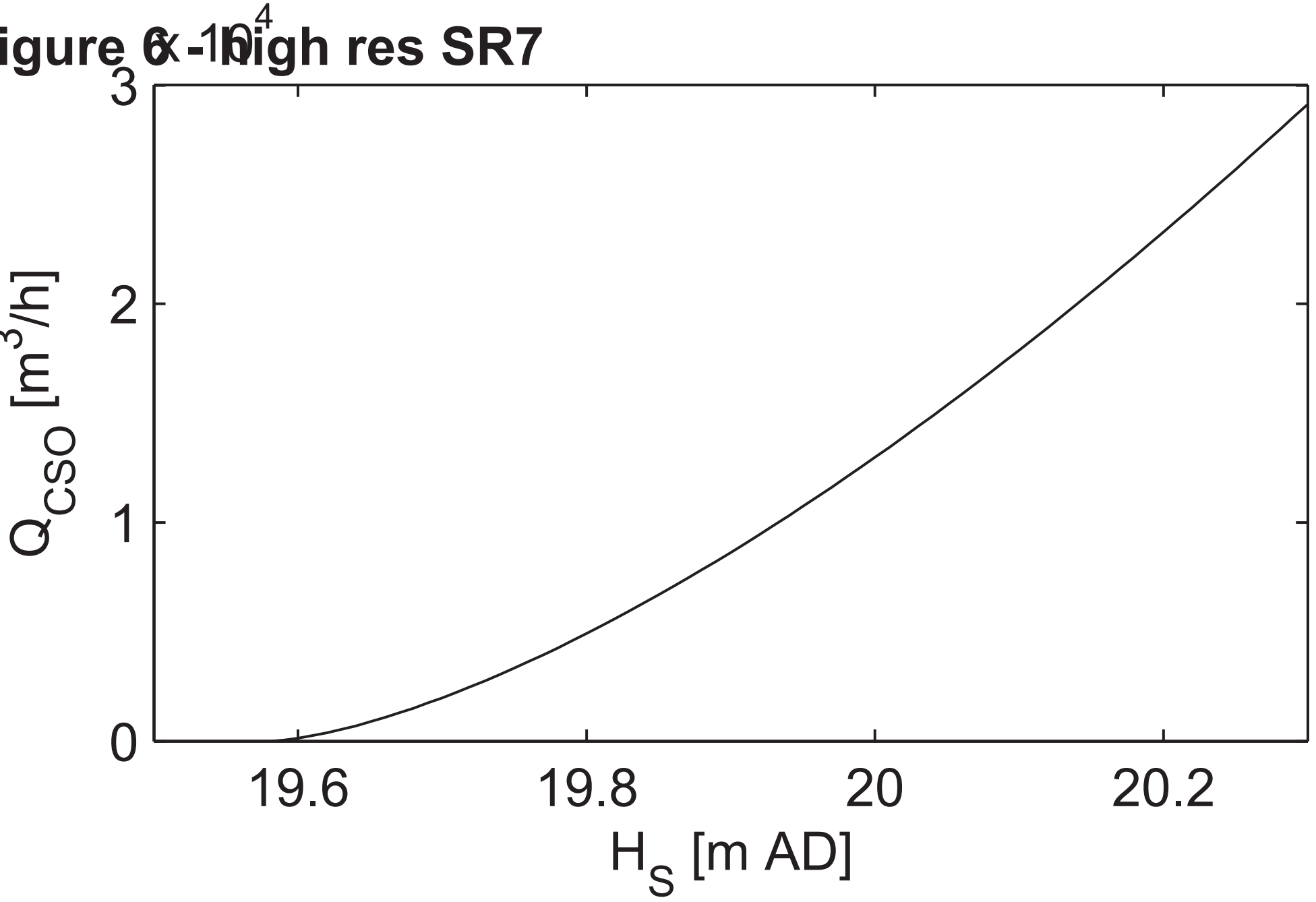


Figure 6 - high res SR8

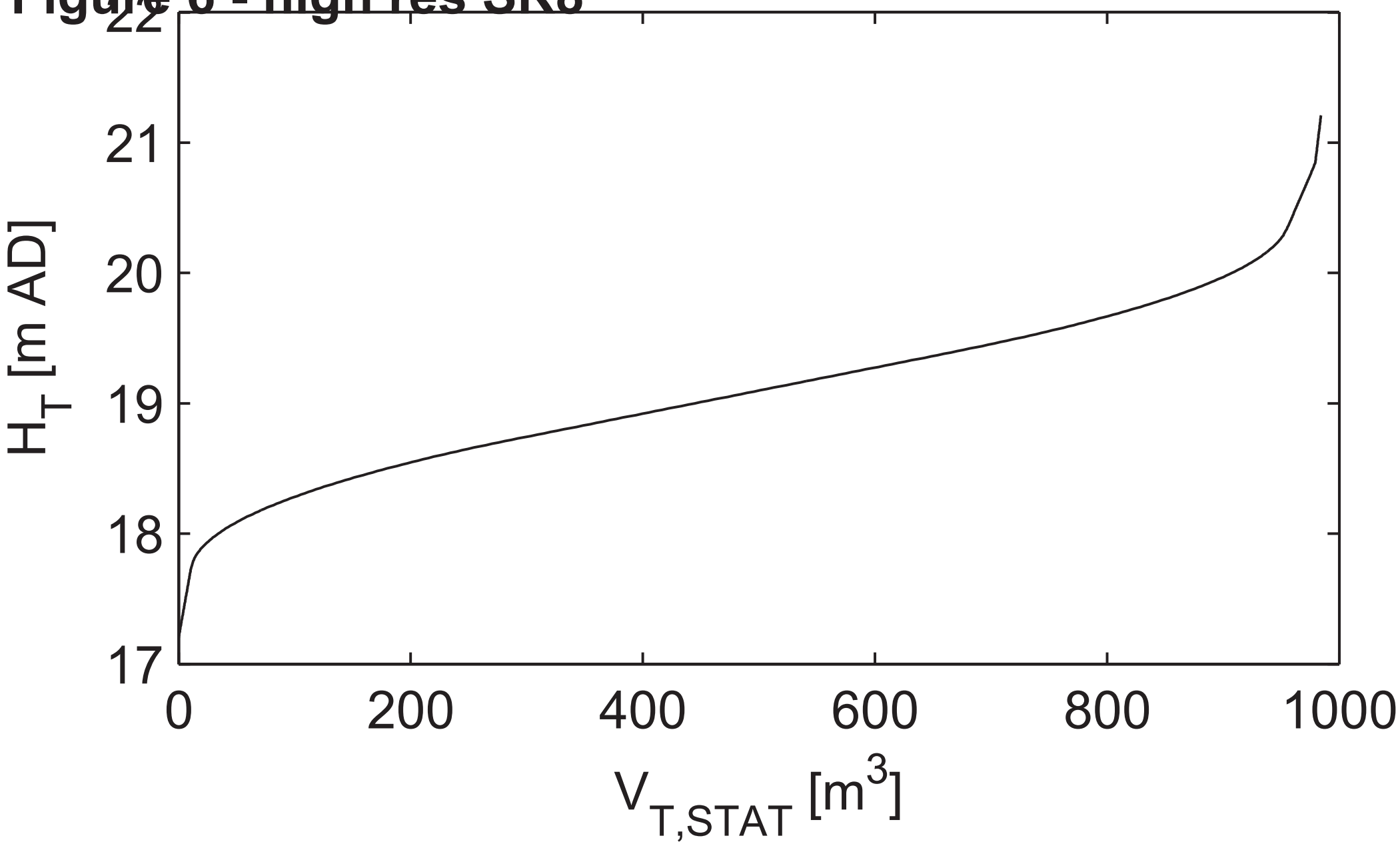


Figure 6 - high res SR9

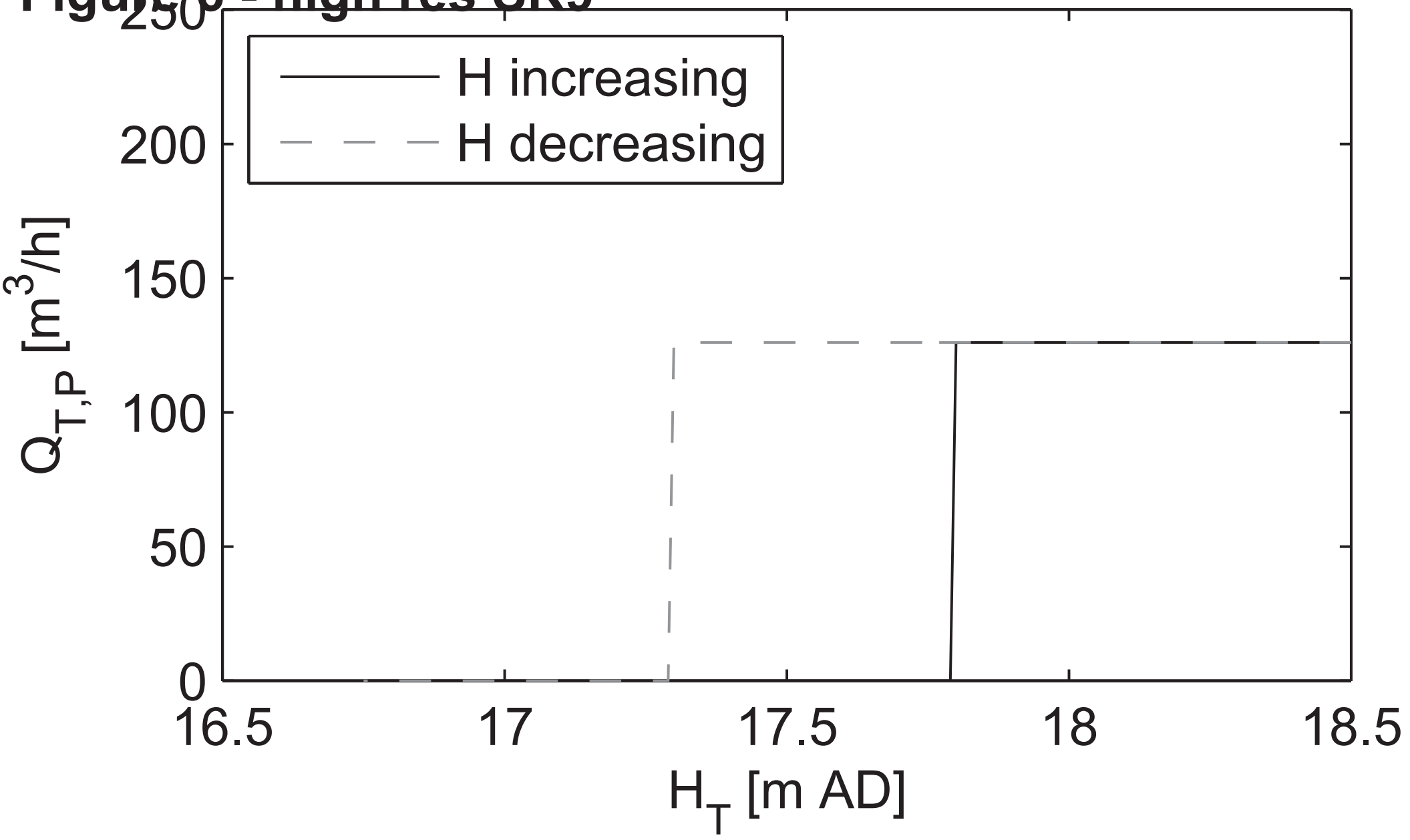


Figure 6 - High res SR10

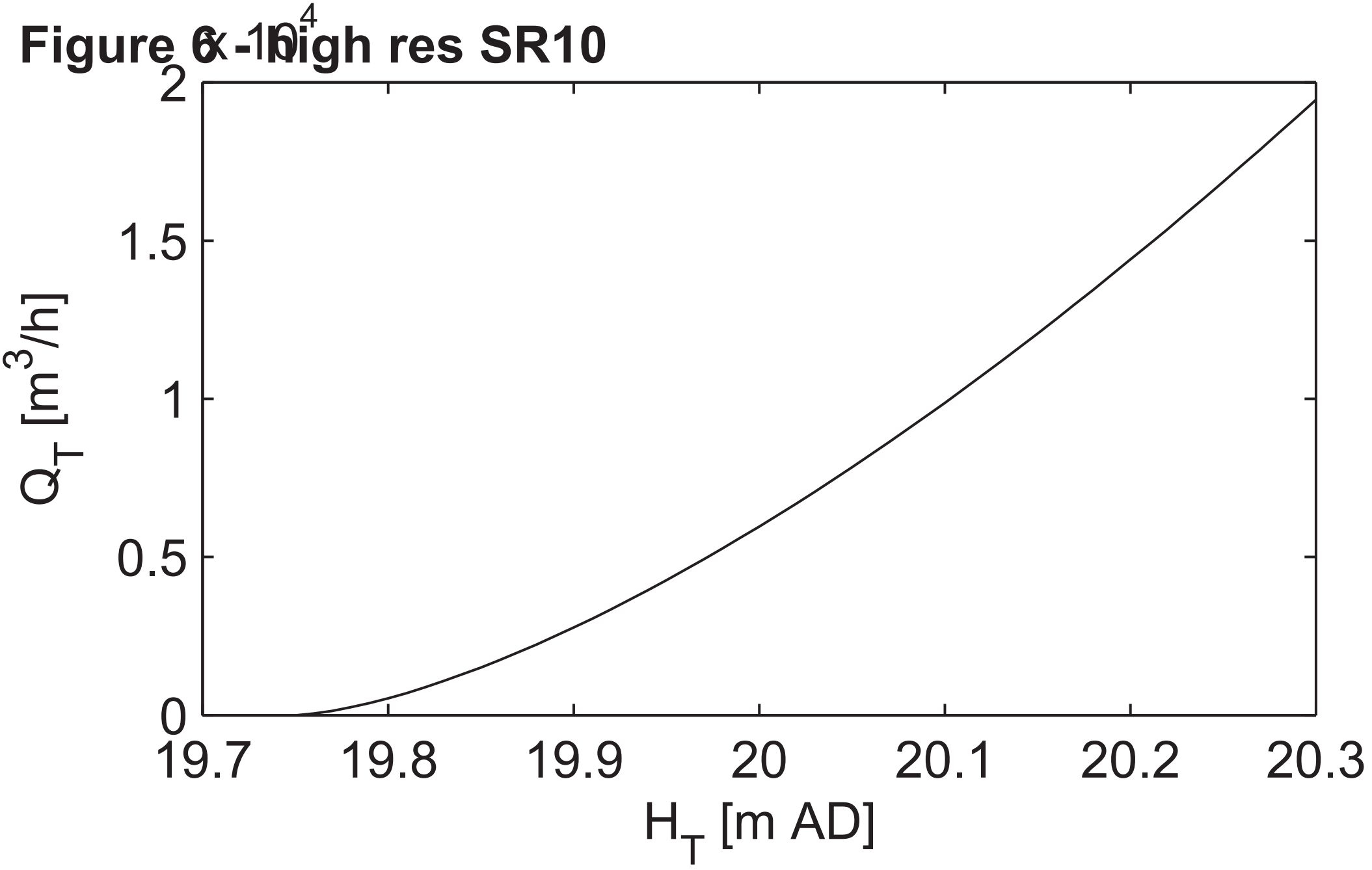


Figure 7 - total DR model Loenen with graphs DR1-DR4

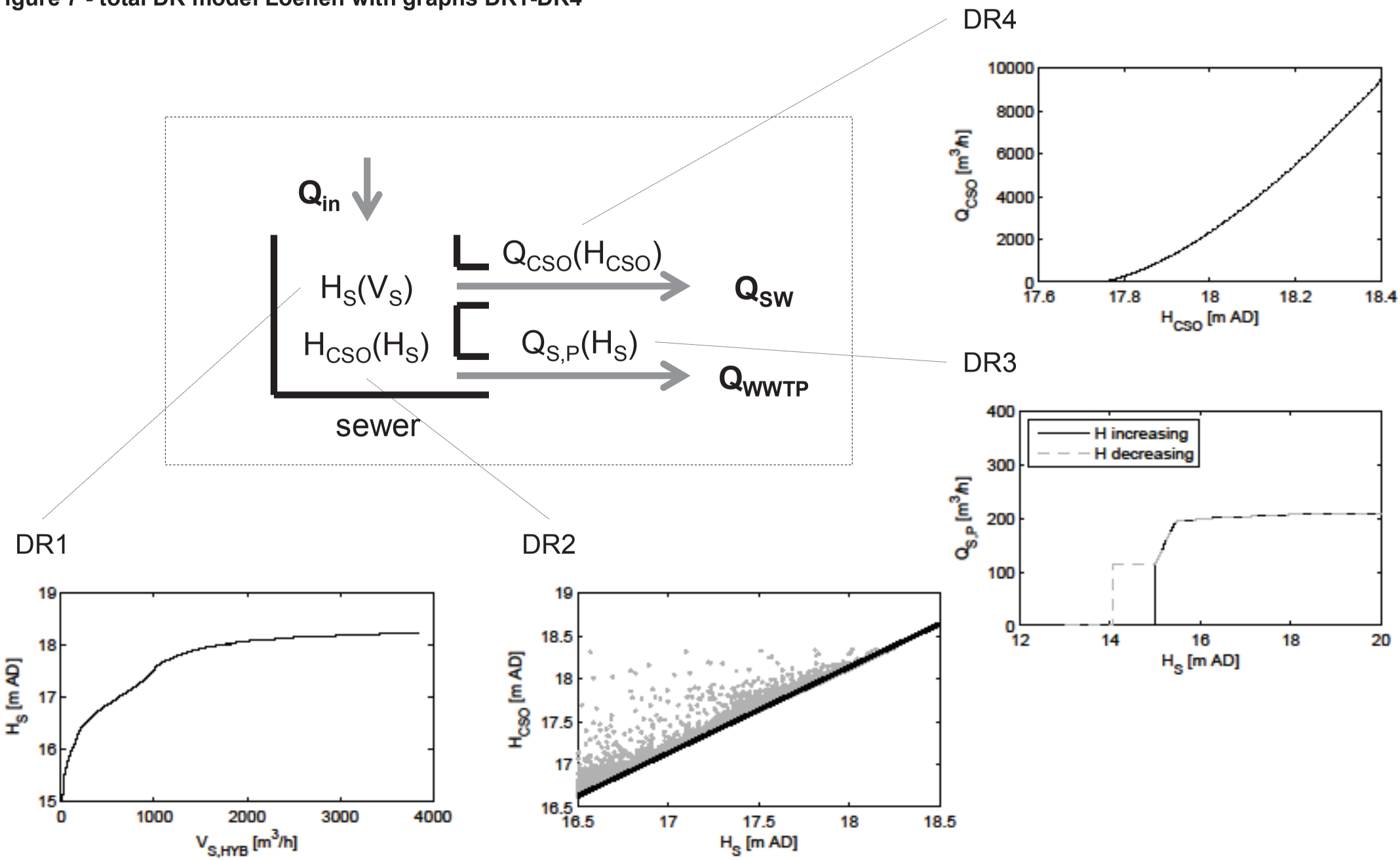


Figure 7 - high res DR1

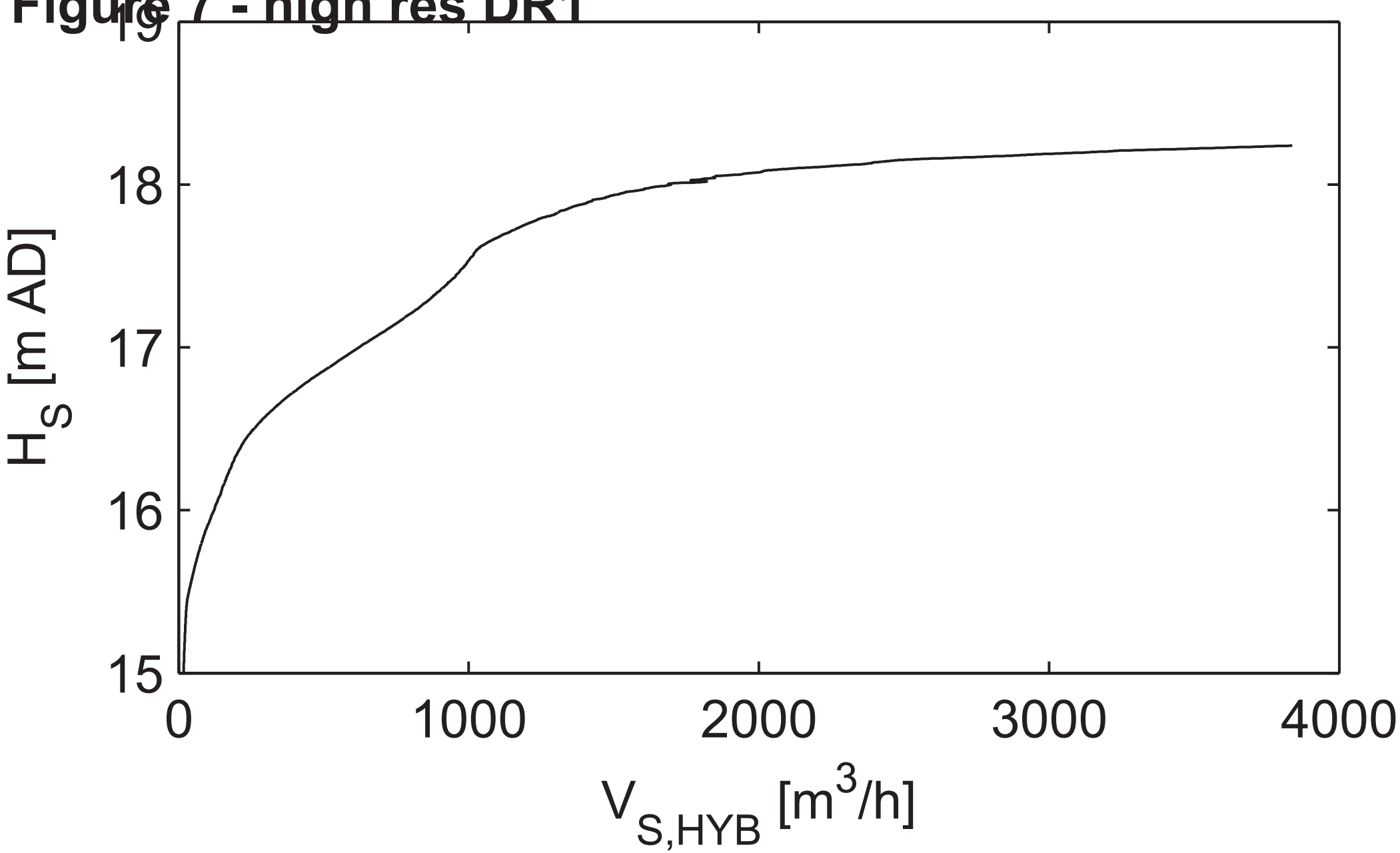


Figure 7 - high res DR2

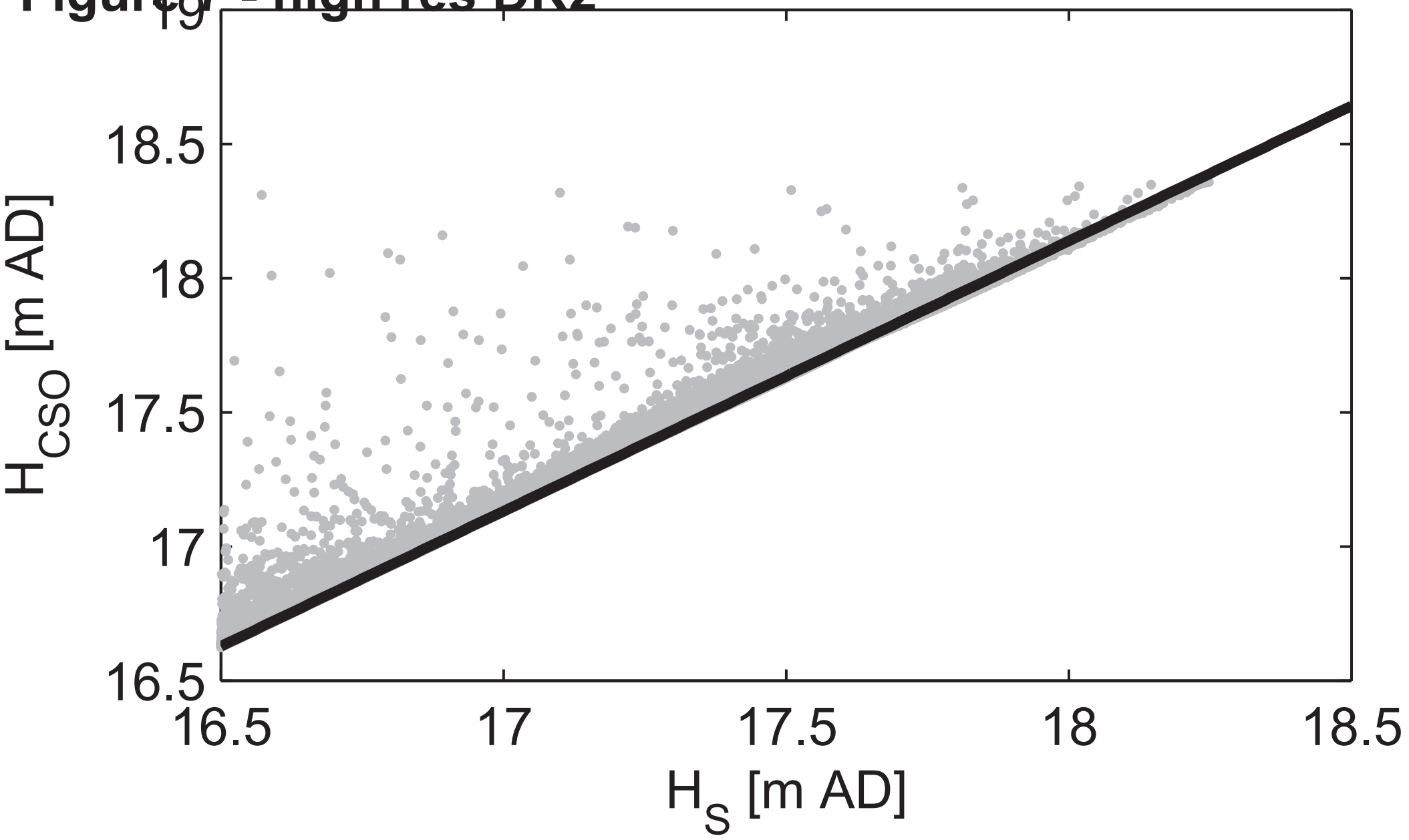


Figure 7 - high res DR3

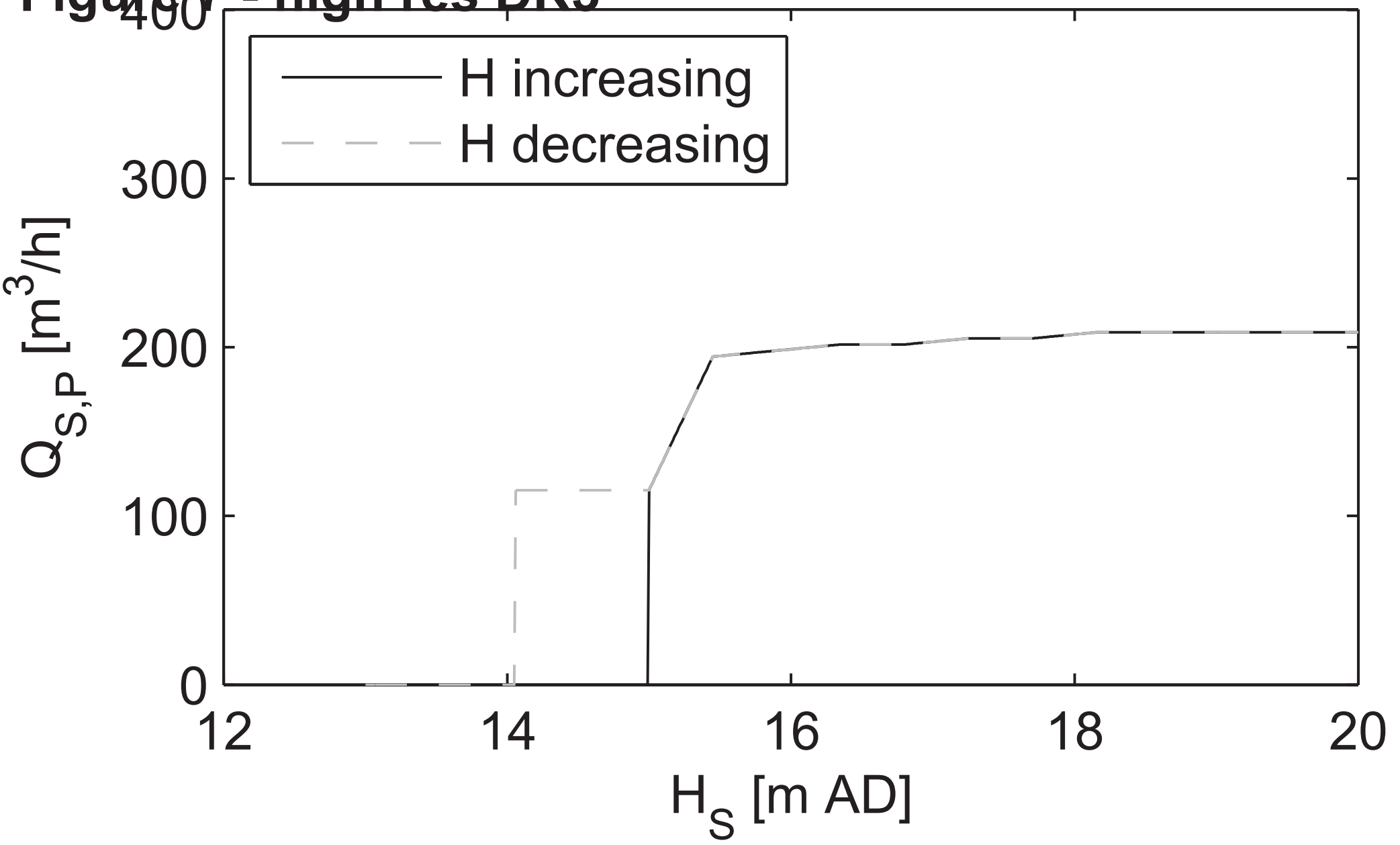


Figure 7 - high res DR4

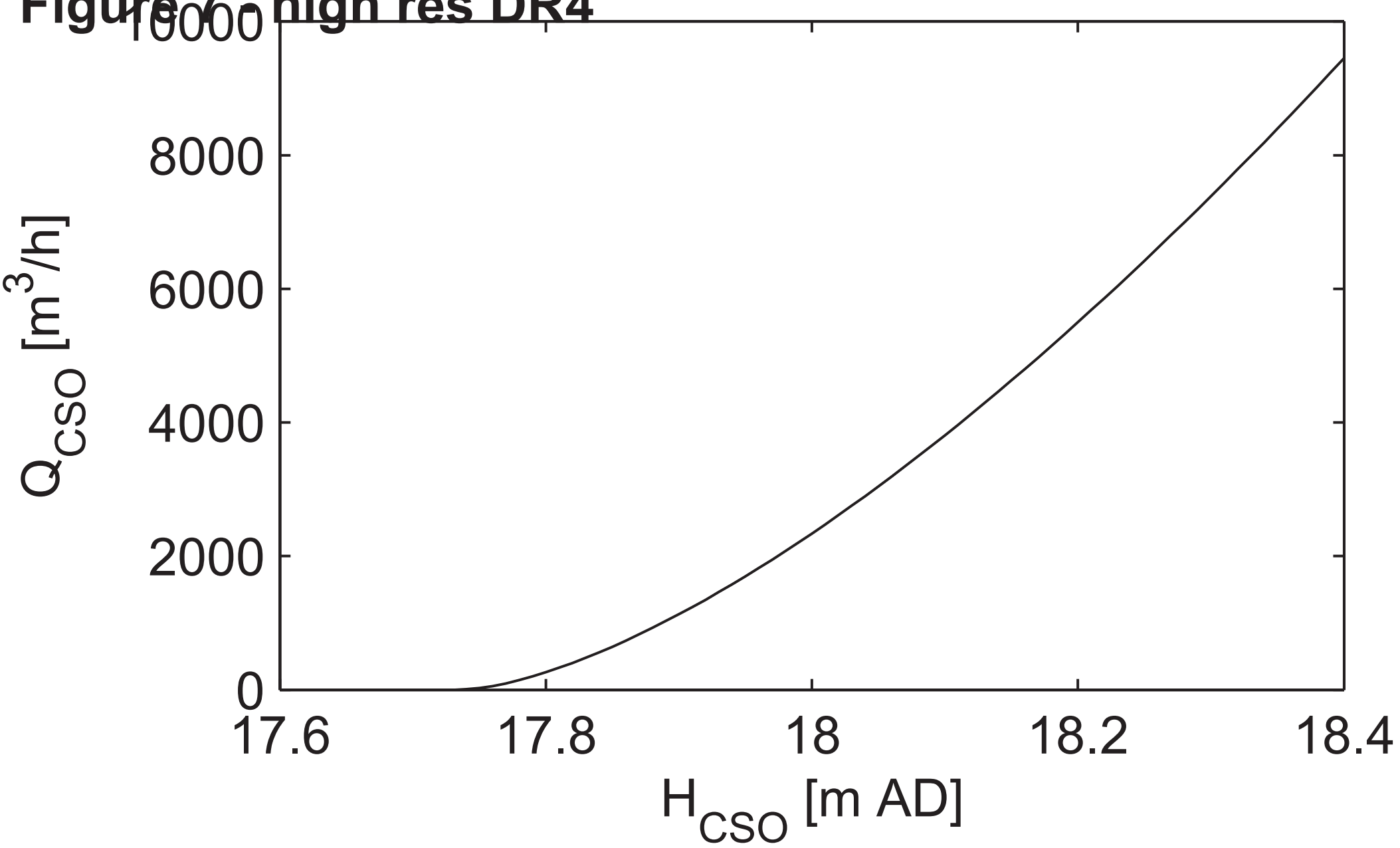


Figure 8 - left

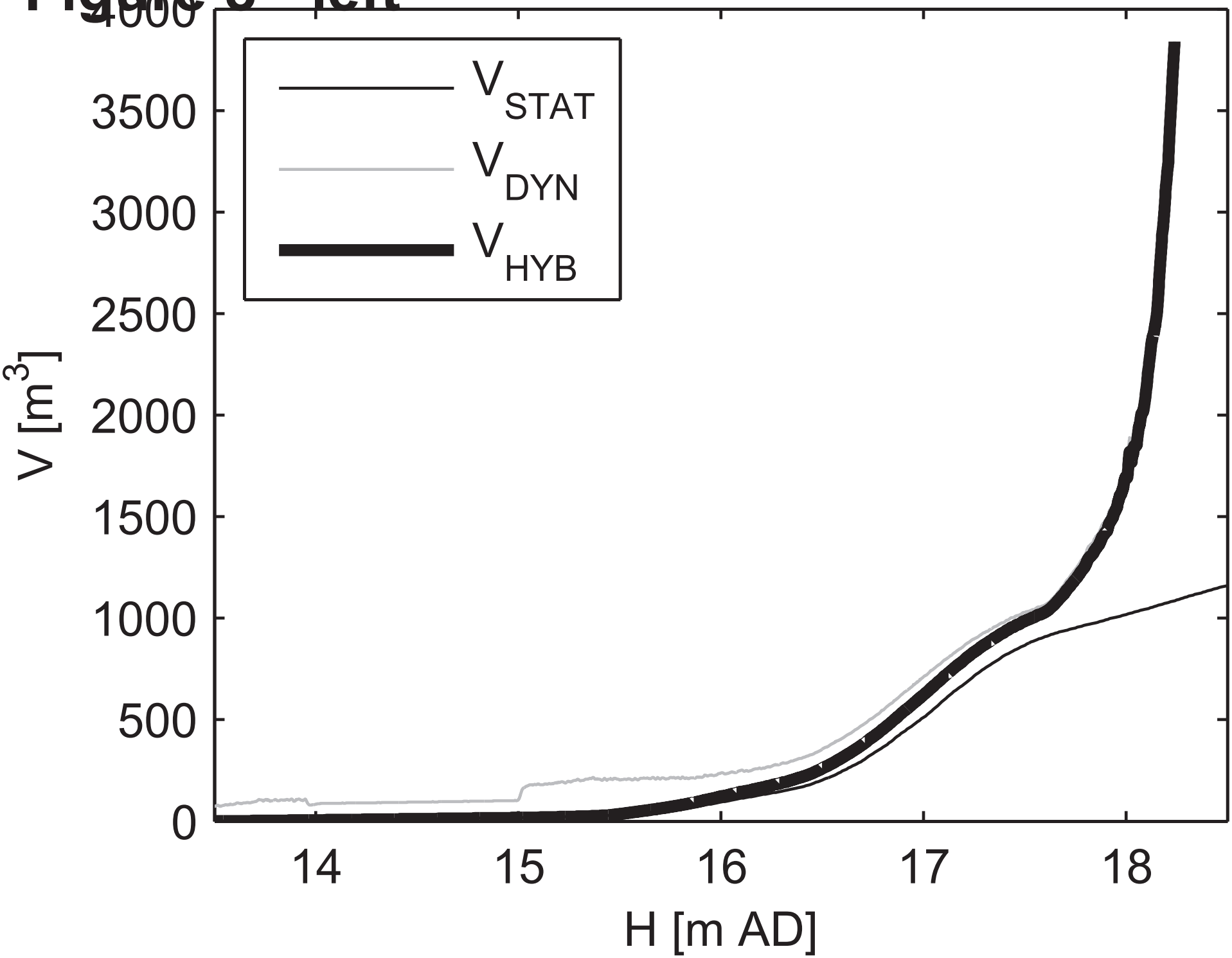


Figure 8 - right

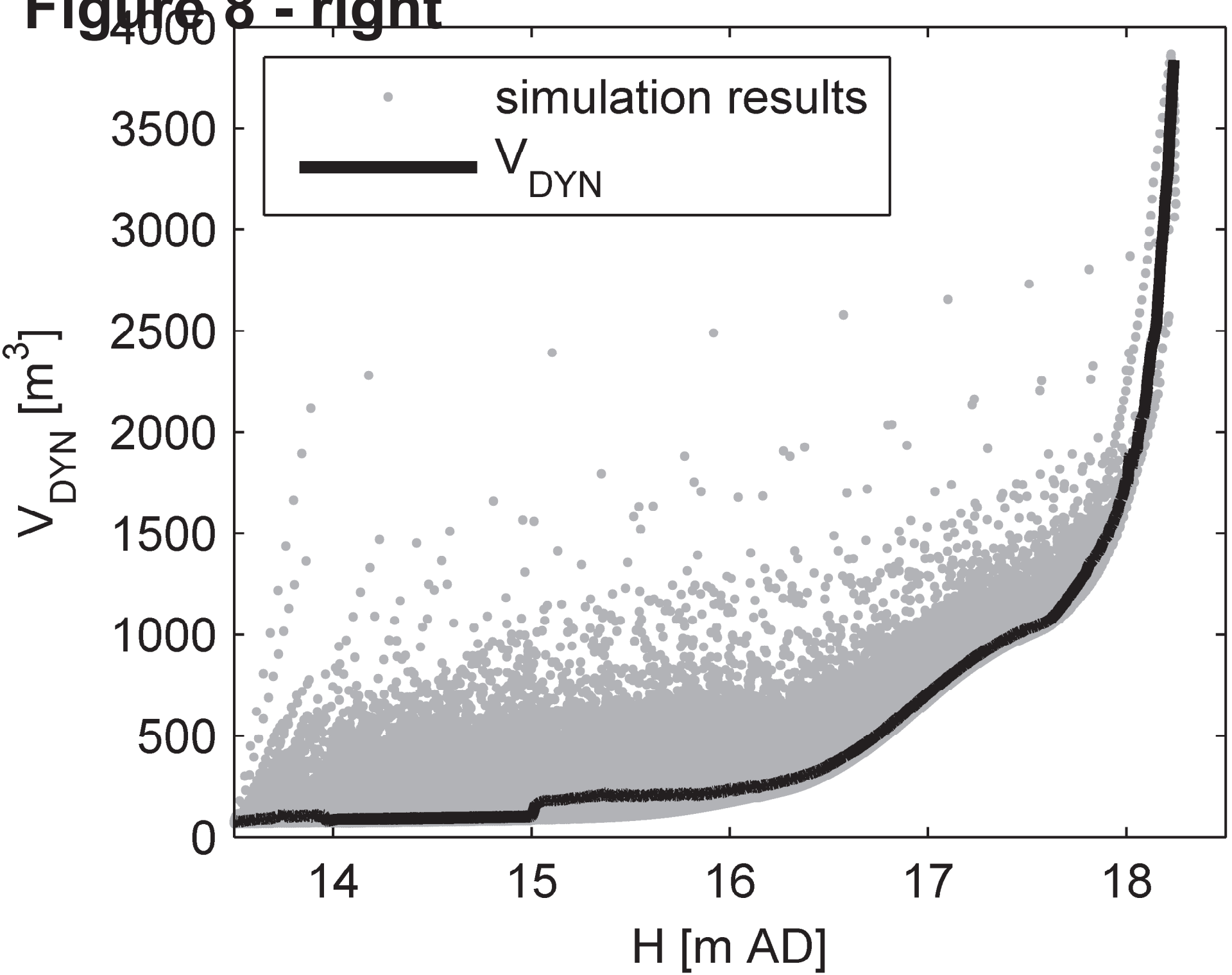


Figure 9 - total DR model Waalre with graphs DR5-DR13

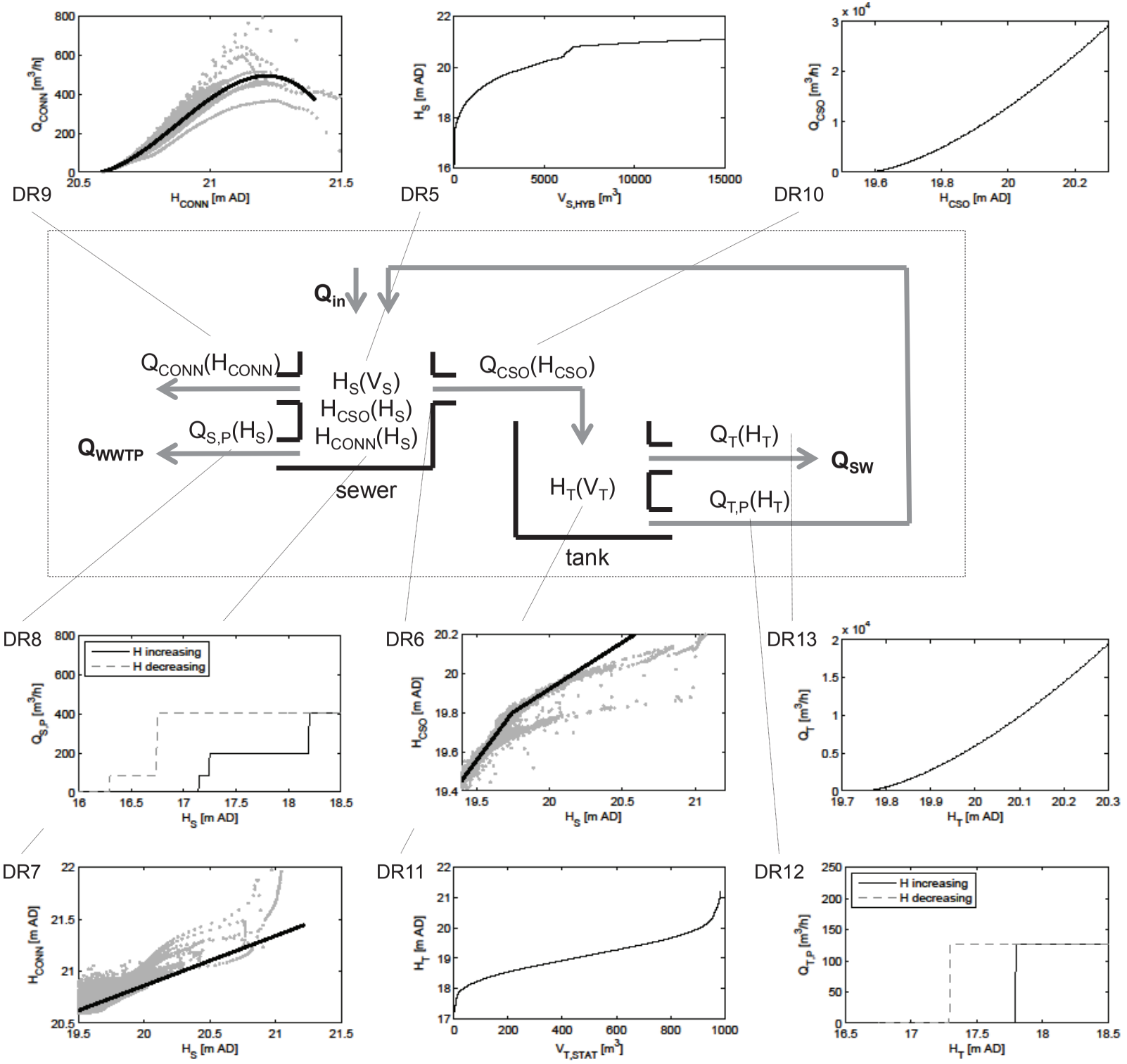


Figure 9 - high res DR5

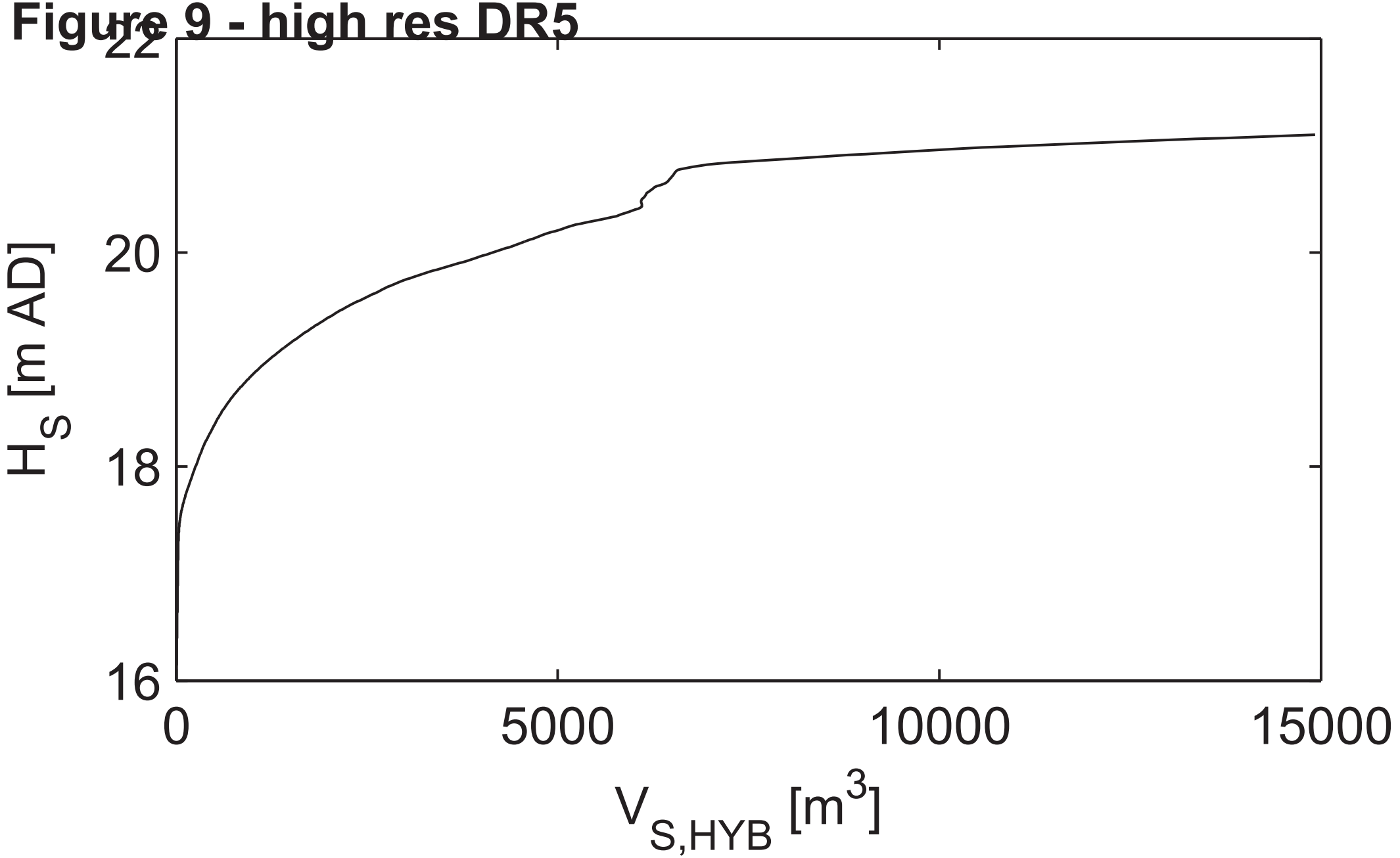


Figure 9 - high res DR6

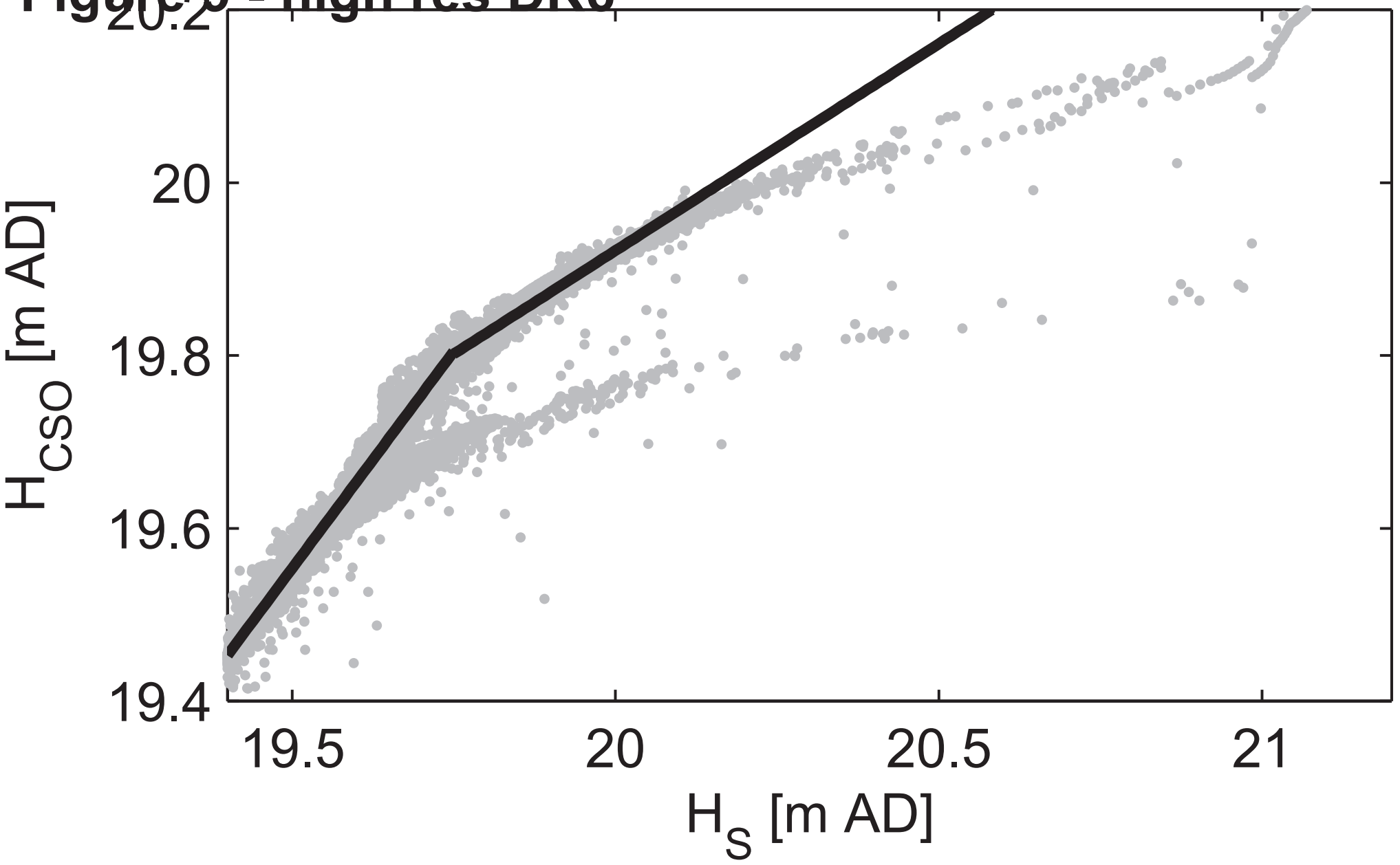


Figure 9 - high res DR7

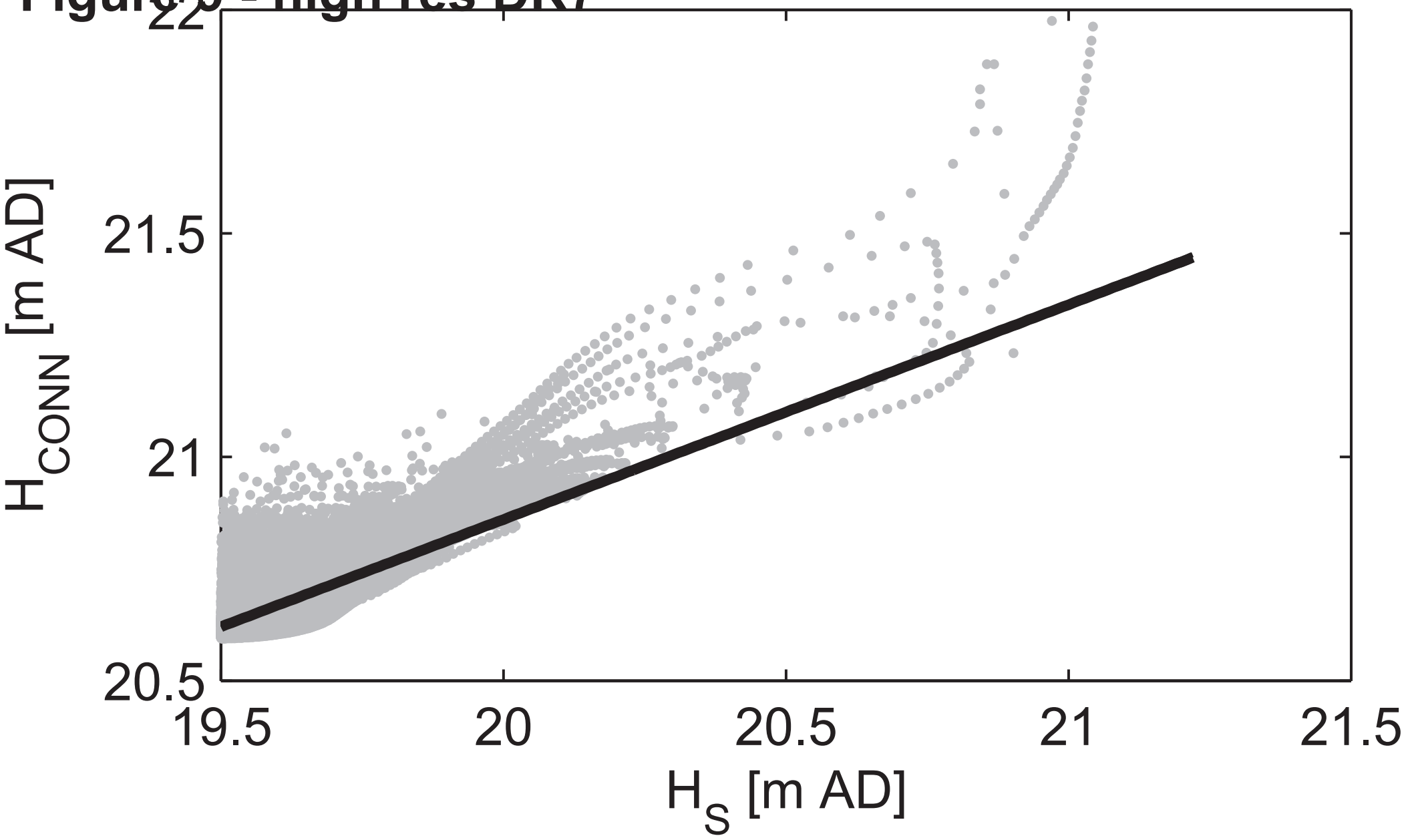


Figure 9 - high res DR8

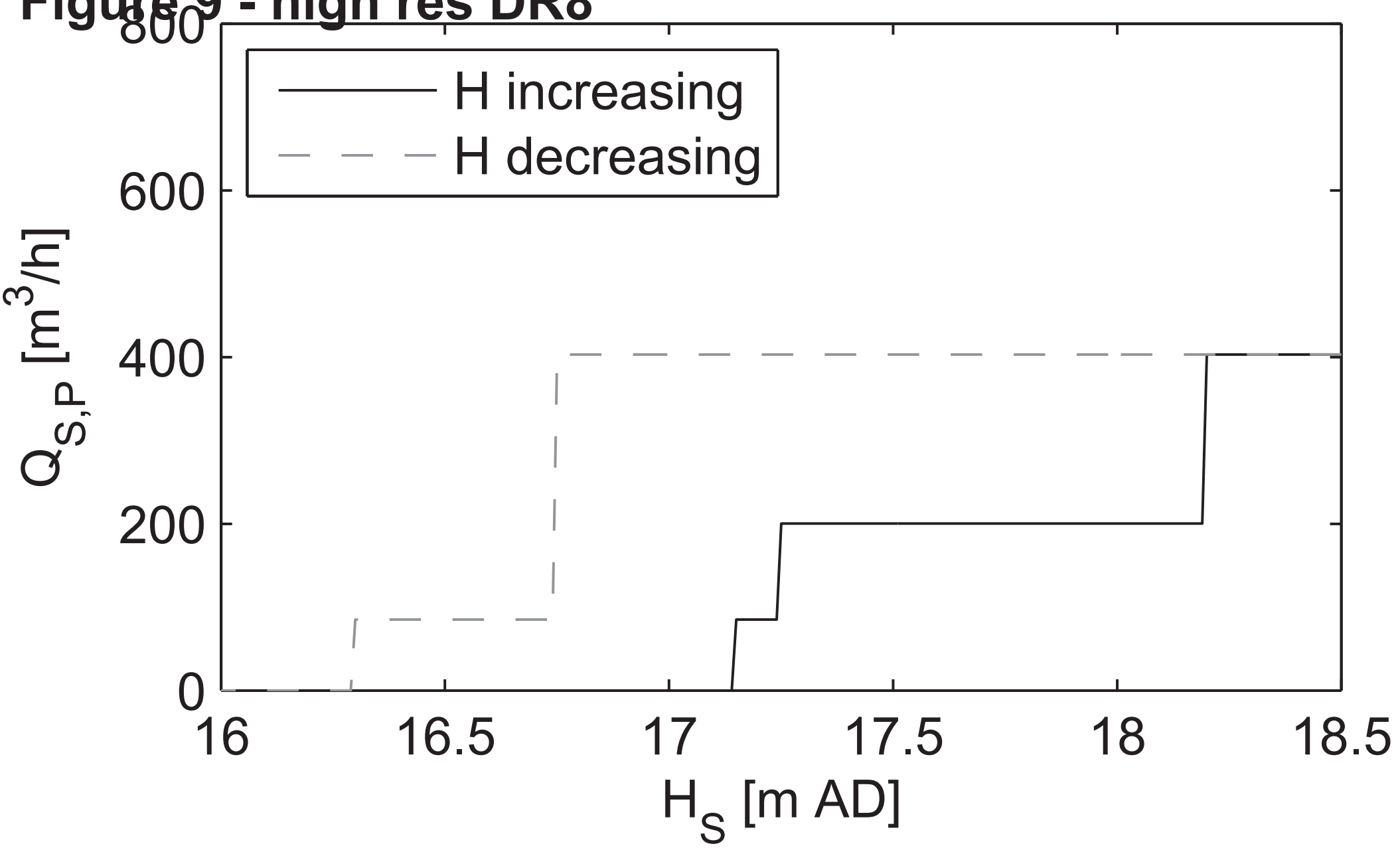


Figure 9 - High res DR10

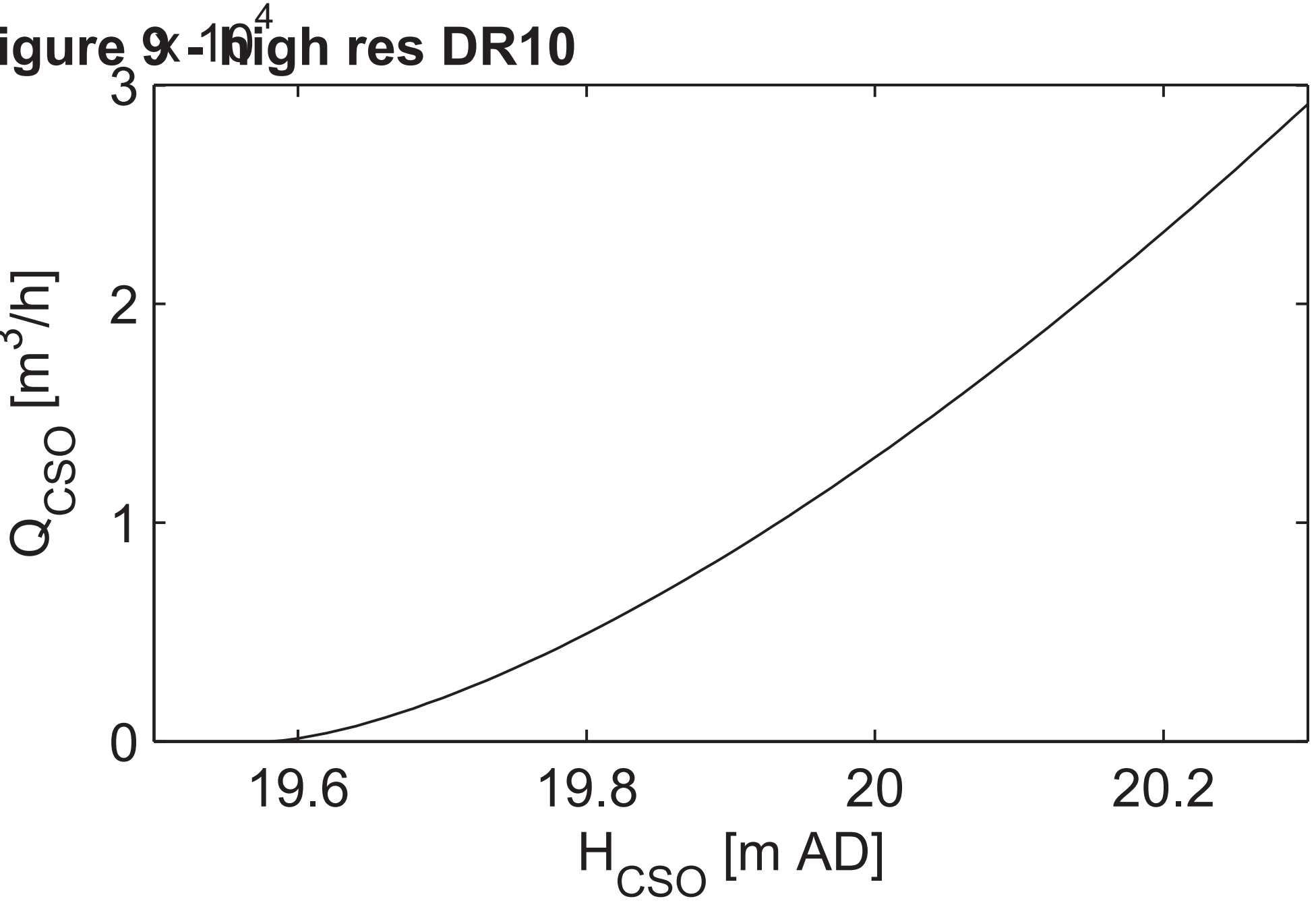


Figure 9 - high res DR9

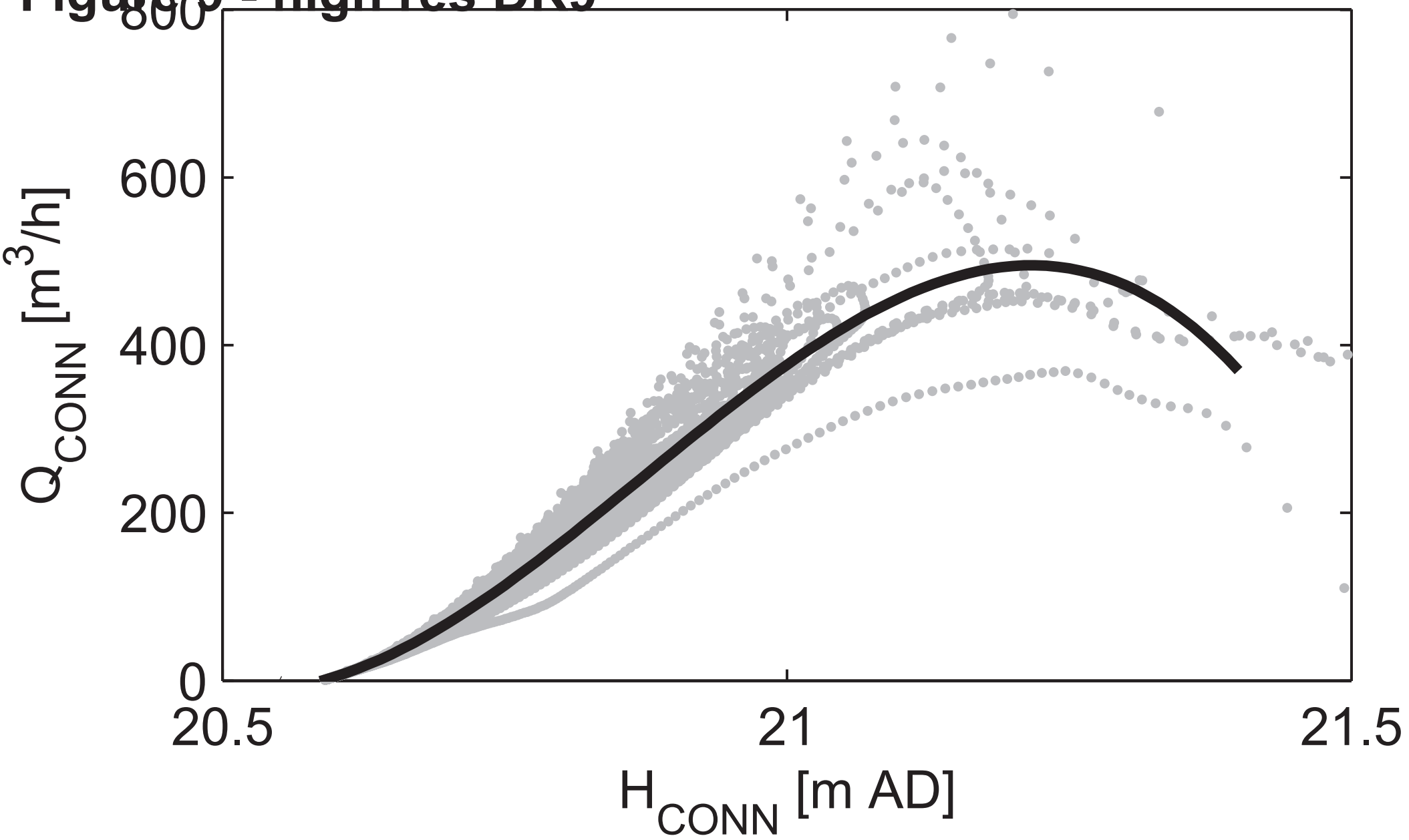


Figure 9 - high res DR11

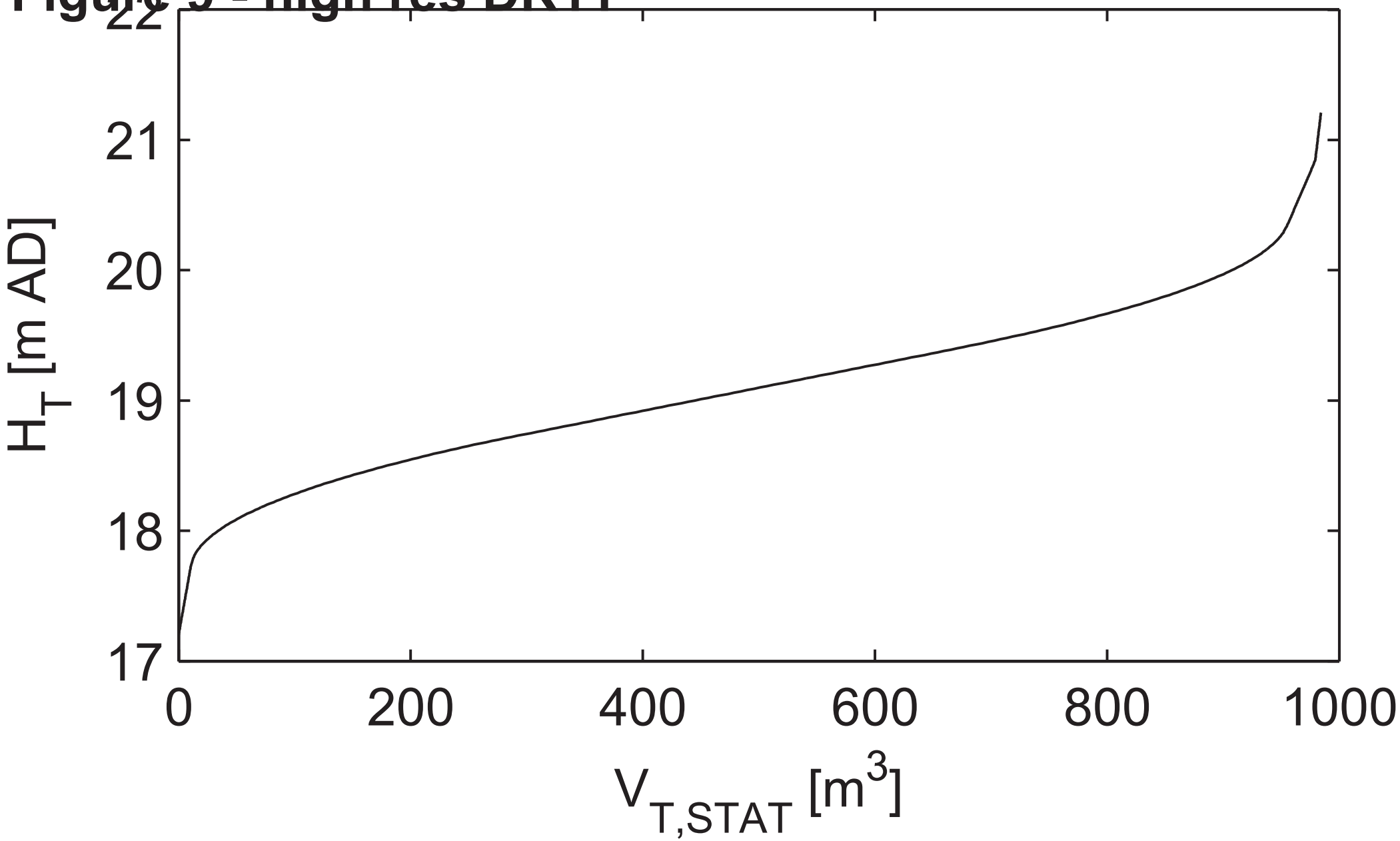


Figure 9 - high res DR12

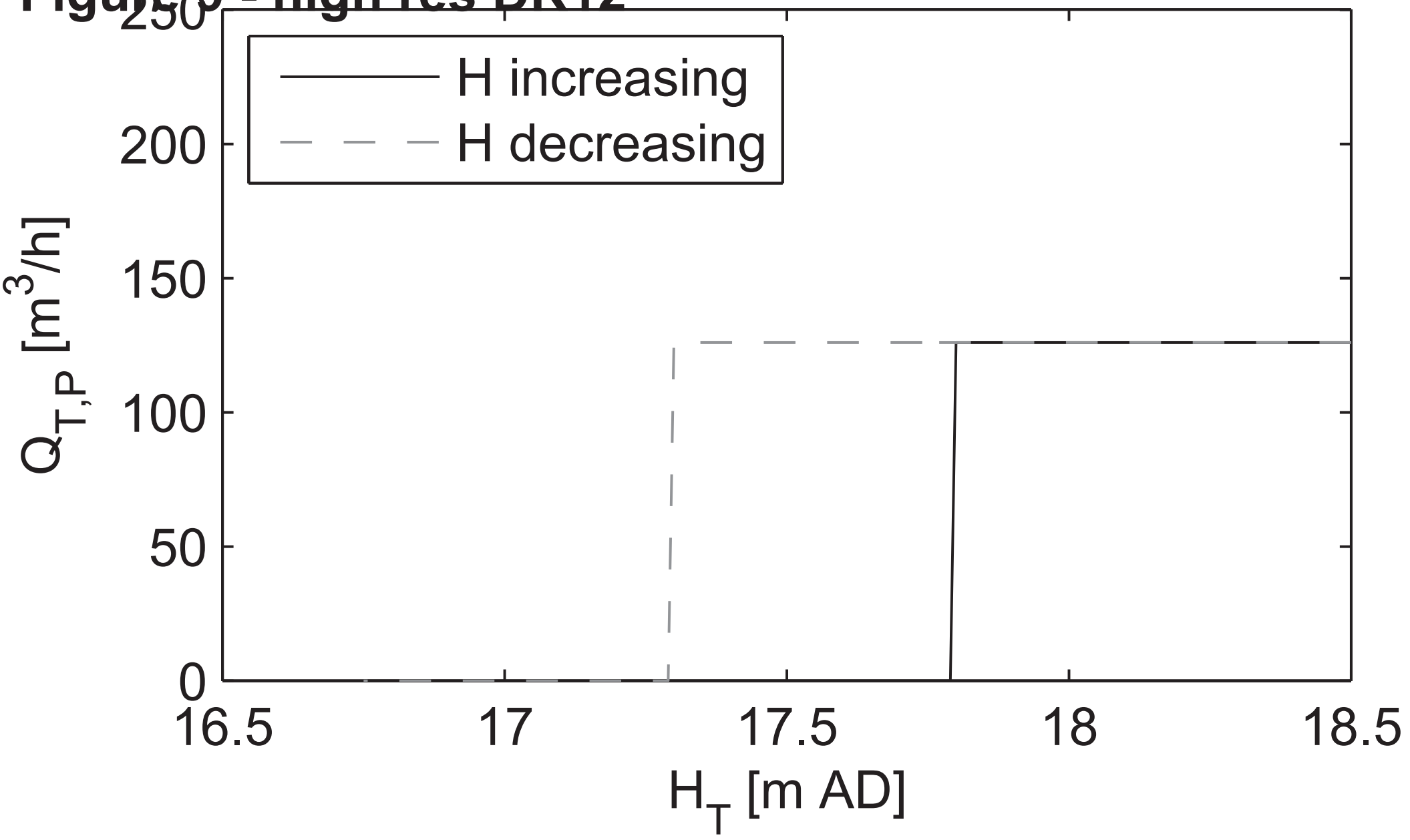


Figure 9 - High res DR13

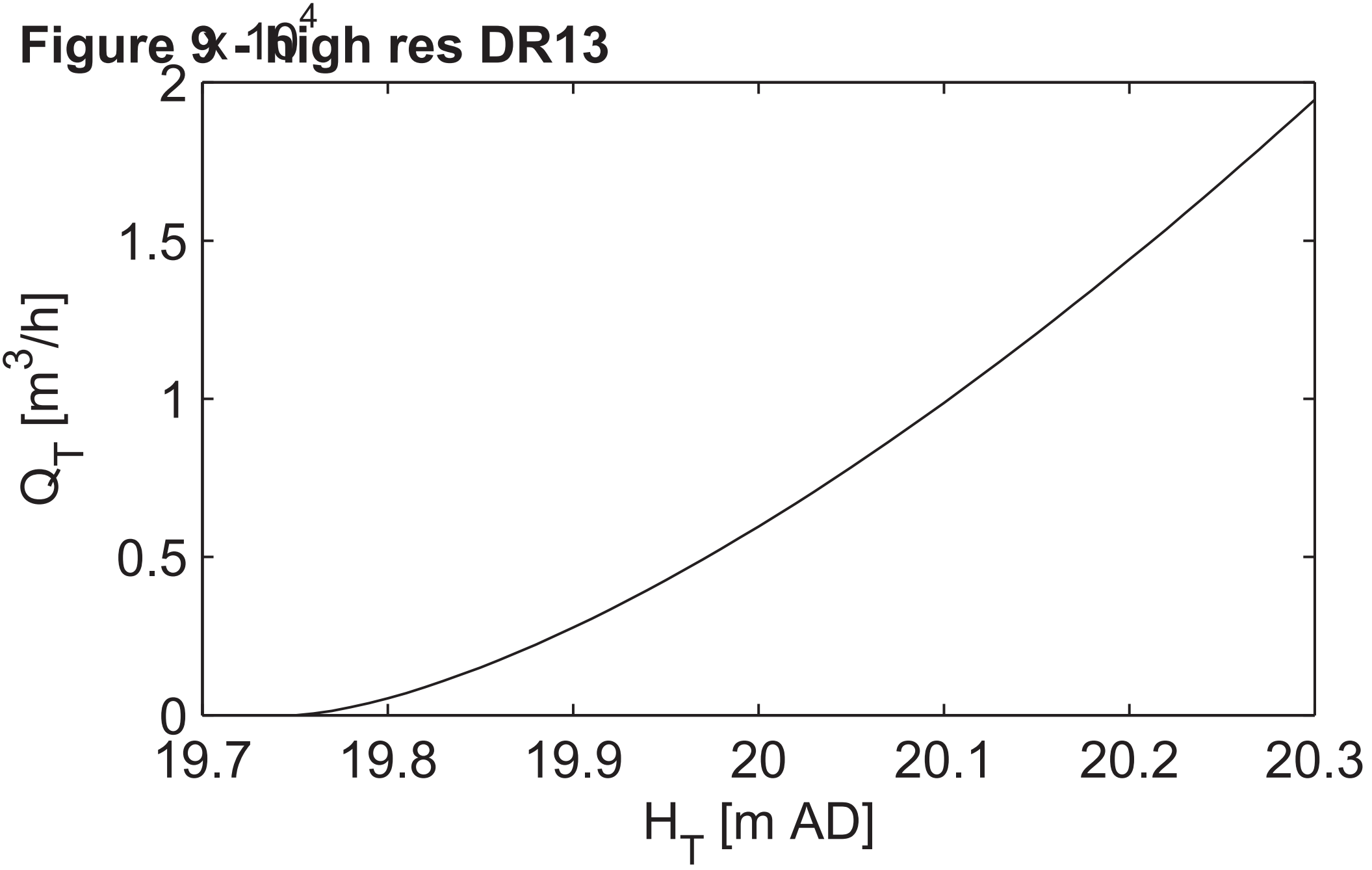


Figure 10 - left

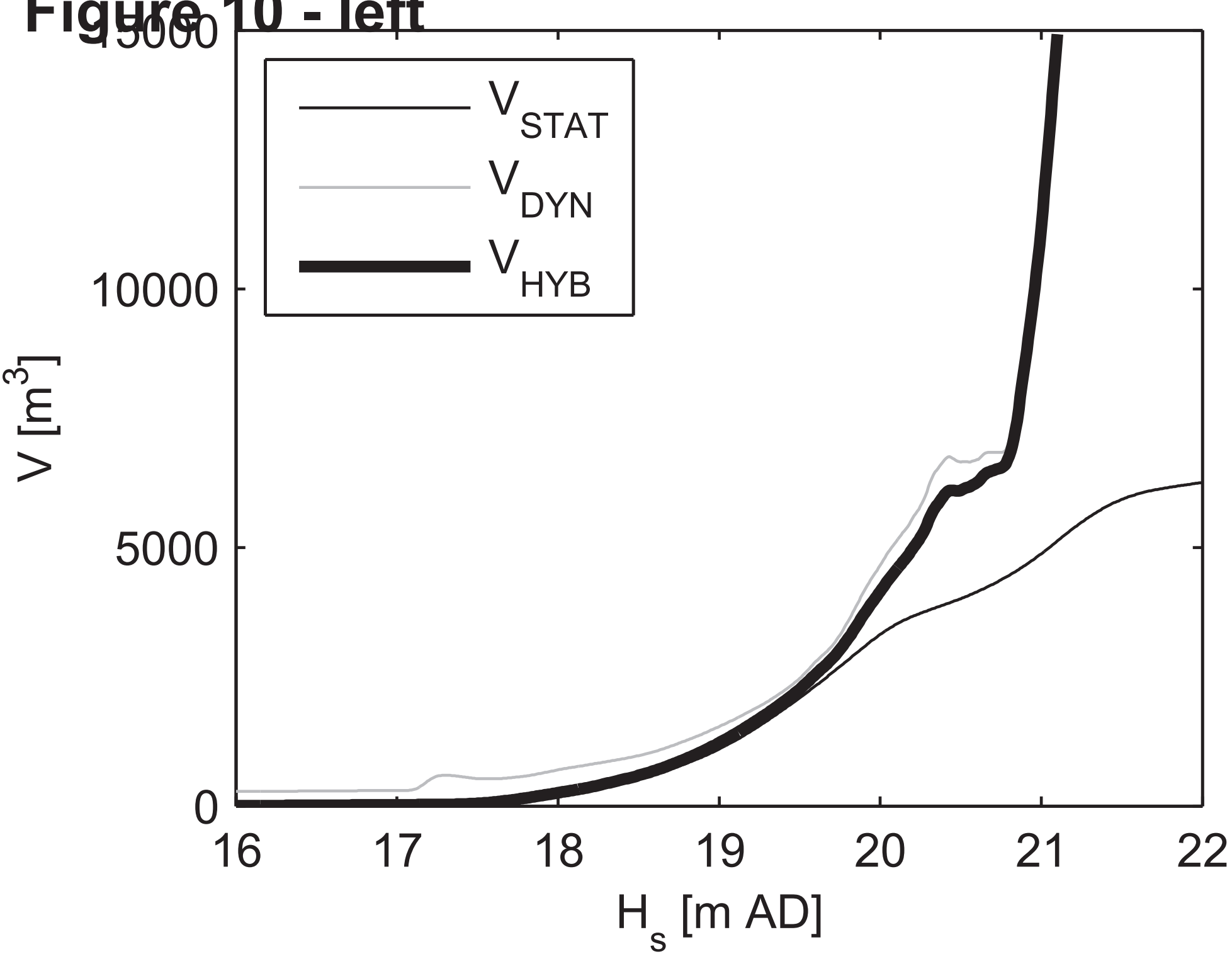


Figure 10 - right

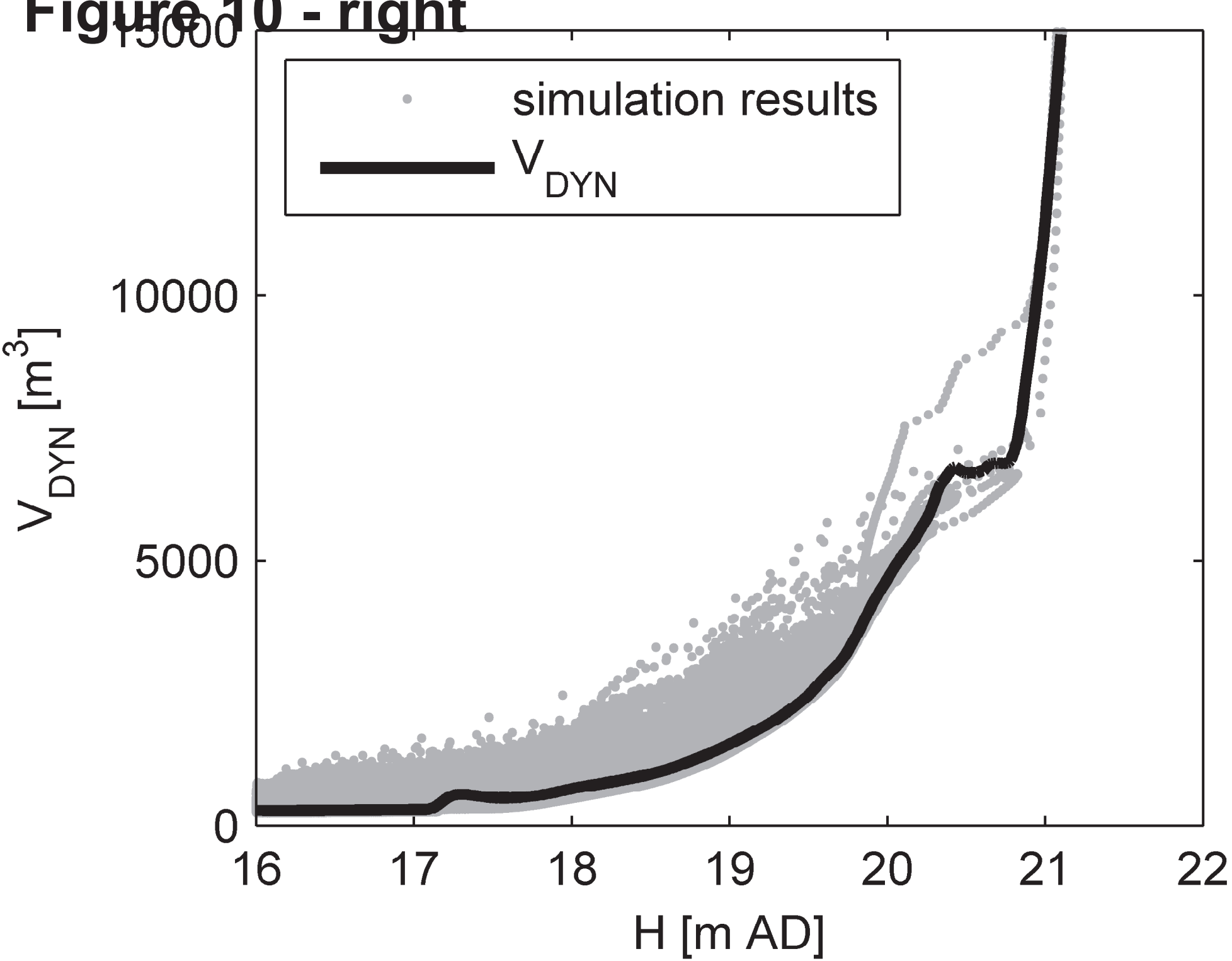


Figure 11

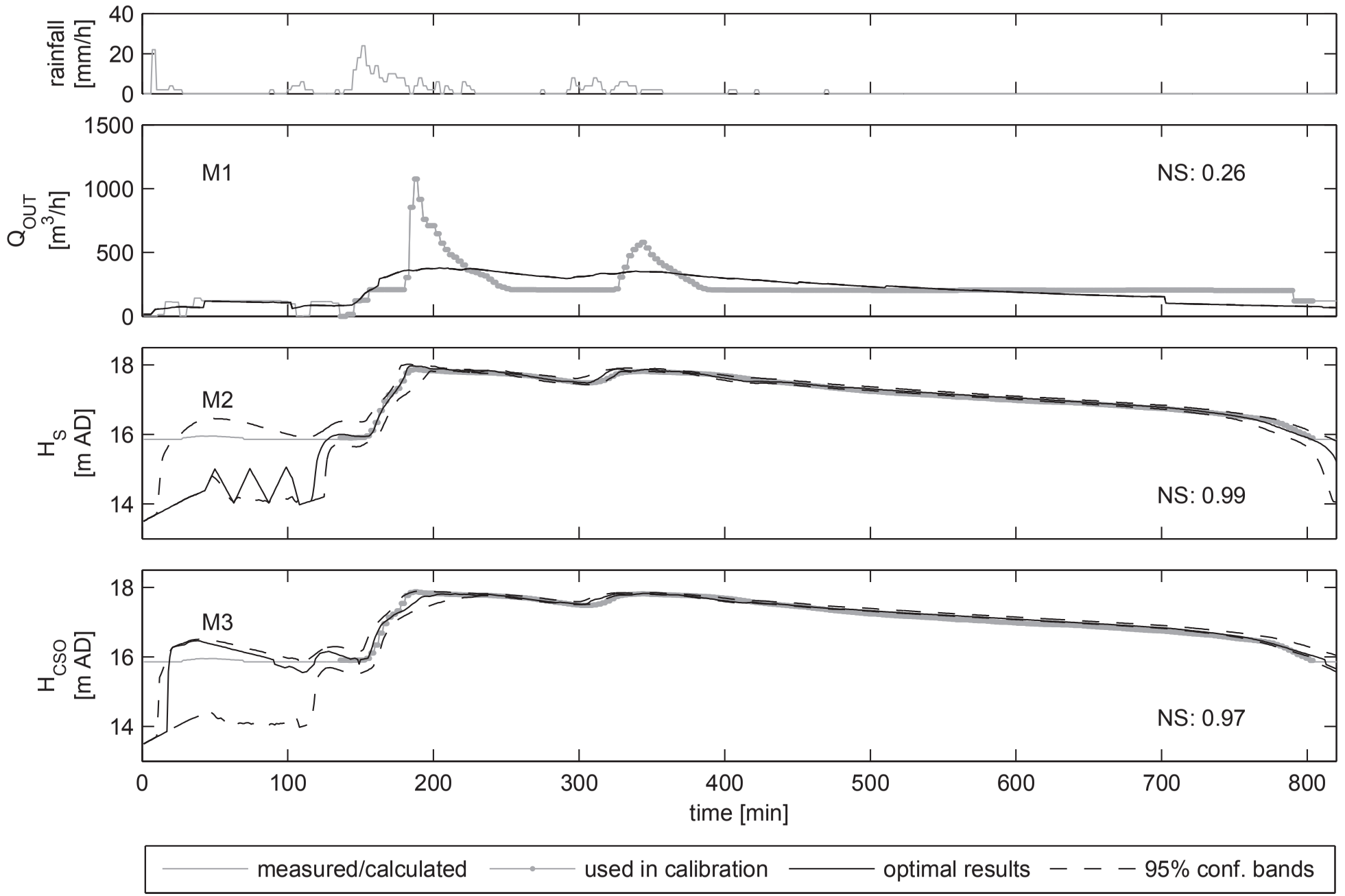

rainfall [mm/h]
40
20
0
1500
1000
500
0
Q_{OUT} [m^3/h]
M1
NS: 0.26
18
16
14
H_S [m AD]
M2
NS: 0.99
18
16
14
H_{CSO} [m AD]
M3
NS: 0.97
0
100
200
300
400
500
600
700
800
time [min]
measured/calculated
used in calibration
optimal results
95% conf. bands

Figure 12

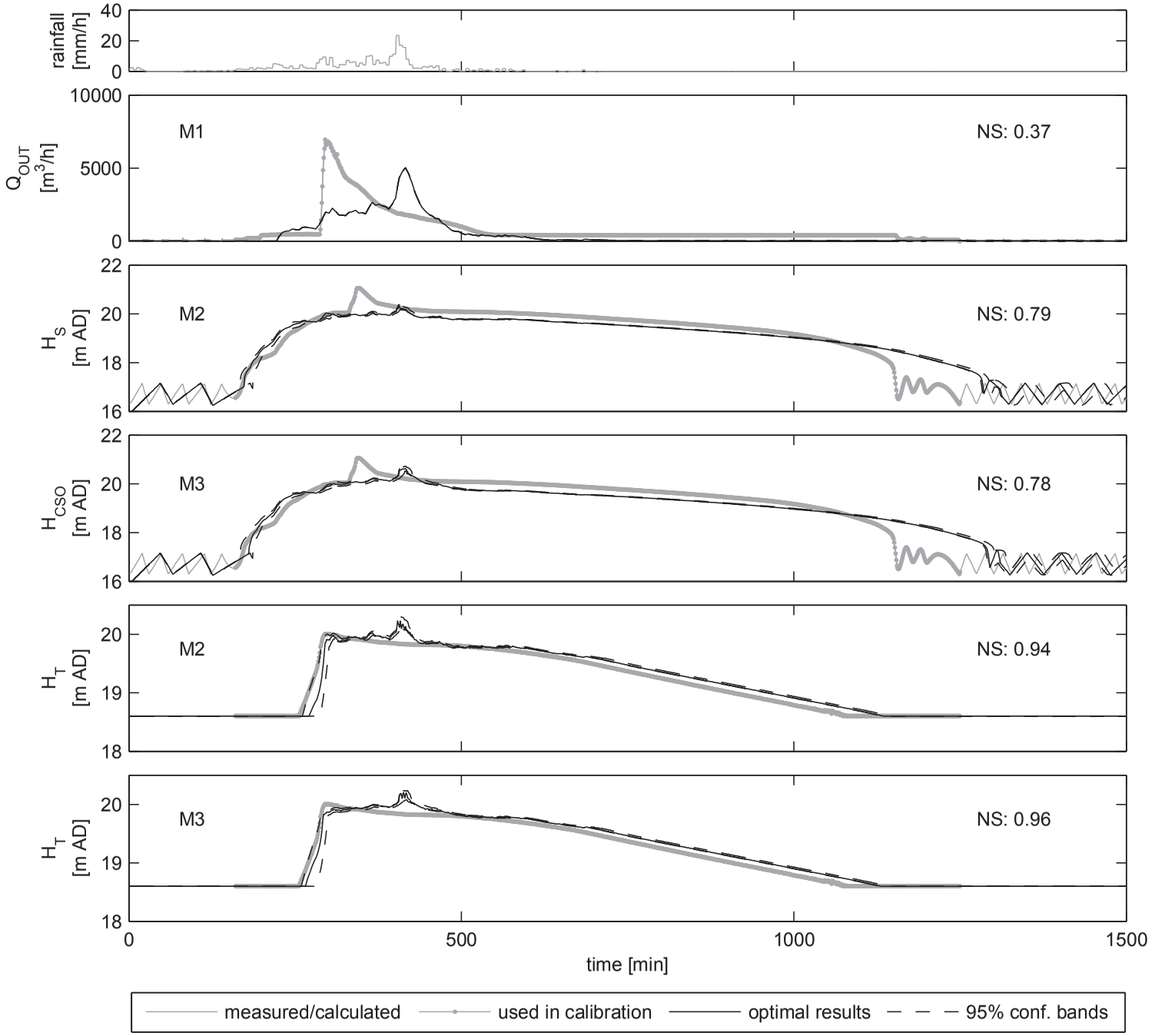

rainfall [mm/h]
40
20
0
Q_{OUT} [m^3/h]
10000
5000
0
M1
NS: 0.37
H_S [m AD]
22
20
18
16
M2
NS: 0.79
H_{CSO} [m AD]
22
20
18
16
M3
NS: 0.78
H_T [m AD]
20
19
18
M2
NS: 0.94
H_T [m AD]
20
19
18
M3
NS: 0.96
0
500
1000
1500
time [min]
measured/calculated
used in calibration
optimal results
95% conf. bands

Figure 13

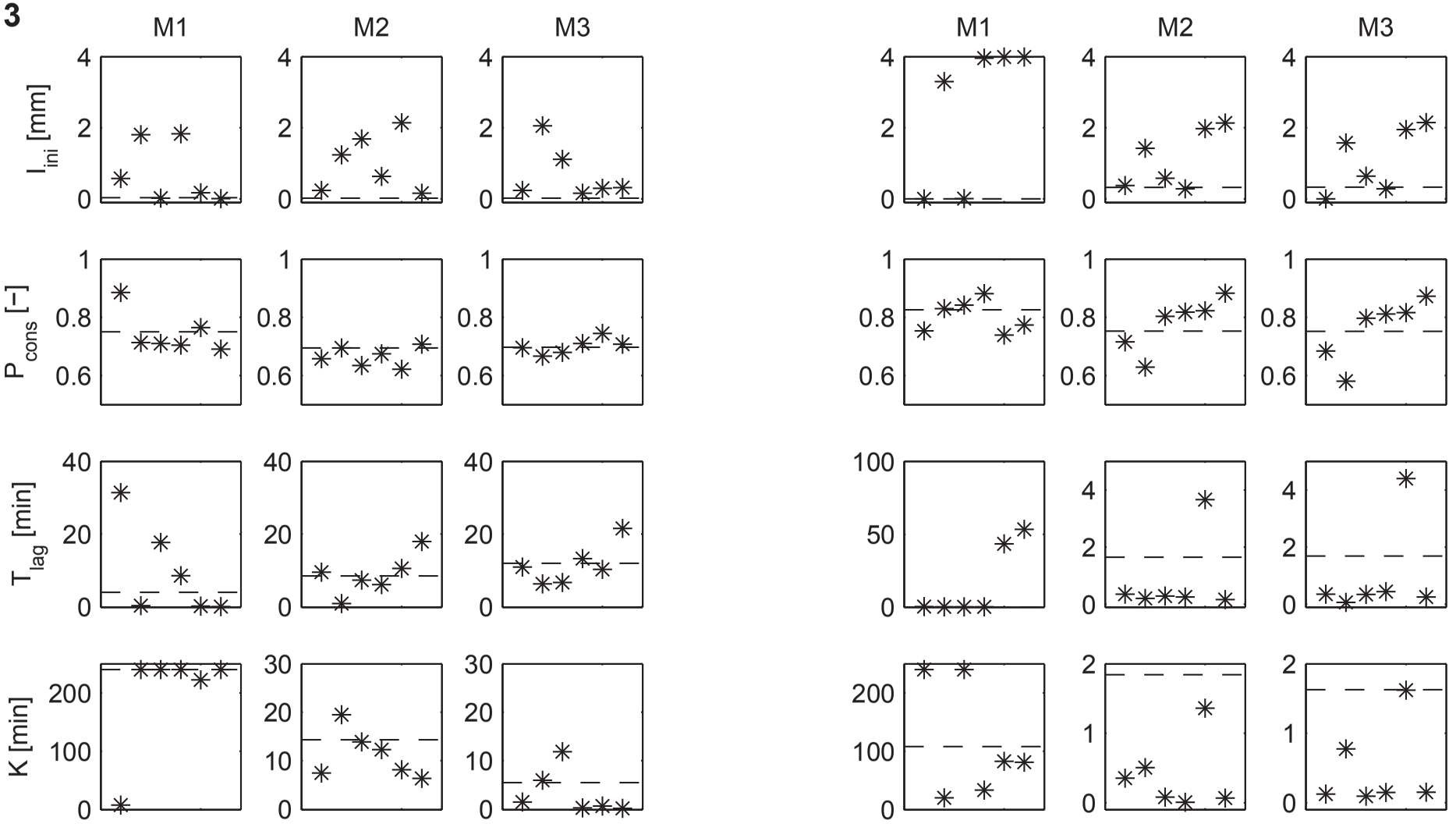


Figure 14

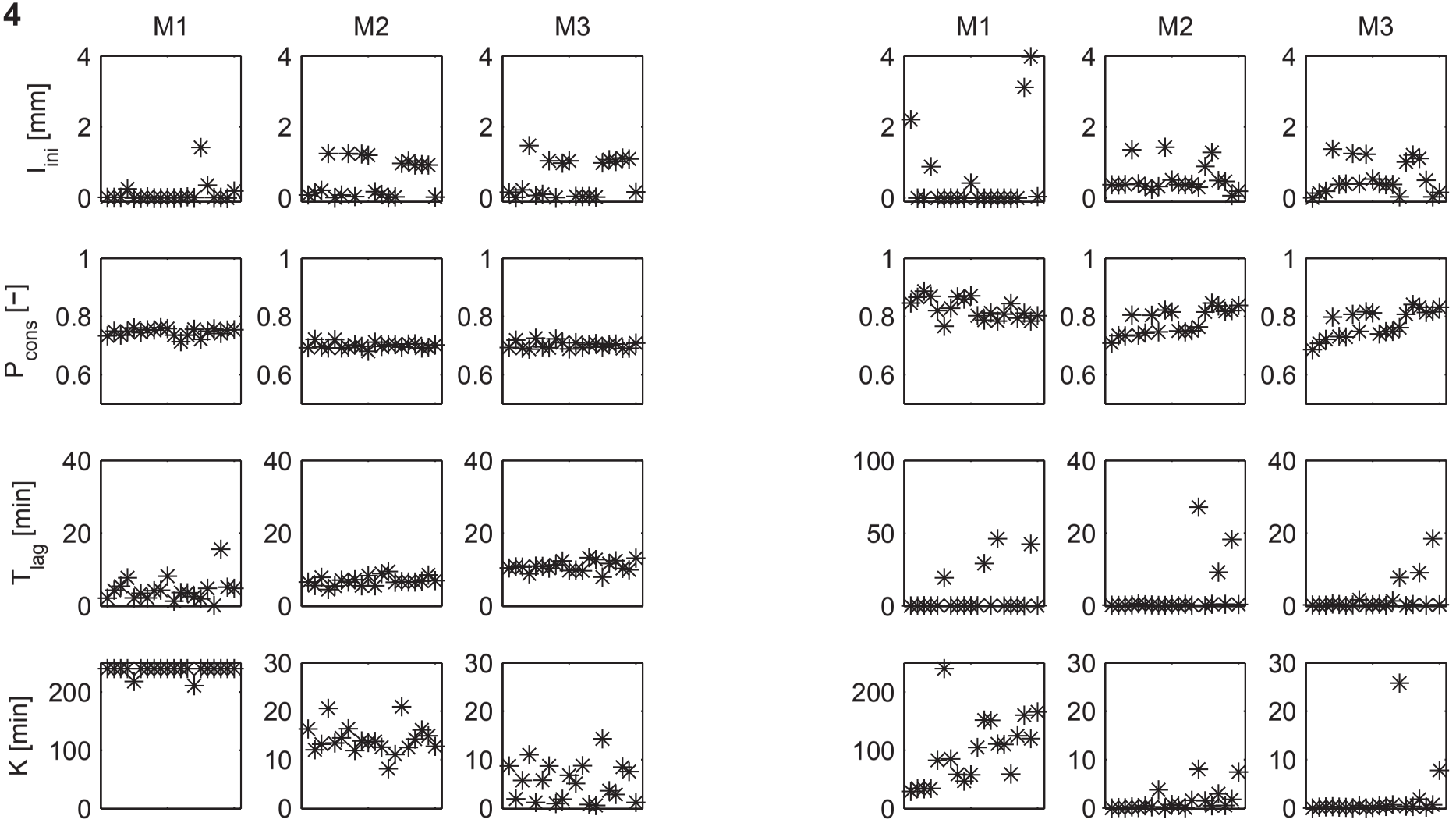

M1
M2
M3
M1
M2
M3
I_{ini} [mm]
P_{cons} [-]
T_{lag} [min]
K [min]
4
2
0
1
0.8
0.6
40
20
0
100
50
200
30
10

Figure 15

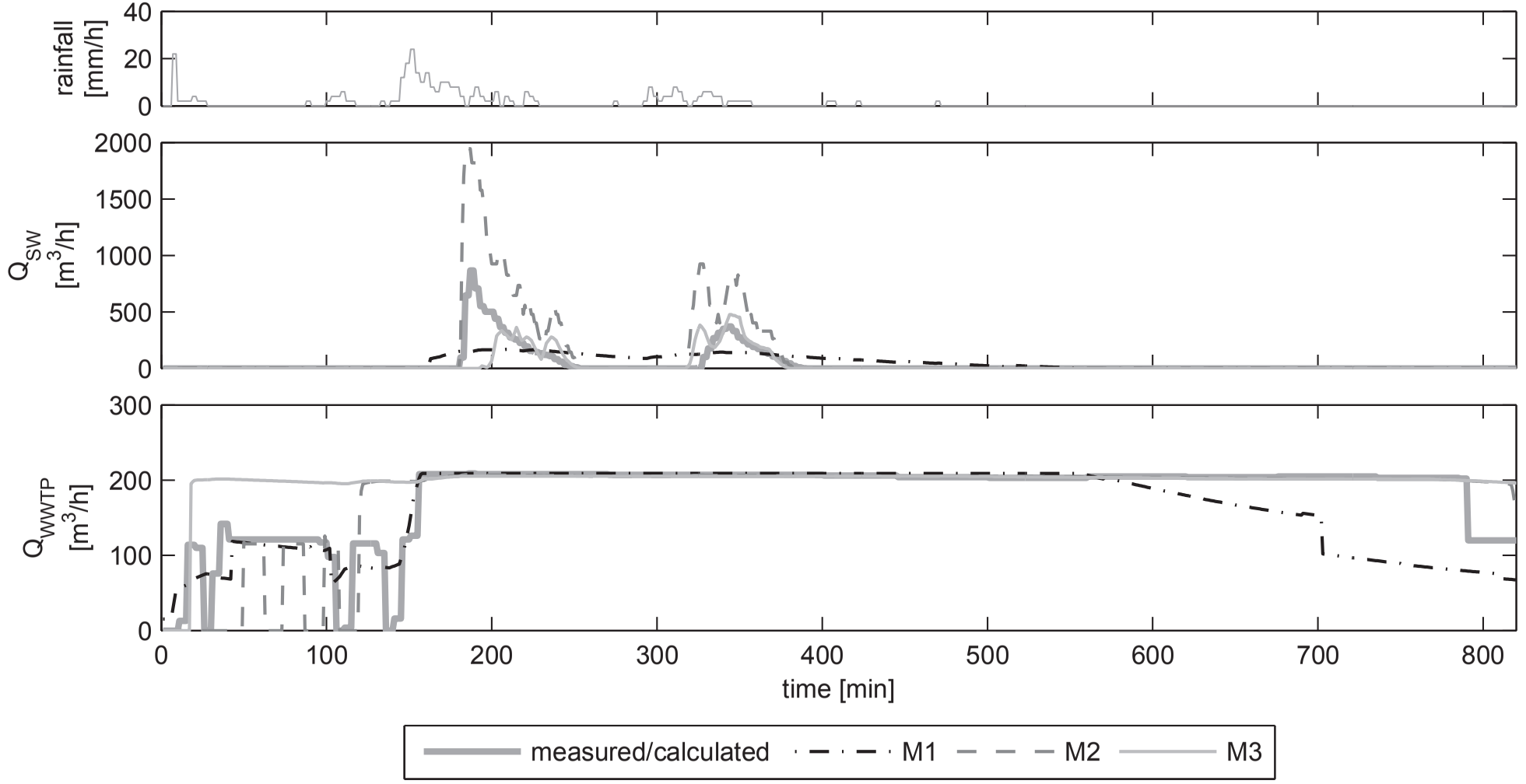

rainfall [mm/h]
40
20
0
Q_{SW} [m^3/h]
2000
1500
1000
500
0
Q_{WWTP} [m^3/h]
300
200
100
0
0
100
200
300
400
500
600
700
800
time [min]
measured/calculated
M1
M2
M3

Figure 16

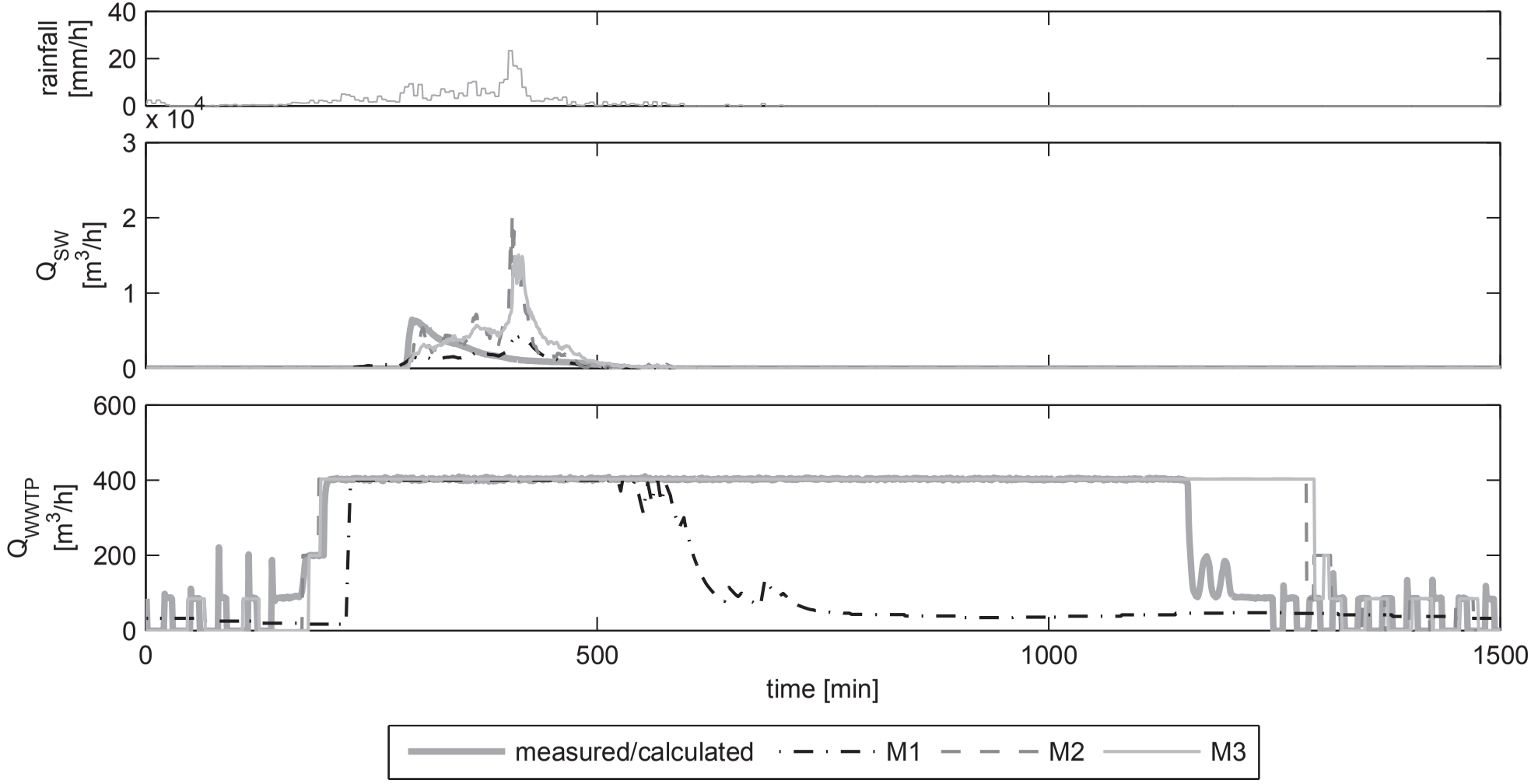

rainfall [mm/h]
40
20
0
x 10^4
3
2
1
0
Q_SW [m^3/h]
600
400
200
0
Q_WWTP [m^3/h]
0
500
1000
1500
time [min]
measured/calculated
M1
M2
M3

Figure 17

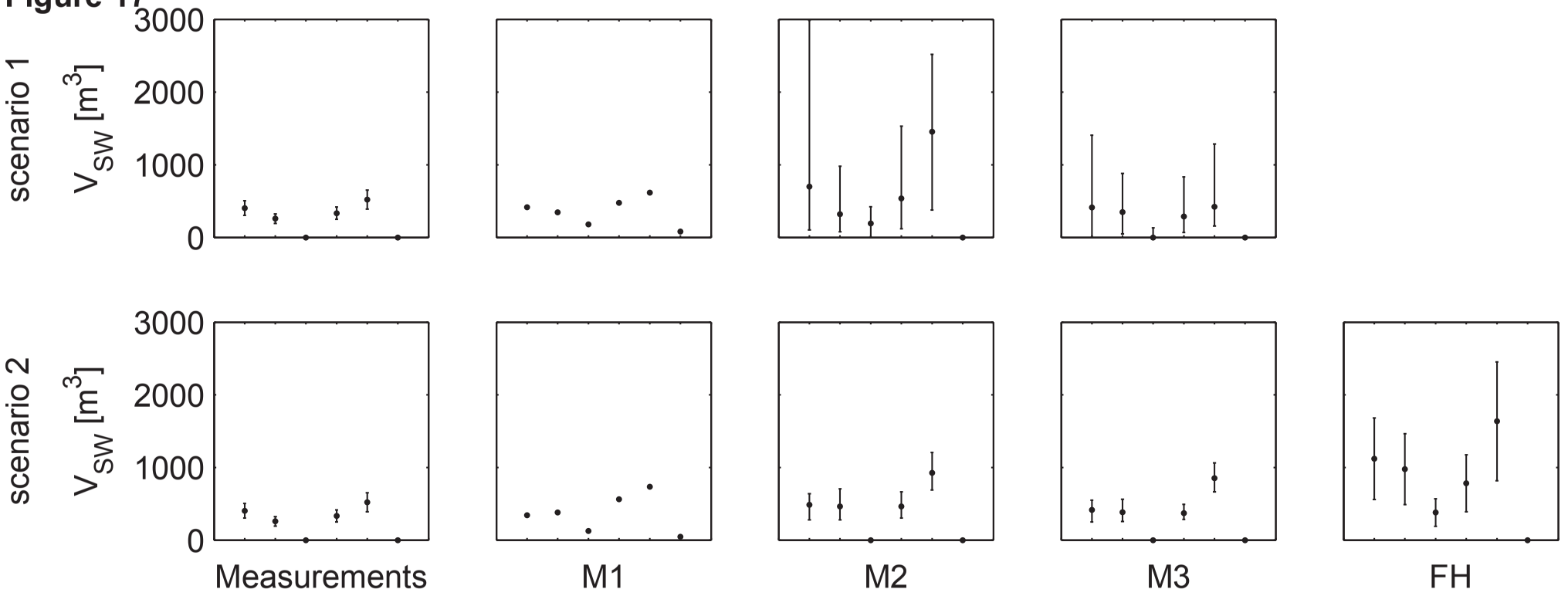
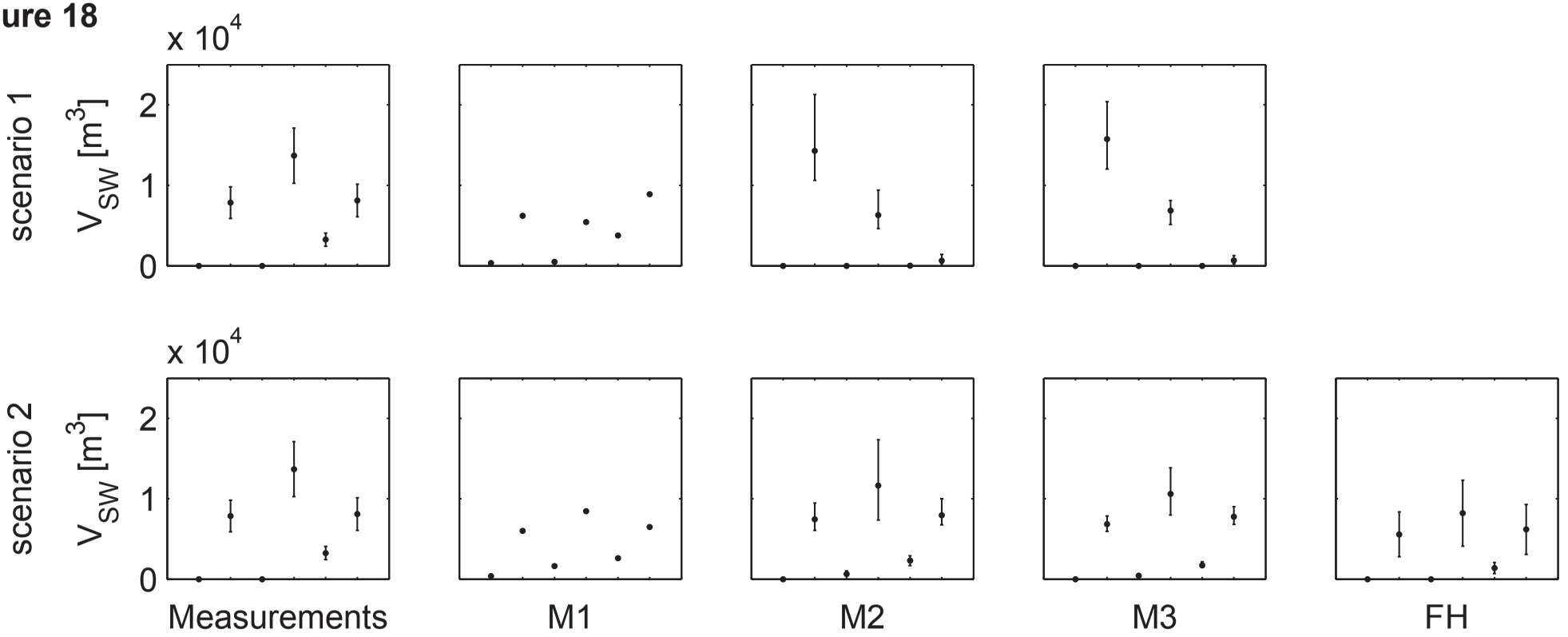

scenario 1
scenario 2
V_{SW} [m^3]
3000
2000
1000
0
Measurements
M1
M2
M3
FH

Figure 18


x 10^4
scenario 1
V_SW [m^3]
2
1
0
x 10^4
scenario 2
V_SW [m^3]
2
1
0
Measurements
M1
M2
M3
FH

DESIGN AND PERFORMANCE EVALUATION OF A SIMPLIFIED DYNAMIC MODEL FOR COMBINED SEWER OVERFLOWS IN PUMPED SEWER SYSTEMS

Petra VAN DAAL-ROMBOUTS[1,2,*], Siao SUN[3], Jeroen LANGEVELD[1,4], Jean-Luc BERTRAND-KRAJEWSKI[5], François CLEMENS[1,6]

[1] Delft University of Technology, P.O. Box 5048, 2600 GA Delft, the Netherlands

[2] Witteveen+Bos, P.O. Box 233, 7400 AE Deventer, the Netherlands

[3] Institute of Geographical Sciences and Natural Resource Research, Chinese Academy of Sciences, Beijing, 100101, People's Republic of China

[4] Partners4UrbanWater, Javastraat 104A, 6524 MJ Nijmegen, the Netherlands

[5] University of Lyon, INSA Lyon, DEEP, F-69621 Villeurbanne Cedex, France

[6] Deltares, P.O. Box 177, 2600 MH Delft, the Netherlands

*Corresponding author's e-mail: p.m.m.vandaal-rombouts@tudelft.nl

Abstract

Optimisation or real time control (RTC) studies in wastewater systems increasingly require rapid simulations of sewer systems in extensive catchments. To reduce the simulation time calibrated simplified models are applied, with the performance generally based on the goodness of fit of the calibration. In this research the performance of three simplified and a full hydrodynamic (FH) model for two catchments are compared based on the correct determination of CSO event occurrences and of the total discharged volumes to the surface water. Simplified model M1 consists of a rainfall runoff outflow (RRO) model only. M2 combines the RRO model with a static reservoir model for the sewer behaviour. M3 comprises

the RRO model and a dynamic reservoir model. The dynamic reservoir characteristics were derived from FH model simulations. It was found that M2 and M3 are able to describe the sewer behaviour of the catchments, contrary to M1. The preferred model structure depends on the quality of the information (geometrical database and monitoring data) available for the design and calibration of the model. Finally, calibrated simplified models are shown to be preferable to uncalibrated FH models when performing optimisation or RTC studies.

Keywords

calibration, conceptual models, full hydrodynamic models, integrated modelling, monitoring, urban drainage systems

1. Introduction

Optimisation studies in wastewater management are increasingly common (Bach et al., 2014; Benedetti et al., 2013), requiring model simulations for the wastewater system as a whole, i.e. the contributing sewer systems, wastewater treatment plants (WWTP) and receiving surface waters. These model simulations are performed by coupling models for each sub system into an integrated model. In integrated modelling studies and real time control (RTC) applications two properties are of main importance: accuracy of the results and the required simulation time. Accurate results are essential for any modelling study. When working with integrated models this is especially true since faulty results from one sub model serve as input for the next sub model. As the simulation time increases with the model size, integrated model simulations take much time to perform. For example, simulating the full hydrodynamic sewer model for the Eindhoven case study (4,000 ha) as described in (Langeveld et al., 2013) for a period of 24 hours takes approximately 45 minutes on a regular laptop (4 cores of 2.8 GHz each). As optimisation studies generally consist of scenario analysis or the application of RTC, making evaluation of alternative scenarios beforehand or in real time necessary, the need for rapid simulation is evident.

To reduce the simulation time, simplified models, also commonly referred to as conceptual or surrogate models, are applied. Simplified models consist in many representations, see e.g. (Coutu et al., 2012; Mannina and Viviani, 2010; Motiee et al., 1997; Vaes and Berlamont, 1999; Wolfs and Willems, 2014), but all aim to compress the complexity of the real system in only a few characteristics and/or relationships. To ensure their representativeness, the simplified models are calibrated against field measurements. The model structure and parameter set that lead to the best overall fit with the measurements is accepted as the best simplified

model. Attempts to find appropriate calibration algorithms are described in e.g. (Krebs et al., 2014; Mair et al., 2012; Vrugt et al., 2009; Wolfs et al., 2013).

Previous research, see e.g. (Del Giudice et al., 2015; Dotto et al., 2014; Kleidorfer et al., 2009; Sun and Bertrand-Krajewski, 2013a, 2012; Vaes et al., 2001), made clear that the model input can have a major impact on the simplified models performance. When constructing simplified models for sewer systems in practice, however, usually only a few measurements are available for model calibration. Sewer systems that are not specifically monitored for research purposes will likely have water level measurements at the systems edges, at the discharges to the WWTP and surface water and flow measurements if sewerage is pumped to the WWTP. No flow measurements are generally available at free flow discharges to the WWTP and at combined sewer overflow (CSO) locations. Simplified models are therefore, in the majority of cases, calibrated based on the available water level measurements. The best performing model is obtained by adjusting model parameters to reproduce the measurements based on criteria such as Nash-Sutcliffe or root mean squared errors (RMSE).

The outputs of a (simplified) sewer model applied in integrated modelling are the discharges to the other sub systems: the WWTP and surface water. Although the quality of the calibration is a measure for the capability of the simplified sewer model to reproduce observations, it does not necessarily imply a sufficiently accurate determination of the discharges. Therefore, in the study presented here, simplified sewer models are calibrated with the established DREAM algorithm (Vrugt et al., 2008 and 2009), while the performance is evaluated on the correct determination of the occurrence of CSO events and the best estimation of the total volumes discharged to the surface water.

Three simplified models are used in this paper to represent the processes in sewer systems: i) rainfall runoff outflow (RRO) model, ii) static reservoir model (SR) and iii) dynamic reservoir model (DR). RRO models simulate the surface runoff generation process and the discharges at the outlet of small catchments equipped with sloped sewer systems. Among RRO models, (Sun and Bertrand-Krajewski, 2013b) have demonstrated the effectiveness of the standard linear reservoir model for such cases. However, the simple linear relation between the discharge and the storage in the fictitious reservoir of the model is likely not to be effective for looped sewer systems equipped with pumping stations and CSO structures. Other process descriptions are needed in order to characterize the flow behaviour in these more complicated systems. In this study, a standard RRO model is thus complemented with either the SR model or the more elaborate DR model to represent looped, pumped, systems. For the derivation of the SR models geometrical information and pumping station settings are taken from a full hydrodynamic (FH) model, i.e. a 1D model taking into account hydrodynamic processes in the sewer system. For the DR models additional key relationships between variables are obtained through FH model simulations. In the development of SR and DR models, simplicity was constantly balanced against physical representativeness. Simplicity, and by that reproducibility and applicability in practical RTC situations, was pursued.

This paper thus presents a comparison of three simplified models: i) a single RRO model, ii) a combination RRO + SR models and iii) a combination RRO + DR models for the simulation of CSO events and volumes. Finally, the performances of the simplified and FH models are compared. This study has been conducted for two catchment areas in the Netherlands: Loenen and Waalre. Both catchments consist of pumped, combined sewer systems, but differ in size, structure and average ground level slope.

2. Materials and method

2.1. Catchment areas

Two combined sewer systems have been selected to test the simplified models: Loenen and Waalre. Loenen is located in the central east of the Netherlands in a mildly sloping area. This system has a partly looped and partly branched character. It is equipped with one pumping station and two CSOs. One CSO, referred to as primary, is located downstream in the sewer system and discharges much more and more often than the upstream, secondary, CSO. At the location of the pumping station an additional inflow from a small neighbouring sewer system is incorporated. Sewer system characteristics and layout can be found in table 1 and figure 1 (left).

Waalre is located in the south of the Netherlands. The sewer system is looped with one pumping station, a primary CSO equipped with a settling tank and a secondary CSO that rarely discharges. Additionally Waalre is connected to a neighbouring catchment in the east. Although water can flow both ways, it serves as a discharge for Waalre. Characteristics of the sewer systems are listed in table 1, while figure 1 (right) displays the sewer system layout.

2.2. Monitoring data

For Loenen monitoring data is available at a one minute interval from June 2001 to January 2002, collected as part of a dedicated research project. Flow measurements are available at the pumping station and an inflow into the pumping station from a neighbouring catchment. Level measurements are available in the pumping chamber and at the CSO locations, as displayed in figure 1 (left). Additionally, two rain gauges were installed in the catchment. Due to various reasons no continuous data set is available for the measuring period.

For Waalre monitoring data at the sewer system edges is available at a one minute interval. Flow is measured at the pumping station. Level measurements are available in the pumping chamber, inside the settling tank and at the secondary CSO location. The measuring locations are indicated in figure 1 (right). Rain radar data with pixel sizes of one square kilometre are available. The radar data is calibrated against rain gauge measurements located approximately 10 km away using a procedure based on conditional merging as described in (De Niet et al., 2013). The calibrated rain radar data is available only during wet weather days and when the rain gauges functioned in the period April 2011 to January 2012. All other measurements are registered permanently. Data validation was performed applying the algorithms described in (Van Bijnen and Korving, 2008).

Dry Weather Flow (DWF)

Daily dry weather flow (DWF) profiles have been derived from the monitoring data for both catchments. For Waalre it was based on the pump flow measurements in 2011. The mean hourly pumped discharge at DWF days was used to represent a typical daily DWF profile. DWF days are defined as having received less than 0.05 mm of precipitation after exponential smoothing (80% accounted to the current day and 20% to the following day) to prevent false detection of DWF days due to the absence of rain gauges inside the catchment. Unrealistic measurements and periods with snowfall have been manually discarded. The DWF profile for Loenen was previously derived by (Langeveld, 2004) based on the pump flow measurements using a similar strategy. The resulting profiles can be found in figure 2.

2.3. Full hydrodynamic (FH) models

FH models for both catchments are available in InfoWorks ICM (www.innovyze.com). The FH model for Loenen was calibrated by (Langeveld, 2004), following the procedure described by (Clemens, 2001). The calibration involved a detailed check of the geometrical database and tuning of several parameters to match measured and modelled water levels at up to ten locations. As the calibration resulted in very close resemblance between the modelled and measured water levels (deviations < 5 cm), it was concluded that the geometrical database was virtually without errors. The FH model for Waalre was validated as described in (Langeveld et al., 2013). It involved comparison of the measured and modelled water levels as a function of time at the three monitoring locations. No parameter optimisation was performed. As the measured and modelled water levels resembled one another in general (based on expert judgement), it was concluded that no large errors in the geometrical database existed. Nevertheless, occasional deviations in measured and modelled water levels of up to 50 cm were present.

The FH models are applied in this study for three purposes: i) properties of the geometrical database and pumping station settings are utilized in the design of the SR and DR models, ii) key relationships between variables are obtained by means of FH model simulations and applied in the DR model, and iii) the performance of the simplified models is compared to the performance of the FH models. For all simulations with the FH models for any of the above purposes, a standard (uncalibrated) parameter set is employed as (Korving and Clemens, 2005) showed that the portability of event specific parameter sets for FH models is low. The main distinction between the calibrated FH model for Loenen and validated FH model for Waalre lies therefore in the trustworthiness of the underlying geometrical database.

The simulations performed with the FH model for the second purpose, application in the design of the DR model, are based on ten years (1955-1964) of 15 minute interval rainfall measurements in De Bilt in the Netherlands. The simulations were executed with a one minute time step, recording for every time step the volume, water level and flows in all manholes, conduits, pumps, CSOs etc. The derivation of the required relationships is described in detail in section 2.4.3.

2.4. Model structures

The general structure of the three simplified models tested in this paper is shown in figure 3. Model M1 includes only a RRO model. Model M2 combines a RRO model and a SR model, while model M3 combines a RRO model and a DR model. Rainfall, DWF and optional additional flows are model inputs, while flows to the surface water (Q_{SW}) and to the WWTP (Q_{WWTP}) are model outputs. In the following sections, all models are explained in more detail.

2.4.1. Rainfall runoff outflow (RRO) model

The standard linear reservoir model is a typical RRO model, see e.g. (Sun and Bertrand-Krajewski, 2013b). It comprises of a rainfall loss model followed by a linear reservoir. The rainfall loss model consists of initial (I_{ini} [mm]) and proportional (P_{cons} [-]) rainfall losses, i.e. depression losses and ratio of contributing and total area. The resulting net rainfall (I_{net} [mm]) occurs with a time lag (T_{lag} [min]) and feeds the linear reservoir with a reservoir constant (K [min]). The outflow of the standard linear reservoir (Q_{out}) is derived from the inputs using:

$$Q_{out}(t) = \exp\left(-\frac{\Delta t}{K}\right) Q_{out}(t-\Delta t) + \left[1-\exp\left(-\frac{\Delta t}{K}\right)\right] I_{net}(t-T_{lag})A, \qquad (1)$$

205 with A the catchment area [ha]. For more details on the standard linear reservoir model the
206 reader is referred to (Sun and Bertrand-Krajewski, 2013b).
207
208 To determine the total inflow into the sewer models (Q_{in} in figure 3) for models M2 and M3,
209 Q_{DWF} and $Q_{optional}$ are simply added to Q_{out}. For model M1, Q_{out} together with Q_{DWF} and $Q_{optional}$
210 represent both the surface runoff and the subsequent flow routing within the sewer system. It
211 is split in the two sewer discharges Q_{SW} and Q_{WWTP} on the assumption that as much water is
212 pumped to the WWTP as possible, i.e. all discharges up to the maximum pumping capacity is
213 accounted to Q_{WWTP} as illustrated in figure 4 for Loenen. For Waalre, Q_{WWTP} is determined using
214 the same method. From the remainder the discharge through the connection to the
215 neighbouring catchment (determined from FH model simulations as it is not monitored) is
216 subtracted before accounting it to Q_{SW}.

217 **2.4.2. Static reservoir (SR) model**

218 The SR model aims to represent processes within the sewer system that the basic RRO model
219 cannot explicitly simulate. FH model properties of the geometrical database and pumping
220 station settings are applied in its design. A schematic representation of the SR model for
221 Loenen is shown in figure 5. It consists of a single basin for the sewer system which is filled by
222 Q_{in} as described in the previous section. It empties through a pump resulting in Q_{WWTP}, and a
223 single CSO resulting in Q_{SW}.
224
225 Several characteristics or relationships are applied in the SR model, numbered S SR1-SR3 in
226 figure 5. Their representation and derivation were performed as follows:
227 SR1. Static storage-level curve

The static storage-level curve is used to convert the sewer volume (V_S) into the water level in the sewer (H_S). It is derived from the geometrical database of the FH model as the cumulative volume of all manholes, conduits, etc. of the sewer system under each possible water level.

SR2. Discharge through pump

The discharge through the pump ($Q_{S,P}$) is calculated through H_S and the pump characteristic. The pump characteristic is taken from the FH model.

SR3. Discharge through CSO

The discharge through the CSO (Q_{CSO}) is taken to be only caused by the primary CSO. The discharge is calculated through H_S and the standard weir equations for frontal weirs:

$$Q_{free} = c_1 h^{c_2} \quad (2)$$

for free outflow, with flow Q_{free} [m^3/s], h [m] water level above the weir crest, c_1 [m^{3-c_2}/s] taken to be 1.36 times the weir width [m] and c_2 [-] taken to be 1.5. Or

$$Q_{sub} = c_3 \mathrm{h}_{DS} \sqrt{2g(h_{US} - h_{DS})} \quad (3)$$

for submerged outflow, with flow Q_{sub} [m^3/s], h_{US} and h_{DS} [m] the upstream and downstream water level above the weir crest, c_3 [m] taken to be 0.8 times the weir width [m] and g the standard acceleration due to gravity [9.81 m/s^2]. Submerged outflow is assumed to occur when $2/3 * h_{US} < h_{DS}$. For Loenen only free outflow is assumed.

A schematic representation of the SR model for Waalre is depicted in figure 6. It consists of a basin for the sewer system and a basin for the settling tank. The sewer basin is filled by Q_{in} and has three discharges: one through the pump resulting in Q_{WWTP}, one through the connection with the neighbouring catchment and one through a single CSO to the settling tank. The discharge through the CSO fills the settling tank that is emptied either through a pump back into the sewer basin, or through a CSO to the surface water resulting in Q_{SW}.

Again several characteristics or relationships have been applied in the model, numbered SR4-SR10 in figure 6. Their representation and derivation were performed as follows:

SR4. Static storage-level curve sewer

See SR1, and excluding the settling tank.

SR5. Discharge sewer through pump

The discharge through the pump ($Q_{S,P}$) is calculated through the water level in the sewer (H_S) and the pump characteristic. The pump characteristic is derived from analysis of the water level and flow measurements at the pumping station, and (Van Daal-Rombouts, 2012).

SR6. Discharge sewer through connection

From simulations with the FH model it was found that water only flows from Waalre to the neighbouring catchment. The discharge through the connection (Q_{CONN}) is calculated through H_S and the standard equation for a free outflow over a V-notch weir,

$$Q = c_1 \tan(\theta/2) h^{5/2}, \quad (4)$$

as the connecting sewer is egg shaped. Here Q is the flow [m^3/s], c_1 a constant [$m^{1/2}/s$] taken to be 1.4, θ the notch angle taken to be 67°, and h [m] the water level over the weir crest. Free outflow is assumed at all times and the bottom of the notch is taken to be the highest invert of the connecting conduit.

SR7. Discharge sewer through CSO

The discharge through the CSO (Q_{CSO}) is taken to be caused only by the primary CSO and is calculated through H_S and equations 2 and 3. Both free and submerged outflow are allowed (only free outflow is displayed).

SR8. Static storage-level curve settling tank

The static storage-level curve is used to convert the settling tank volume (V_T) into the water level in the tank (H_T). It is derived from the FH model, similar to SR1.

SR9. Discharge settling tank through pump

The discharge of the settling tank through the pump ($Q_{T,P}$) is based on H_T and the pump characteristic. The pump characteristic was taken from the FH model, where the pumping capacity was adjusted to match the monitoring data.

SR10. Discharge settling tank

The discharge of the settling tank (Q_T) is calculated through H_T and equation 2.

2.4.3. Dynamic reservoir (DR) model

The DR models for the sewer systems are similar to the SR models, but contain additional relationships derived from FH model simulations to better account for the dynamic behaviour of a sewer system. A schematic representation of the DR model for Loenen is shown in figure 7 and can be compared to the SR model in figure 5. Differences are expressed in the storage-level curve applied (SR1 - DR1) and the water level applied in the CSO discharge (DR2 - no equivalent in the SR model).

The characteristics or relationships applied in the DR model are numbered DR1-DR4 in figure 7. Their representation and derivation are explained bellow:

DR1. Hybrid storage-level curve

A so called hybrid storage-level curve is used to convert the sewer volume (V_S) into the water level in the sewer (H_S). The hybrid curve follows the static storage-level curve (see SR1) for low water levels to correctly model DWF circumstances and pumping behaviour, and gradually turns to the dynamic storage-level curve for high water levels (with possibly pressurised flow conditions) to take the dynamic properties of the sewer system under wet weather flow (WWF) conditions and CSO discharges into account. Figure 8 (left) displays the static, dynamic, and hybrid storage curves for Loenen.

The dynamic storage-level curve was derived from simulations performed with the FH model as described in section 2.3. The resulting water volumes in the entire sewer system (every minute for 10 years) were grouped in one cm intervals of the corresponding water level at the pumping station. The grouped volumes were averaged and smoothed to obtain the dynamic storage-level curve, as displayed in figure 8 (right). Note that the dynamic storage-level curve converges towards the static storage-level curve for DWF conditions or low rain intensities as the water level in the sewer system levels off.

DR2. Level at CSO

H_S is converted into the water level at the primary CSO location (H_{CSO}). The relationship is based on FH model simulations, where a linear relation is fitted through the simulated water levels at the pumping station and the CSO location. Only elevated water levels (WWF conditions) are taken into account.

DR3. Discharge through pump

See SR2.

DR4. Discharge through CSO

See SR3, only now H_{CSO} is applied.

A schematic representation of the DR model for Waalre is shown in figure 9 and can be compared to the SR model in figure 6. Differences are expressed in the storage-level curve applied (DR5-SR4), the water level applied in the CSO discharge (DR6-no equivalent in the SR model) and the water level applied in and the calculation of the flow through the connection (DR7-no equivalent in SR model, DR9-SR6).

The characteristics or relationships applied in the DR for Waalre are numbered DR5-DR13 in figure 9. Their representation and derivation are explained as follows:

DR5. Hybrid storage-level curve sewer

A hybrid storage-level curve is used to convert V_S into H_S. The derivation follows DR1. The resulting curves for Waalre are displayed in Figure 10: (left) the static, dynamic, and hybrid storage curves, (right) the derivation of the dynamic storage-level curve from the FH model simulation results.

DR6. Level sewer at CSO

Similar to DR2, a relationship has been derived between H_{CSO} and H_S. As Waalre is equipped with the settling tank two linear segments that connect at the highest weir crest level of the settling tank have been applied. Only elevated water levels (WWF conditions) are taken into account.

DR7. Level sewer at connection

Similar to H_{CSO} in DR6, a relationship between the water level at the connection to the neighbouring catchment (H_{CONN}) and H_S is derived from the FH model simulations. A

linear relation was fitted, taking only elevated water levels (WWF conditions) into account.

DR8. Discharge sewer through pump

See SR5.

DR9. Discharge sewer through connection

The discharge of the sewer through the connection to the neighbouring catchment (Q_{CONN}) is based on H_{CONN} and a relationship derived from the FH model simulations. The simulated water levels at the connection and the corresponding flow through the connection were fitted with a third order polynomial equation. To prevent unrealistic (negative) output a maximum value is set for H_{CONN}.

DR10. Discharge sewer through CSO

See SR7, where H_{CSO} is applied in the calculation of the discharge from the sewer.

DR11. Static storage-level curve settling tank

See SR8.

DR12. Discharge settling tank through pump

See SR9.

DR13. Discharge settling tank

See SR10.

2.5. Calibration procedure

2.5.1. DREAM algorithm

Calibration, which adjusts model parameters by minimizing the difference between model outputs and measurements, is an important step before applying simplified models. The research on calibration methods in the area of rainfall-runoff modelling is comprehensive, leading to the application of automatic calibration methods instead of traditional manual

375 calibration mainly based on trial and error approaches. In this study an automatic calibration
376 method (the differential evolution adaptive metropolis (DREAM) method (Vrugt et al., 2008,
377 2009)) was applied for the calibration of the RRO models. The DREAM method is based on the
378 Bayesian theorem, which considers model parameters as probabilistic variables revealing the
379 probabilistic belief on the parameters according to observed model outputs. In DREAM the
380 probability distribution function of parameters is derived using an iterative approximation
381 method (the Markov chain Monte Carlo (MCMC) method) coupled with multiple chains in
382 parallel in order to provide a robust exploration of the search space. In addition to an optimal
383 model parameter set, DREAM also results in an evaluation of model parameter uncertainty,
384 which provides important information on model reliability. The effectiveness of DREAM in
385 water related model calibration has been demonstrated in many previous studies, e.g. (Keating
386 et al., 2010; Leonhardt et al., 2014).

387 **2.5.2. Parameter optimisation**

388 The DREAM algorithm is applied to calibrate the parameters of the RRO model to find the
389 minimal difference between the simplified model output and the measurements. Table 2
390 shows the parameters, units and the searching range for the calibration procedure.
391
392 The algorithm minimises the sum of squared errors (SSE) between the model output and
393 measurements. Water level measurements are applied in the calibration as they are the actual
394 monitoring data available, containing all information on the sewer systems behaviour. For
395 Loenen the water level measurement at the primary CSO location is used to calibrate M2 and
396 M3. For Waalre the water level measurements at the pumping station and inside the settling
397 tank are applied, by minimising the sum of the SSEs for each model output-measurement
398 combination. Only periods with elevated water levels are considered in the calibration, as the

RRO model parameters are connected to rainfall only. Since water levels do not have significance in M1, it's calibration is based on the total outflow from the sewer system, i.e. the sum of the measured pump flow and the calculated outflow at the CSO locations (determined with the measured water levels and equation 2) for Loenen and Waalre. For Waalre the outflow through the connection with the neighbouring catchment is added. As this flow is not monitored, it is based on FH model simulations for the respective rain events.

The information content on which the models are calibrated is similar, especially for the elevated water levels relevant for CSO discharges. M2 and M3 are calibrated on measured water levels at the CSO locations. The discharge to the surface water in M2 and M3 is calculated using the modelled water level and equation 2. The same equation with the measured water levels is applied to determine the outflow for the calibration of M1. Additionally, the pumped outflow supplies information during low intensity rainfall, as contained in the level measurements at the pumping station (in case of Waalre) or the primary CSO location (for Loenen) when it is not yet discharging.

The calibration is performed using 10,000 iterations in DREAM, as it was found from test runs that the cumulative density functions of the parameters do not change (within the parameter stability) after several thousand iterations. The last 5,000 iterations are used for further analysis: the optimal parameter set and model output are derived, and the model is run with all 5,000 parameter sets to determine the 95% confidence intervals for the water levels and discharges.

2.5.3. Events

For each catchment six rain events are available for the parameter optimisation, e.g. they led to a significant rise in water level in the sewer system, with or without discharge to the surface water, no external influences were known and monitoring data was available and judged reliable after data validation. The selected events and their characteristics are summarised in table 3.

(Korving and Clemens, 2005) showed that the portability of event specific parameter sets for FH models is low. (Sun and Bertrand-Krajewski, 2012) investigated the impact of calibration data selection on the model performance of regression models. Given the limited dataset, full consideration of this aspect is considered beyond the scope of this paper. It is clear, however, that comparison of the model structures on single event calibration is insufficient. Therefore three scenarios have been explored:

1. Calibration of single rain events,
2. Calibration on all events together,
3. Calibration on any set of 3 events and verification with the remaining 3 events.

2.6. Performance evaluation

The performance of the calibrated simplified model structures should be evaluated on the capability to correctly represent the sewer systems functioning at the edges of the system. As argued in the introduction this is not obtained by comparing the best fits between the measured and modelled water levels but by comparing the discharges from the system, i.e. to the WWTP and the surface water. As the RRO models are calibrated, i.e. all calibration parameters are related to rainfall, the focus of the performance evaluation will be on the CSO discharges to the surface water. As the discharge to the WWTP is also relevant for integrated studies it will be reported for completeness.

Common sense dictates that the impact of CSO events depends foremost on the occurrence of such events, with the absolute discharged flows of secondary consequence. This is supported by literature stating that impact based RTC can influence the systems performance for small and moderate events, contrary to large events on which it has no influence (Langeveld et al., 2013), and that up to a certain point overflow frequency is a good indicator of receiving water impact (Lau et al., 2002). Therefore the first evaluation criterion for the simplified sewer models is the correct determination of CSO event occurrences. The second evaluation criterion is the correct determination of the total discharged volume.

Based on the monitored water levels at the CSO locations in the sewer systems and settling tank, for each event and catchment the discharge to the surface water (Q_{SW}) is calculated through application of equation 2. Additionally the total discharge to the WWTP (Q_{WWTP}) is calculated from the pump flow measurements. For each model structure and scenario the modelled the total discharged volumes (V_{SW} and V_{WWTP}) are determined as the integral of the model outputs Q_{SW} and Q_{WWTP}.

CSO event occurrences are analysed through false positives (FP) and false negatives (FN). A FP is defined as a CSO event occurrence ($V_{SW} > 0$) in the model output but not in the measurements, a FN as a CSO event occurrence in the measurements but not in the model output. For the comparison of discharged volumes, differences in V_{SW} (and V_{WWTP}) between the model output and the measurements are calculated and listed for each event and scenario. Cumulative results for each scenario are determined by taking the root mean squared errors (RMSE) over all events.

For comparison purposes the selected rain events have also been simulated using the FH models. The comparison between simplified models with calibrated inflow parameters and FH models with uncalibrated inflow parameters is relevant since the FH models simulate the sewer systems behaviour in greatest detail and hence are deemed to be most accurate (Ferreri et al., 2010; Meirlaen et al., 2001; Rubinato et al., 2013). This might hold true for calibrated FH models but not for the much more commonly applied uncalibrated models, as proper calibration of FH models is very time consuming and requires a very large monitoring data set.

Finally, the simulation time needed by different simplified model structures and the FH model will be compared.

3. Results and discussion

3.1. Calibration

As described in the previous section the performance of the simplified model structures will be evaluated based upon the correct determination of CSO occurrences and the total discharge to the surface water. The calibration results, however, provide useful insight into the models functioning. Therefore, a typical calibration result for each catchment will be presented. Nash-Sutcliffe efficiency indexes (NS) (Nash and Sutcliffe, 1970) are supplied for easy comparison of the calibration results. Optimal parameter sets will be given for all events and scenarios.

The results for the individual calibration of rain events 2001-08-27 (Loenen) and 2011-08-14 (Waalre) for all model structures are displayed in figures 11 and 12 respectively. From top to bottom the applied rainfall is shown, followed by the model results for M1 (based on the total sewer outflow), and M2 and M3 (based on the water level in the sewer system). For Waalre additional water level measurements in the settling tank were applied, the results of which have been added to the bottom of figure 12. For each model structure the optimal results are displayed together with their 95% confidence bands.

Figures 11 and 12 show that M2 and M3 are in general well able to describe the sewer systems behaviour: the measurements applied in the calibration are closely followed during the filling of the basins, once they are full and during emptying, resulting in NS values > 0.95 for Loenen and > 0.75 for Waalre. Small differences occur between these models especially during filling and in the response to temporal changes in the rainfall. M1 cannot describe the sewer systems behaviour in detail as it has only the reservoir constant K to account for surface storage and in-

sewer storage. The response to rainfall is therefore more smoothed, which is best demonstrated in figure 11. NS values < 0.4 are found.

For both catchments and all model structures the 95% confidence bands are mostly < 1%. Logically, the influence of the (inflow) calibration parameters on water levels in sewer systems is most apparent at the onset of a rain event or during temporal changes, resulting in confidence bands up to 10% for M2 and M3, while they stay < 1% for M1.

For all scenarios for Loenen NS values for M2 and M3 > 0.90. For M1, values differ strongly from -8.52 to 0.44. For Waalre for M2 and M3 in scenario 1, NS values range between 0.61 and 0.96, with one event around zero. In scenario 2 the values drop to 0.5 to 0.6. The NS values for M1 again differ strongly between events and scenarios from -9.42 to 0.82.

Figure 13 shows the optimal parameter values for Loenen (left) and Waalre (right) for all model structures. In asterisks the results for scenario 1 (calibration on single rain events) are given, the line indicates the parameter values for scenario 2 (all events together). Results for all twenty possible combinations of three calibration events in scenario 3 can be found in figure 14. The optimal parameter values reflect the results for the water levels and NS values: the parameters for M2 and M3 show much resemblance within a catchment, while M1 deviates. Especially the difference in K stands out, as the RRO model in M1 has to account for the surface and in-sewer storage, while in M2 and M3 only for the surface storage. The optimal parameter values between scenarios 2 (line in figure 13) and 3 (figure 14) are consistent, indicating that the exact split in a calibration and verification set does not have a major impact on the outcome.

3.2. Performance evaluation

3.2.1. Model discharge

As the calibration of the simplified models is performed on rainfall related parameters, the focus of the performance evaluation will be on the discharge to the surface water (Q_{SW}) while the discharge to the WWTP (Q_{WWTP}) is included for completeness.

Optimal Q_{SW} and Q_{WWTP} for all model structures for the calibration of the single events of 2001-08-27 (Loenen) and 2011-08-14 (Waalre) are displayed in figures 15 and 16 as well as the discharges determined from the measurements. The difference between M1 and M2/M3 observed in the calibration results are also clear from these figures, as Q_{SW} for M1 tends to be more smoothed because of the higher value for K.

3.2.2. Determination of CSO events

FPs and FNs for all events for each model structure and scenario, based on the optimal parameter sets, are given in table 4. For scenarios 1 and 2 the total number is reported, for scenario 3 the results have been averaged over all combinations and multiplied by two for easy comparison. Additionally, results for the FH model have been added.

Based on the FPs and FNs in table 4, M1 can be immediately discarded for these catchments. For each scenario and catchment two FPs were recorded, the exact number of rain events that did not lead to a CSO event. This is easily explained since a rain event leading to a significant rise in water level in a pumped sewer system will likely contain rain intensities higher than the pumping capacity of the sewer system reserved for WWF (design guideline in the Netherlands: 0.7 mm/h). In M1 all rainfall in excess of this capacity has to be discharged to the surface water, leading to a CSO event. The calibration algorithm unsuccessfully tries to overcome this

553 inadequacy in the model structure by delaying the rainfall (high T_{lag}) and smoothing the
554 response (high K), as can be found from the optimal parameter values in figure 13.
555
556 For M2 and M3 the results are less conclusive. Single FPs or FNs occur depending on the
557 catchment and scenario applied. The floating point values for scenario 3 for Waalre (due to
558 averaging over all possible combinations) and the optimal parameter values in figure 13
559 further indicate that the inflow parameters are calibrated differently depending on the
560 selection of calibration/verification events. Only for M3 for Loenen no FPs or FNs occur in any
561 scenario signalling that the M3, combining the RRO and DR models, is likely the best
562 performing model for Loenen.

563 **3.2.3. Determination of discharged volumes**

564 The total volumes discharged to the surface water (V_{SW}) for each model structure and
565 scenarios 1 and 2 are displayed in figure 17 for Loenen and 18 for Waalre. V_{SW} is the integrated
566 model output Q_{SW}, for which the optimal values and 95% confidence bands are determined as
567 described in section 2.5.2. The calculation of the 95% confidence intervals for the
568 measurements is based on an uncertainty in the standard weir equation of 25%. This
569 percentage is estimated on previous work by (Van Daal-Rombouts et al., 2014) on scale models
570 and (Fach et al., 2009) on computational fluid dynamics. Both studies indicate deviations
571 between the actual (measured or calculated) CSO discharge and the discharge determined
572 with the standard weir equation of up to 50%. They also indicate that this strongly depends on
573 the water level over the weir crest leading to under and over estimations of the flow.
574 Therefore an intermediate value was chosen. For the FH model an uncertainty of 50% was
575 applied based on the possibility to calibrate FH models up to 5 cm difference in water levels
576 and equation 2.

577

578 The cumulative results for V_{SW} and V_{WWTP}, given in table 5, were determined by taking the
579 RMSE of the results from the optimal parameter sets over all events. The RMSE for scenario 3
580 have been averaged over all possible combinations and values for the FH model have been
581 added.

582

583 The results for V_{SW} in figures 17 and 18 and table 5 support the preliminary conclusion that M3
584 outperforms M2 for Loenen. For all scenarios the RMSE and the uncertainty bands for M3 are
585 smaller than for M2. Despite the inability of M1 to correctly determine CSO event occurrences,
586 it outperforms M2 based on V_{WS}. For Waalre the performance of M2 and M3 are similar,
587 corresponding to the determination of the CSO events. Nevertheless, M2 consistently
588 performs better than M3. Similar to Loenen, M1 generally performs well based on V_{SW}. The
589 difference in the performance of M2 and M3 between the catchments is also reflected in the
590 optimal parameter values (figure 13). The parameter values for Waalre are close resulting in
591 similar RMSE values in table 5, while for Loenen there is more variety between the model
592 structures especially for I_{ini} and K.

593

594 These results can be explained by the information available for the simplified model design
595 and calibration as described in sections 2.2 and 2.3. All information is better known or of
596 higher quality for Loenen: i) The monitoring data for Loenen was gathered for research
597 purposes, while the monitoring campaign for Waalre received less dedicated attention. ii) For
598 Loenen two rain gauges were installed in the catchment itself, while for Waalre no local rain
599 gauges were available. iii) The geometrical database underlying the FH model for Loenen is
600 better known than for Waalre. The results for the RMSE of V_{SW} indicate that the more detailed
601 model M3, i.e. RRO model for the runoff combined with the DR model for the sewer system, is

602 favoured when high quality information is available (in this case Loenen), while the less
603 detailed model M2, RRO with SR, suffices when the information is of lower quality (Waalre).
604
605 One main source of uncertainty for Waalre likely stems from the calibrated rain radar input.
606 The rainfall in general seems reasonable with NS values for M2 or M3 > 0.6. In detail the
607 rainfall seems off in intensities and/or timing, an example of which can be found in figure 16.
608 Judging from the rainfall, the models responses in Q_{SW} are in accordance (main peak in the
609 outflow after main peak in the rainfall). However, in the measurements the main peak in the
610 outflow occurs right at the beginning of the rain event. The other events display a similar
611 mismatch between the rainfall and the outflow. This may also explain the very low values for
612 the parameters T_{lag} and K, see figure 13, as the calibration procedure tries to correct the
613 mismatch in the input data.
614
615 For V_{WWTP} the RMSE values in table 5 show that model M1 consistently performs worse than
616 M2 and M3 for all scenarios and both catchments. M2 and M3 generally perform on a similar
617 level, which is to be expected as the pumping regime in the SR and DR model structures is the
618 same.
619
620 The NS values reported in section 3.1 are based on the calibration parameters for each time
621 step, and the FP/FN in table 4 and RMSE in table 5 on V_{SW}. Each presents information on the
622 performance of the model structure. NS indicates the quality of the description of the sewer
623 systems behaviour in general, while the others are specific for CSO discharges. The difference
624 between the best performing model structure based on these criterions, especially for Loenen,
625 is striking. Model M2 and M3 have similar NS values > 0.9, but M3 is much more accurate
626 based on FP/FN and RMSE. Simplified sewer models are calibrated on measurements,

627 generally only water levels, but used to determine CSO discharges. These results show that
628 care should be taken in choosing performance indicators suitable to the purpose of the model,
629 likely leading to multiple indicators.

630 **3.2.4. Uncalibrated FH models**

631 Finally the performance of the FH models is compared to the performance of the calibrated
632 simplified models. The comparison is made for scenario 2, calibration for all events together,
633 since there a single parameter set is derived for each model structure, similar to the single
634 standard parameter set for the FH model.
635
636 Based on the determination of CSO event occurrences (table 4) the FH model performs at a
637 similar level as M2 and M3. For Loenen one FP is noted for the FH model, while none for M2
638 and M3. For Waalre it is reversed.
639
640 Taking the RMSE for V_{SW} (table 5) into account, the FH model is easily outperformed by both
641 M2 and M3, while V_{WWTP} is worse for Loenen and better for Waalre. The results for the
642 simplified models for V_{SW} (scenario 3) imply little loss of accuracy when the available data is
643 split into a calibration and verification set. This suggests that, if a sufficiently large data set
644 were available, the optimal parameter set should be applicable to other events without much
645 loss of accuracy.
646
647 The simulation time for the FH models takes 1,000-5,000 times longer than for M2/M3 or
648 250,000-475,000 times longer than for M1.
649

650 From the perspective of both the simulation time and accuracy of results it is concluded that it
651 is better to apply simplified calibrated models in optimisation or RTC studies than uncalibrated
652 FH models.
653

4. Conclusions and future research

The research described dealt with the design and performance evaluation of a so called dynamic simplified sewer model for the accurate and rapid calculation of sewer system discharges for optimisation and RTC studies. The dynamic simplified sewer model (M3) consists of a calibrated rainfall runoff outflow (RRO) model and a dynamic reservoir (DR) model for the sewer behaviour. It contains characteristics derived from full hydrodynamic (FH) model simulations to account for the dynamic properties of the sewer system behaviour.

The performance of M3 was tested for two combined, pumped catchments and compared against two other simplified models, M2 (calibrated RRO model with a static reservoir (SR)) and M1 (calibrated RRO model only), and uncalibrated FH models. The performance was not solely based on the goodness of fit of the calibration but primarily on the correct determination of CSO event occurrences, and secondly on the correct determination of the total discharged volumes to the surface water.

From this research the following conclusions can be drawn:

- Model M1 simulates > 100,000 times faster than the FH model; models M2/M3 are > 1,000 times faster than the FH model.
- M1 is unsuitable to correctly predict CSO occurrences for pumped catchments. The model structure is unable to retain rain intensities higher than the pumping capacity reserved for WWF, resulting in too many CSO discharges.
- M2 and M3 are able to describe the behaviour of pumped sewer systems.
- Performance indicators for the selection of the most appropriate model structure should be chosen carefully, likely leading to multiple indicators.

- In case of detailed and trustworthy information available for the design and calibration of the model (Loenen), M3 outperforms M2 for all scenarios. If the available information is of lower quality (Waalre), M2 consistently performs slightly better indicating that the derivation of the more detailed DR model is not useful.
- For rainfall driven modelling trustworthy and local rain measurements remain necessary despite the availability of rain radar data, to either apply as direct input or the correction of radar data.
- M2 and M3 outperform the uncalibrated FH models based on the total discharge to the surface water. In optimisation or RTC studies the application of suitable calibrated simplified models is preferred over uncalibrated FH models.

Future research will focus on retrieving more reliable monitoring data (especially rainfall) for the catchment of Waalre to investigate the impact on the performance of the detailed M3 model. Calibrated simplified sewer models will be derived for the catchments in the case study area of Eindhoven for application in an integrated model to research the possibilities for quality based RTC.

Acknowledgements

The authors would like to acknowledge Innovyze (www.innovyze.com) for kindly supplying a research licence for the use of the software program InfoWorks ICM. Also the authors would like to thank the Van Gogh Programme for supplying a Travel Grant to cover the travel expenses for the cooperation between TU Delft and INSA Lyon.

The research is performed within the Dutch 'Kennisprogramma Urban Drainage' (Knowledge Programme Urban Drainage). The involved parties are: ARCADIS, Deltares, Evides, Gemeente Almere, Gemeente Arnhem, Gemeente Breda, Gemeente 's-Gravenhage, Gemeentewerken Rotterdam, Gemeente Utrecht, GMB Rioleringstechniek, Grontmij, KWR Watercycle Research Institute, Royal HaskoningDHV, Stichting RIONED, STOWA, Tauw, vandervalk + degroot, Waterboard De Dommel, Waternet and Witteveen+Bos.

References

Bach, P.M., Rauch, W., Mikkelsen, P.S., McCarthy, D.T., Deletic, A., 2014. A critical review of integrated urban water modelling – Urban drainage and beyond. Environ. Model. Softw. 54, 88–107.

Benedetti, L., Langeveld, J.G., Comeau, A., Corominas, L., Daigger, G., Martin, C., Mikkelsen, P.S., Vezzaro, L., Weijers, S.R., Vanrolleghem, P.A., 2013. Modelling and monitoring of integrated urban wastewater systems: review on status and perspectives. Water Sci. Technol. 68, 1203–1215.

Clemens, F.H.L.R., 2001. Hydrodynamic models in urban drainage: application and calibration. TU Delft.

Coutu, S., Del Giudice, D., Rossi, L., Barry, D.A., 2012. Parsimonious hydrological modeling of

720 urban sewer and river catchments. J. Hydrol. 464-465, 477–484.

721 De Niet, A.C., De Jonge, J., Korving, H., Langeveld, J.G., Van Nieuwenhuijzen, A., 2013. Correctie
722 van neerslagradar op basis van grondstations voor toepassing in stedelijk gebied: het
723 beste van twee werelden. H2O online 1–5.

724 Del Giudice, D., Reichert, P., Bareš, V., Albert, C., Rieckermann, J., 2015. Model bias and
725 complexity – Understanding the effects of structural deficits and input errors on runoff
726 predictions. Environ. Model. Softw. 64, 205–214.

727 Dotto, C.B.S., Kleidorfer, M., Deletic, A., Rauch, W., McCarthy, D.T., 2014. Impacts of measured
728 data uncertainty on urban stormwater models. J. Hydrol. 508, 28–42.

729 Fach, S., Sitzenfrei, R., Rauch, W., 2009. Determining the spill flow discharge of combined
730 sewer overflows using rating curves based on computational fluid dynamics instead of
731 the standard weir equation. Water Sci. Technol. 60, 3035–43.

732 Ferreri, G.F., Freni, G., Tomaselli, P., 2010. Ability of Preissmann slot scheme to simulate
733 smooth pressurisation transient in sewers. Water Sci. Technol. 62, 1848–1858.

734 Keating, E.H., Doherty, J., Vrugt, J.A., Kang, Q., 2010. Optimization and uncertainty assessment
735 of strongly nonlinear groundwater models with high parameter dimensionality. Water
736 Resour. Res. 46, 1–18.

737 Kleidorfer, M., Möderl, M., Fach, S., Rauch, W., 2009. Optimization of measurement campaigns
738 for calibration of a conceptual sewer model. Water Sci. Technol. 59, 1523–30.

739 Korving, H., Clemens, F.H.L.R., 2005. Impact of dimension uncertainty and model calibration on
740 sewer system assessment. Water Sci. Technol. 52, 35–42.

741 Krebs, G., Kokkonen, T., Valtanen, M., Setälä, H., Koivusalo, H., 2014. Spatial resolution
742 considerations for urban hydrological modelling. J. Hydrol. 512, 482–497.

743 Langeveld, J.G., 2004. Interactions within wastewater systems. TU Delft.

744 Langeveld, J.G., Benedetti, L., De Klein, J., Nopens, I., Amerlinck, Y., Van Nieuwenhuijzen, A.,
745 Flameling, T., Van Zanten, O., Weijers, S.R., 2013. Impact-based integrated real-time
746 control for improvement of the Dommel River water quality. Urban Water J. 10, 312–329.

747 Lau, J., Butler, D., Schütze, M., 2002. Is combined sewer overflow spill frequency/volume a
748 good indicator of receiving water quality impact? Urban Water 4, 181–189.

749 Leonhardt, G., Sun, S., Rauch, W., Bertrand-Krajewski, J.-L., 2014. Comparison of two model
750 based approaches for areal rainfall estimation in urban hydrology. J. Hydrol. 511, 880–
751 890.

752 Mair, M., Kleidorfer, M., Rauch, W., 2012. Performance of auto-calibration algorithms in the
753 field of urban drainage modelling, in: Proceedings of UDM9. Belgrade, pp. 1–10.

754 Mannina, G., Viviani, G., 2010. An urban drainage stormwater quality model: Model
755 development and uncertainty quantification. J. Hydrol. 381, 248–265.

756 Meirlaen, J., Huyghebaert, B., Sforzi, F., Benedetti, L., Vanrolleghem, P.A., 2001. Fast,
757 simultaneous simulation of the integrated urban wastewater system using mechanistic
758 surrogate models. Water Sci. Technol. 43, 301–309.

759 Motiee, H., Chocat, B., Blanpain, O., 1997. A storage model for the simulation of the hydraulic
760 behaviour of drainage networks. Water Sci. Technol. 36, 57–63.

761 Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I - A
762 discussion of principles. J. Hydrol. 10, 282–290.

763 Rubinato, M., Shucksmith, J., Saul, A.J., Shepherd, W., 2013. Comparison between InfoWorks
764 hydraulic results and a physical model of an Urban drainage system. Water Sci. Technol.
765 68, 372–379.

766 Sun, S., Bertrand-Krajewski, J.-L., 2012. On calibration data selection: The case of stormwater
767 quality regression models. Environ. Model. Softw. 35, 61–73.

768 Sun, S., Bertrand-Krajewski, J.-L., 2013a. Input variable selection and calibration data selection
769 for storm water quality regression models. Water Sci. Technol. 68, 50–58.

770 Sun, S., Bertrand-Krajewski, J.-L., 2013b. Separately accounting for uncertainties in rainfall and
771 runoff: Calibration of event based conceptual hydrological models in small urban
772 catchments using Bayesian method. Water Resour. Res. 49, 1–14.

773 Vaes, G., Berlamont, J., 1999. Emission predictions with a multi-linear reservoir model. Water
774 Sci. Technol. 39, 9–16.

775 Vaes, G., Willems, P., Berlamont, J., 2001. Rainfall input requirements for hydrological
776 calculations. Urban Water 3, 107–112.

777 Van Bijnen, M., Korving, H., 2008. Application and results of automatic validation of sewer
778 monitoring data, in: Proceedings of ICUD11. Edinburgh, pp. 1–10.

779 Van Daal-Rombouts, P., 2012. Personal communication.

780 Van Daal-Rombouts, P., Tralli, A., Verhaart, F., Langeveld, J.G., Clemens, F.H.L.R., 2014.
781 Applicability of CFD Modelling in Determining Accurate Weir Discharge-Water Level
782 Relationships, in: Proceedings of ICUD13. Sarawak, pp. 1–8.

783 Vrugt, J.A., Ter Braak, C.J.F., Clark, M.P., Hyman, J.M., Robinson, B.A., 2008. Treatment of input
784 uncertainty in hydrologic modeling: Doing hydrology backward with Markov chain Monte
785 Carlo simulation. Water Resour. Res. 44, 1–15.

786 Vrugt, J.A., Ter Braak, C.J.F., Gupta, H.V., Robinson, B.A., 2009. Equifinality of formal (DREAM)
787 and informal (GLUE) Bayesian approaches in hydrologic modeling? Stoch. Environ. Res.
788 Risk Assess. 23, 1011–1026.

789 Wolfs, V., Villazon, M.F., Willems, P., 2013. Development of a semi-automated model
790 identification and calibration tool for conceptual modelling of sewer systems. Water Sci.
791 Technol. 68, 167–175.

792 Wolfs, V., Willems, P., 2014. Development of discharge-stage curves affected by hysteresis
793 using time varying models, model trees and neural networks. Environ. Model. Softw. 55,
794 107–119.

795

796

797 **Table 1.** Sewer system characteristics for Loenen and Waalre.

property	unit	Loenen	Waalre
number of inhabitants	-	2,100	6,200
contributing area	ha	23.4	52.3
average slope ground level	%	0.91	0.14
static storage volume	m^3 - mm	947 - 4.0	2,704 - 5.2
WWF pumping capacity	m^3/h	209	400
number of CSO structures	-	2	2 (incl. 1 SST)
length of conduits	km	12.3	27.6

798

799 **Table 2.** Calibration parameters with searching range.

parameter	abbreviation	unit	searching range
initial rainfall loss	I_{ini}	mm	0 - 4
proportional rainfall loss	P_{cons}	-	0 - 1
lag time	T_{lag}	min	0 - 120
reservoir constant	K	min	0 - 240

800

801 **Table 3.** Selected rain events with key characteristics.

catchment area	event [dd-mm-yyyyy]	rainfall depth [mm]	max rain intensity [mm/h]	duration [hh:mm]	discharge to surface water [y/n]
Loenen	30-06-2001	9.9	24.8	6:12	y
	18-07-2001	13.9	25.4	14:36	y
	19-07-2001	12.2	34.0	12:15	n
	23-07-2001	12.3	19.4	7:48	y
	27-08-2001	17.0	24.0	7:45	y
	23-10-2001	7.4	6.0	7:39	n
Waalre	29-04-2011	6.5	5.2	6:20	n
	14-08-2011	27.0	23.4	10:35	y
	18-08-2011	12.0	14.9	7:20	n
	22-08-2011	39.2	68.8	23:04	y
	14-12-2011	15.4	11.9	23:31	y
	16-12-2011	33.4	8.5	22:15	y

802

803 **Table 4.** FPs and FNs for all 6 events for each model structure and scenario based on the
804 optimal parameter sets. The results for scenario 3 have been averaged over all combinations
805 and multiplied by two for easy comparison.

scenario	1: individual events		2: all events together		3: 3 events calibration, 3 verification			
					calibration		verification	
catchment / model structure	total FP	total FN	total FP	total FN	mean FP	mean FN	mean FP	mean FN
Loenen								
M1	2	0	2	0	2.0	0.0	2.0	0.0
M2	1	0	0	0	1.0	0.0	1.0	0.0
M3	0	0	0	0	0.0	0.0	0.0	0.0
FH			1	0				
Waalre								
M1	2	0	2	0	2.0	0.0	1.9	0.0
M2	0	1	1	0	0.4	0.2	0.6	0.1
M3	0	1	1	0	0.4	0.2	0.6	0.1
FH			0	0				

806

807

Table 5. RMSE for V_{SW} and V_{WWTP} for all 6 events for each model structure and scenario (1: individual events, 2: all events together, 3: calibrate and verify on 3 events each) based on the optimal parameters sets.

	RMSE [m^3]							
	V_{SW}				V_{WWTP}			
catchment / model structure	1	2	3 calibra-tion	3 verifica-tion	1	2	3 calibra-tion	3 verifica-tion
Loenen								
M1	112	150	147	178	445	242	248	255
M2	416	197	346	364	67	150	135	158
M3	57	145	94	125	124	143	133	132
FH		661				399		
Waalre								
M1	3,470	2,469	2,448	2,157	3,072	2,075	2,307	2,240
M2	5,202	967	2,593	2,212	422	1,331	995	1,330
M3	5,398	1,480	2,788	2,487	556	1,346	1,027	1,354
FH		2,658				619		

Highlights

1 • Design of simplified static and dynamic reservoir models for pumped sewer systems.

2 • Performance evaluation on CSO event occurrences and total discharged volumes.

3 • Static and dynamic models can describe behaviour of pumped sewer systems.

4 • Best performing model depends on quality of information for design and calibration.

5 • Calibrated simplified models outperform uncalibrated FH models.

Figure captions

Figure 1. Sewer system layout for Loenen (left) and Waalre (right). Monitoring locations and locations of pumping stations and CSOs are indicated. Line colour and width indicate pipe diameter ranges: >= 1500 mm (thick black), >= 1000 (black), >= 600 (thick grey), >= 400 (grey) and < 400 mm (light grey).

Figure 2. Daily DWF profiles per person for Loenen and Waalre.

Figure 3. The three simplified models M1-M3 convert the three inputs to two discharges to the surface water (Q_{SW}) and the WWTP (Q_{WWTP}). RRO: rainfall runoff outflow, SR: static reservoir, DR: dynamic reservoir.

Figure 4. The output of the RRO model is split into Q_{SW} and Q_{WWTP} based on the maximum pumping capacity of the catchment (209 m^3/h for Loenen).

Figure 5. Schematic representation of the SR model for Loenen. Applied characteristics or relationships as displayed in graphs SR1-SR3 are elaborated upon in the main text.

Figure 6. Schematic representation of the SR model for Waalre. Applied characteristics or relationships as displayed in graphs SR4-SR10 are elaborated upon in the main text.

Figure 7. Schematic representation of the DR model for Loenen. Applied characteristics or relationships as displayed in graphs DR1-DR4 are elaborated upon in the main text.

Figure 8. Hybrid storage-level curve (left) and derivation of the dynamic storage-level curve from the FH model simulation results (right) for Loenen.

Figure 9. Schematic representation of the DR model for Waalre. Applied characteristics or relationships as displayed in graphs DR5-DR13 are elaborated upon in the main text.

Figure 10. Hybrid storage-level curve (left) and derivation of the dynamic storage-level curve from the FH model simulation results (right) for Waalre.

Figure 11. Results for the individual calibration of rain event 2001-08-27 for all model structures for Loenen.

Figure 12. Results for the individual calibration of rain event 2011-08-14 for all model structures for Waalre.

Figure 13. Optimal parameter values for scenarios 1 (individual calibrated events (asterisks)) and scenario 2 (all events together (line)) for Loenen (left) and Waalre (right). The horizontal axis presents event numbers. Please note the changing scale for T_{lag} and K.

Figure 14. Optimal parameter values for scenario 3 for Loenen (left) and Waalre (right). The horizontal axis presents the 20 possible combinations to take 3 events from 6. Please note the changing scale for T_{lag} and K.

Figure 15. Q_{SW} and Q_{WWTP} for the individually calibrated event of 2001-08-27 for Loenen.

Figure 16. Q_{SW} and Q_{WWTP} for the individually calibrated event of 2011-08-14 for Waalre.

Figure 17. V_{SW} with 95% confidence bands for all events and each model structure for Loenen. For scenarios 1 (individual events, top) and 2 (all events together, bottom). The horizontal axis presents event numbers.

Figure 18. V_{SW} with 95% confidence bands for all events and each model structure for Waalre. For scenarios 1 (individual events, top) and 2 (all events together, bottom). The horizontal axis presents event numbers.