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

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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

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). 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 (Liefing, 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:

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

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 m³/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} [m³/s], h [m] water level above the weir crest, c_1 [m^{3-c₂}/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} [m³/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/s²]. Submerged

outflow is assumed to occur when $\frac{2}{3} \cdot h_{US} < h_{DS}$. 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 m³/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 [$\text{m}^{1/2}/\text{s}$] 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_5 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 below:

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

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

330 DR3. Discharge through pump
 331 See SR2.

332 DR4. Discharge through CSO
 333 See SR3, only now H_{CSO} is applied.
 334

335 A schematic representation of the DR model for Waalre is shown in figure 9 and can be
 336 compared to the SR model in figure 6. Differences are expressed in the storage-level curve
 337 applied (DR5-SR4), the water level applied in the CSO discharge (DR6-no equivalent in the SR
 338 model) and the water level applied in and the calculation of the flow through the connection
 339 (DR7-no equivalent in SR model, DR9-SR6).
 340

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

343 DR5. Hybrid storage-level curve sewer
 344 A hybrid storage-level curve is used to convert V_s into H_s . The derivation follows DR1.
 345 The resulting curves for Waalre are displayed in Figure 10: (left) the static, dynamic,
 346 and hybrid storage curves, (right) the derivation of the dynamic storage-level curve
 347 from the FH model simulation results.

348 DR6. Level sewer at CSO
 349 Similar to DR2, a relationship has been derived between H_{CSO} and H_s . As Waalre is
 350 equipped with the settling tank two linear segments that connect at the highest weir
 351 crest level of the settling tank have been applied. Only elevated water levels (WWF
 352 conditions) are taken into account.

353 DR7. Level sewer at connection

354 Similar to H_{CSO} in DR6, a relationship between the water level at the connection to the

355 neighbouring catchment (H_{CONN}) and H_s is derived from the FH model simulations. A

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

357 account.

358 DR8. Discharge sewer through pump

359 See SR5.

360 DR9. Discharge sewer through connection

361 The discharge of the sewer through the connection to the neighbouring catchment

362 (Q_{CONN}) is based on H_{CONN} and a relationship derived from the FH model simulations.

363 The simulated water levels at the connection and the corresponding flow through the

364 connection were fitted with a third order polynomial equation. To prevent unrealistic

365 (negative) output a maximum value is set for H_{CONN} .

366 DR10. Discharge sewer through CSO

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

368 DR11. Static storage-level curve settling tank

369 See SR8.

370 DR12. Discharge settling tank through pump

371 See SR9.

372 DR13. Discharge settling tank

373 See SR10.

374 **2.5. Calibration procedure**

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

2.5.2. Parameter optimisation

The DREAM algorithm is applied to calibrate the parameters of the RRO model to find the minimal difference between the simplified model output and the measurements. Table 2 shows the parameters, units and the searching range for the calibration procedure.

The algorithm minimises the sum of squared errors (SSE) between the model output and measurements. Water level measurements are applied in the calibration as they are the actual 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

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

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.

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

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

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

favoured when high quality information is available (in this case Loenen), while the less detailed model M2, RRO with SR, suffices when the information is of lower quality (Waalre).

One main source of uncertainty for Waalre likely stems from the calibrated rain radar input. The rainfall in general seems reasonable with NS values for M2 or M3 > 0.6. In detail the rainfall seems off in intensities and/or timing, an example of which can be found in figure 16. Judging from the rainfall, the models responses in Q_{SW} are in accordance (main peak in the outflow after main peak in the rainfall). However, in the measurements the main peak in the outflow occurs right at the beginning of the rain event. The other events display a similar mismatch between the rainfall and the outflow. This may also explain the very low values for the parameters T_{lag} and K , see figure 13, as the calibration procedure tries to correct the mismatch in the input data.

For V_{WWTP} the RMSE values in table 5 show that model M1 consistently performs worse than M2 and M3 for all scenarios and both catchments. M2 and M3 generally perform on a similar level, which is to be expected as the pumping regime in the SR and DR model structures is the same.

The NS values reported in section 3.1 are based on the calibration parameters for each time step, and the FP/FN in table 4 and RMSE in table 5 on V_{SW} . Each presents information on the performance of the model structure. NS indicates the quality of the description of the sewer systems behaviour in general, while the others are specific for CSO discharges. The difference between the best performing model structure based on these criteria, especially for Loenen, is striking. Model M2 and M3 have similar NS values > 0.9, but M3 is much more accurate 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.

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

658

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

683 multiple indicators, each one providing a specific approach of the models’
 684 performances.

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

696

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

702

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

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

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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

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). 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 (Liefing, 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:

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

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 m³/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} [m³/s], h [m] water level above the weir crest, c_1 [m^{3-c₂}/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} [m³/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/s²]. Submerged

outflow is assumed to occur when $\frac{2}{3} \cdot h_{US} < h_{DS}$. 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 m³/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 [$\text{m}^{1/2}/\text{s}$] 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_5 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 below:

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

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

330 DR3. Discharge through pump
 331 See SR2.

332 DR4. Discharge through CSO
 333 See SR3, only now H_{CSO} is applied.
 334

335 A schematic representation of the DR model for Waalre is shown in figure 9 and can be
 336 compared to the SR model in figure 6. Differences are expressed in the storage-level curve
 337 applied (DR5-SR4), the water level applied in the CSO discharge (DR6-no equivalent in the SR
 338 model) and the water level applied in and the calculation of the flow through the connection
 339 (DR7-no equivalent in SR model, DR9-SR6).
 340

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

343 DR5. Hybrid storage-level curve sewer
 344 A hybrid storage-level curve is used to convert V_s into H_s . The derivation follows DR1.
 345 The resulting curves for Waalre are displayed in Figure 10: (left) the static, dynamic,
 346 and hybrid storage curves, (right) the derivation of the dynamic storage-level curve
 347 from the FH model simulation results.

348 DR6. Level sewer at CSO
 349 Similar to DR2, a relationship has been derived between H_{CSO} and H_s . As Waalre is
 350 equipped with the settling tank two linear segments that connect at the highest weir
 351 crest level of the settling tank have been applied. Only elevated water levels (WWF
 352 conditions) are taken into account.

353 DR7. Level sewer at connection

354 Similar to H_{CSO} in DR6, a relationship between the water level at the connection to the

355 neighbouring catchment (H_{CONN}) and H_s is derived from the FH model simulations. A

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

357 account.

358 DR8. Discharge sewer through pump

359 See SR5.

360 DR9. Discharge sewer through connection

361 The discharge of the sewer through the connection to the neighbouring catchment

362 (Q_{CONN}) is based on H_{CONN} and a relationship derived from the FH model simulations.

363 The simulated water levels at the connection and the corresponding flow through the

364 connection were fitted with a third order polynomial equation. To prevent unrealistic

365 (negative) output a maximum value is set for H_{CONN} .

366 DR10. Discharge sewer through CSO

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

368 DR11. Static storage-level curve settling tank

369 See SR8.

370 DR12. Discharge settling tank through pump

371 See SR9.

372 DR13. Discharge settling tank

373 See SR10.

374 **2.5. Calibration procedure**

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

2.5.2. Parameter optimisation

The DREAM algorithm is applied to calibrate the parameters of the RRO model to find the minimal difference between the simplified model output and the measurements. Table 2 shows the parameters, units and the searching range for the calibration procedure.

The algorithm minimises the sum of squared errors (SSE) between the model output and measurements. Water level measurements are applied in the calibration as they are the actual 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

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

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.

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

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

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

favoured when high quality information is available (in this case Loenen), while the less detailed model M2, RRO with SR, suffices when the information is of lower quality (Waalre).

One main source of uncertainty for Waalre likely stems from the calibrated rain radar input. The rainfall in general seems reasonable with NS values for M2 or M3 > 0.6. In detail the rainfall seems off in intensities and/or timing, an example of which can be found in figure 16. Judging from the rainfall, the models responses in Q_{sw} are in accordance (main peak in the outflow after main peak in the rainfall). However, in the measurements the main peak in the outflow occurs right at the beginning of the rain event. The other events display a similar mismatch between the rainfall and the outflow. This may also explain the very low values for the parameters T_{lag} and K , see figure 13, as the calibration procedure tries to correct the mismatch in the input data.

For V_{WWTP} the RMSE values in table 5 show that model M1 consistently performs worse than M2 and M3 for all scenarios and both catchments. M2 and M3 generally perform on a similar level, which is to be expected as the pumping regime in the SR and DR model structures is the same.

The NS values reported in section 3.1 are based on the calibration parameters for each time step, and the FP/FN in table 4 and RMSE in table 5 on V_{sw} . Each presents information on the performance of the model structure. NS indicates the quality of the description of the sewer systems behaviour in general, while the others are specific for CSO discharges. The difference between the best performing model structure based on these criteria, especially for Loenen, is striking. Model M2 and M3 have similar NS values > 0.9, but M3 is much more accurate 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.

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

658

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

683 multiple indicators, each one providing a specific approach of the models’
 684 performances.

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

696

697 Future research is recommended in the area of statistical substantiation of the results as the
 698 available data sets were too limited to allow a statistical analysis of the results themselves.

699 Also the use of continuous data sets instead of the current intermittent ones would be
 700 interesting because more information on the initial conditions prior to events would be
 701 included.

702

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

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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	event	rainfall depth	max rain	duration	discharge to
area			intensity		surface water
	[dd-mm-yyyyy]	[mm]	[mm/h]	[hh:mm]	[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			
catchment / model structure	total		total		calibration		verification	
	FP	FN	FP	FN	FP	FN	FP	FN
	FP	FN	FP	FN	FP	FN	FP	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.

catchment / model structure	RMSE [m ³]							
	V _{SW}				V _{WWTP}			
			3	3			3	3
	1	2	calibra- tion	verifica- tion	1	2	calibra- tion	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 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 ($209 \text{ m}^3/\text{h}$ 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.

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

54

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

Figure 1 - left

secondary CSO level measurement

pumping station flow measurement

primary CSO level measurement



Figure 1 - right

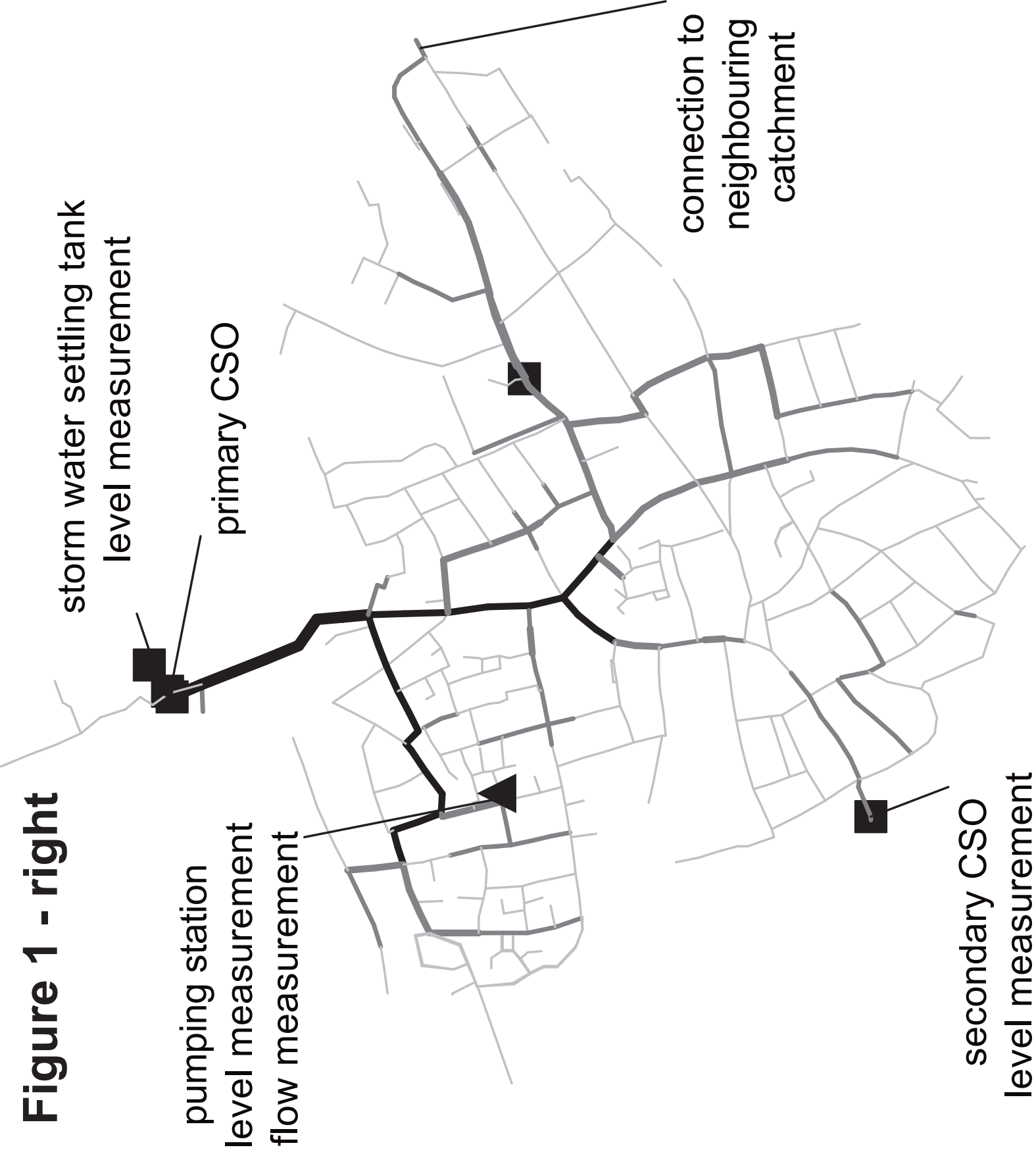


Figure 2

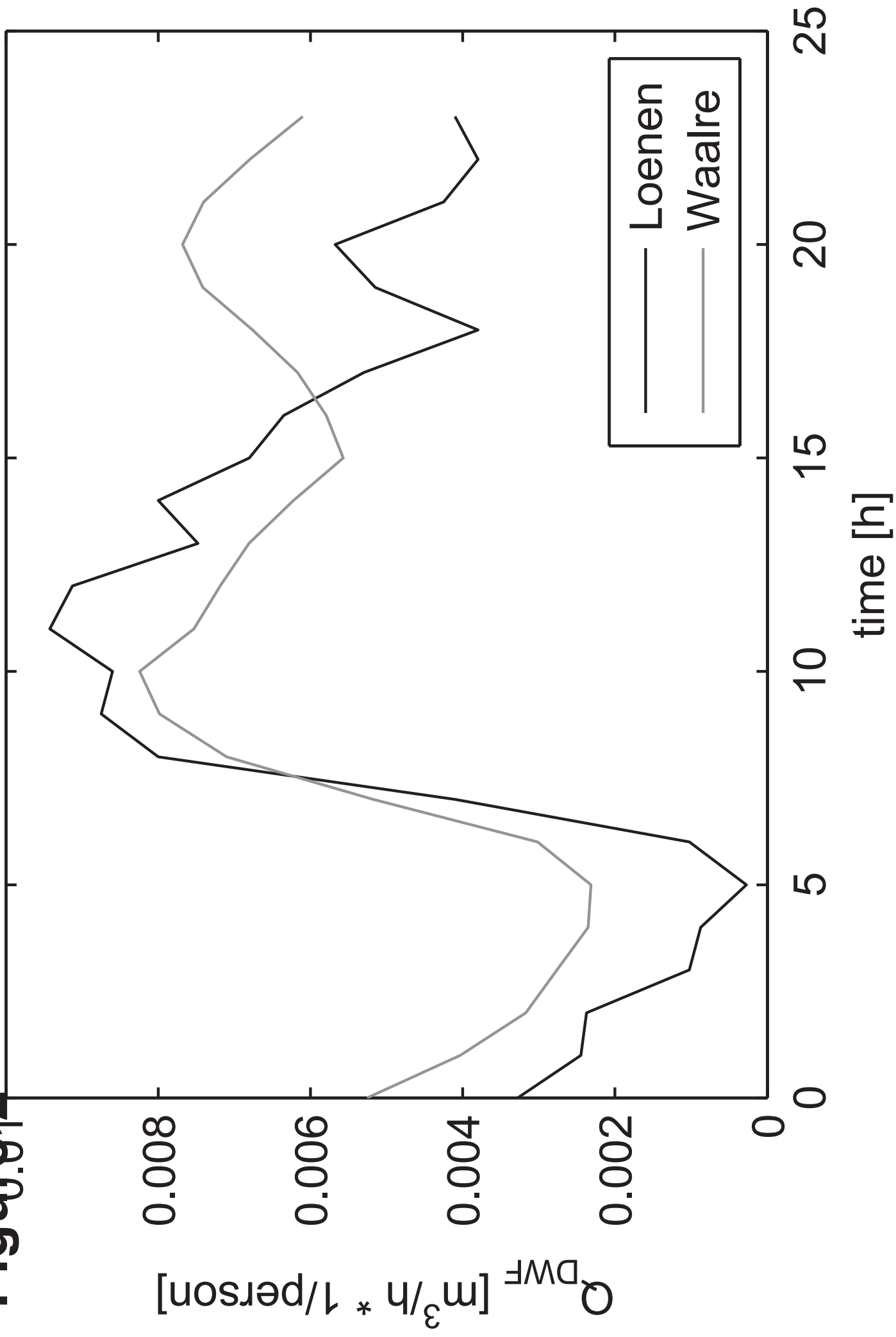


Figure 3

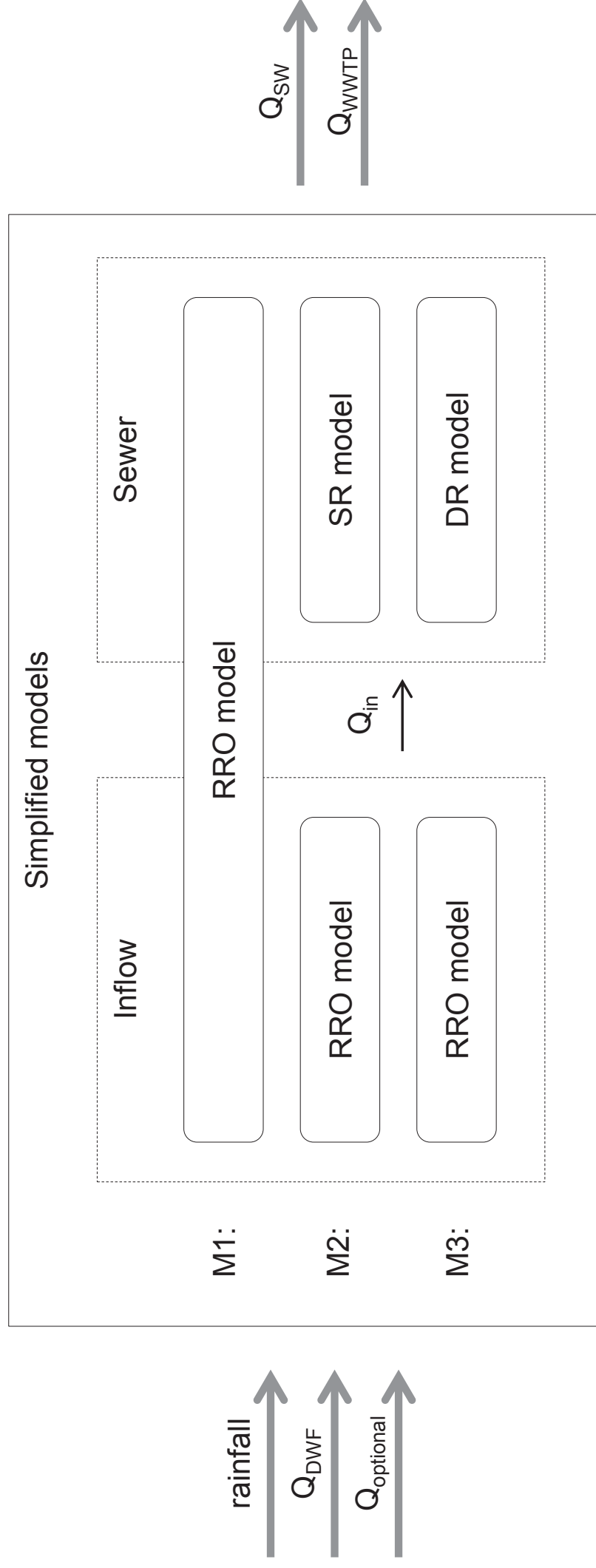


Figure 4

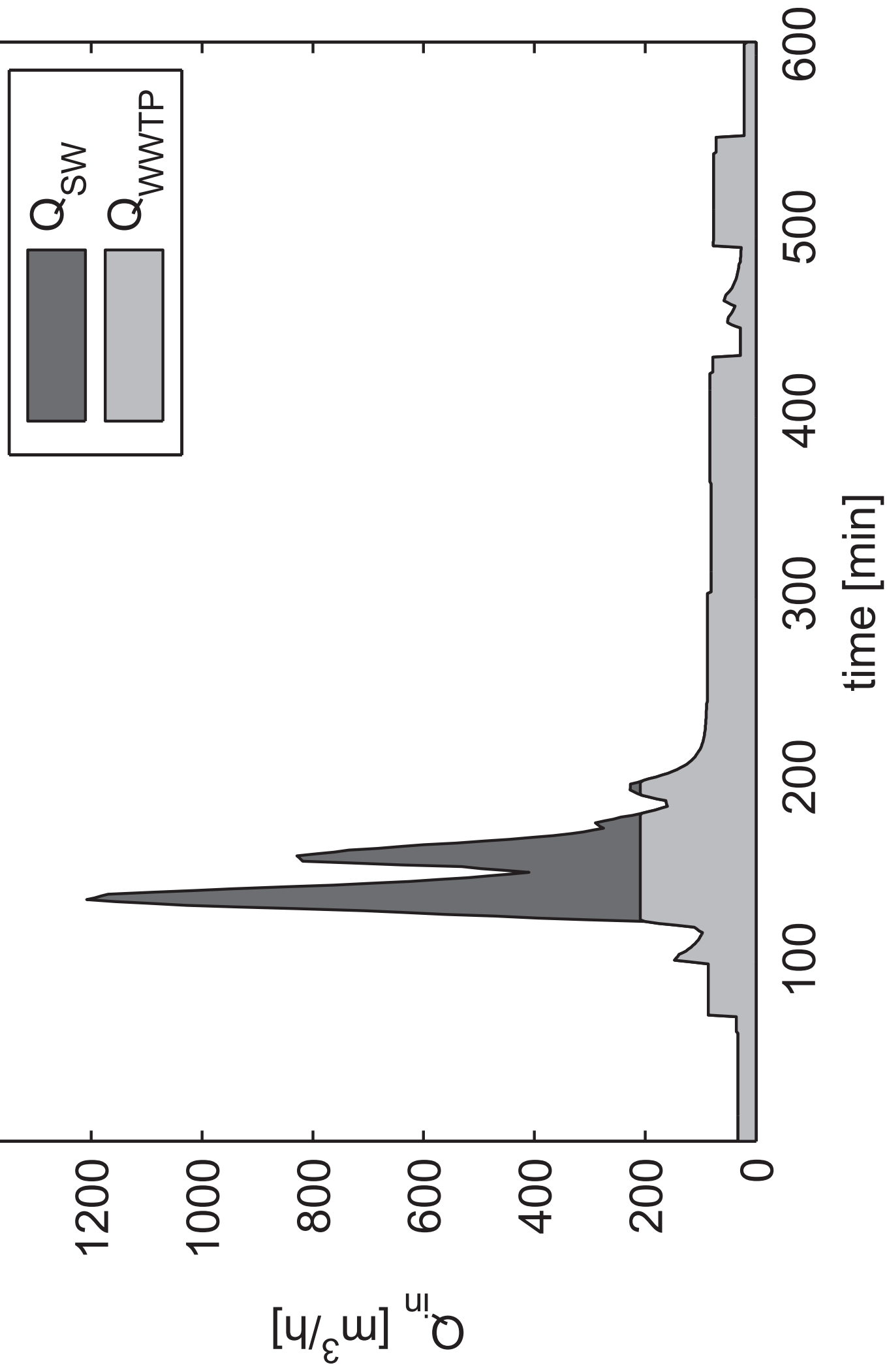


Figure 5 - total SR model Loenen with graphs SR1-SR3

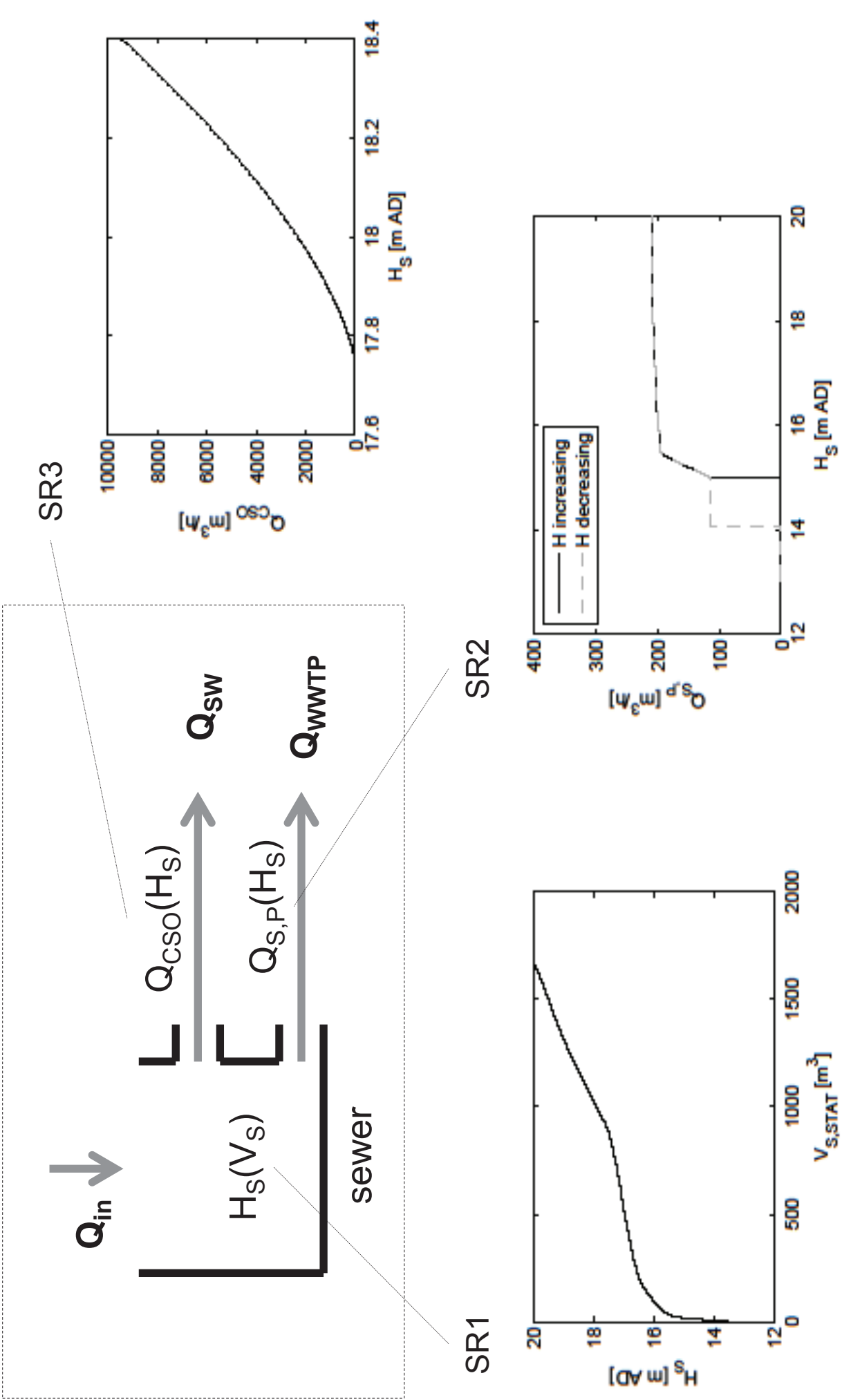


Figure 5 - high res SR1

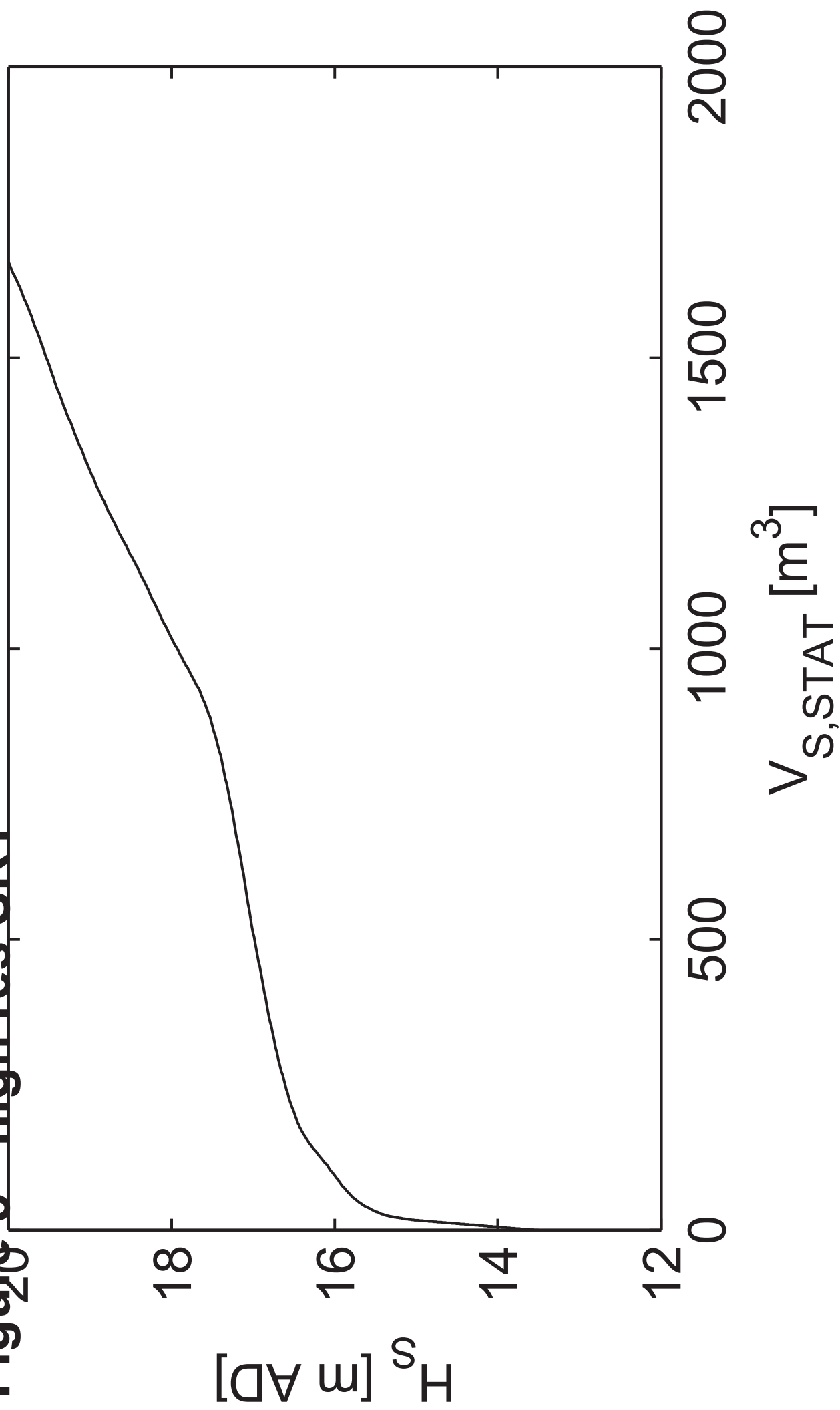


Figure 5 - high res SR2

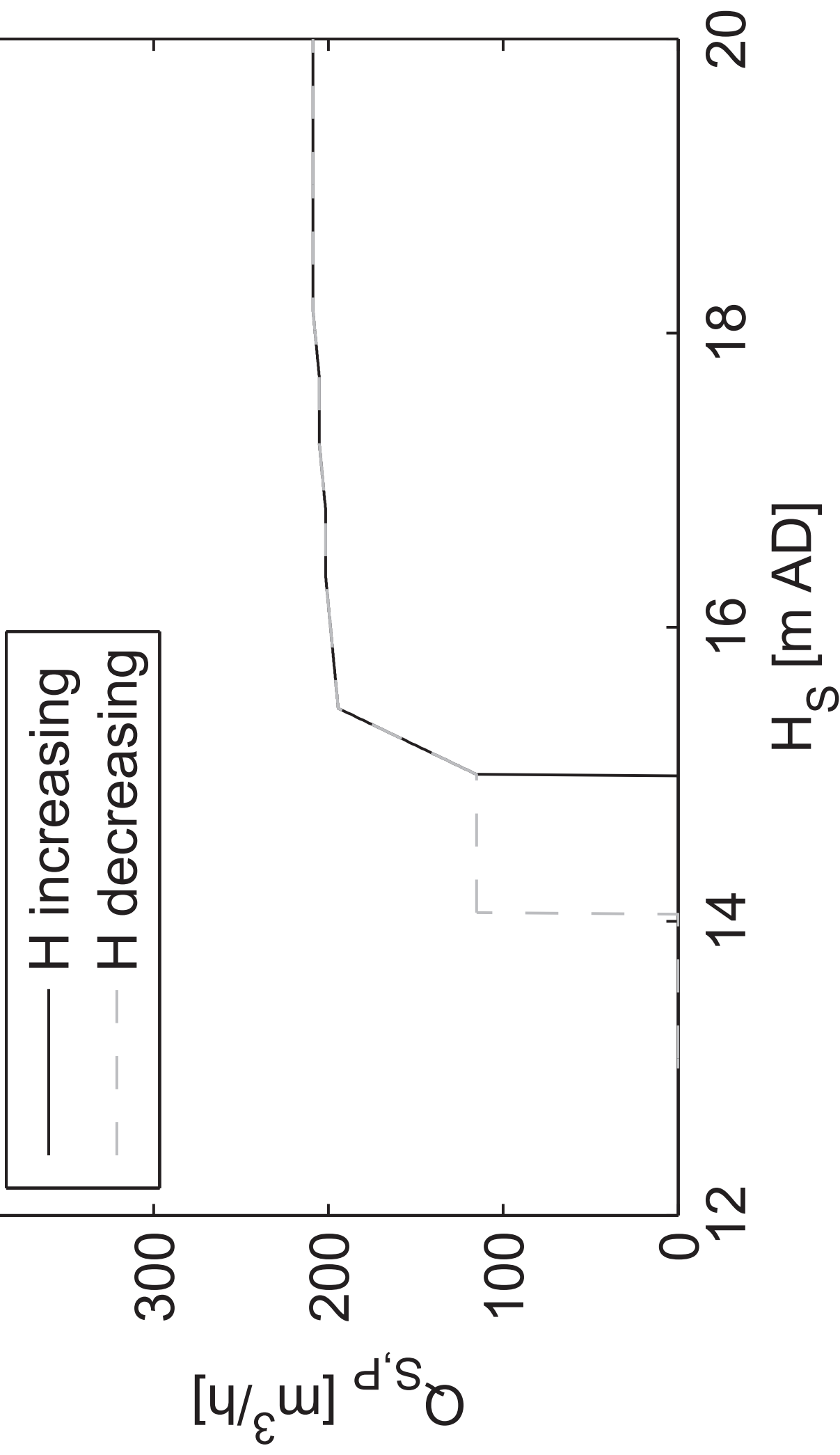


Figure 5 high res SR3

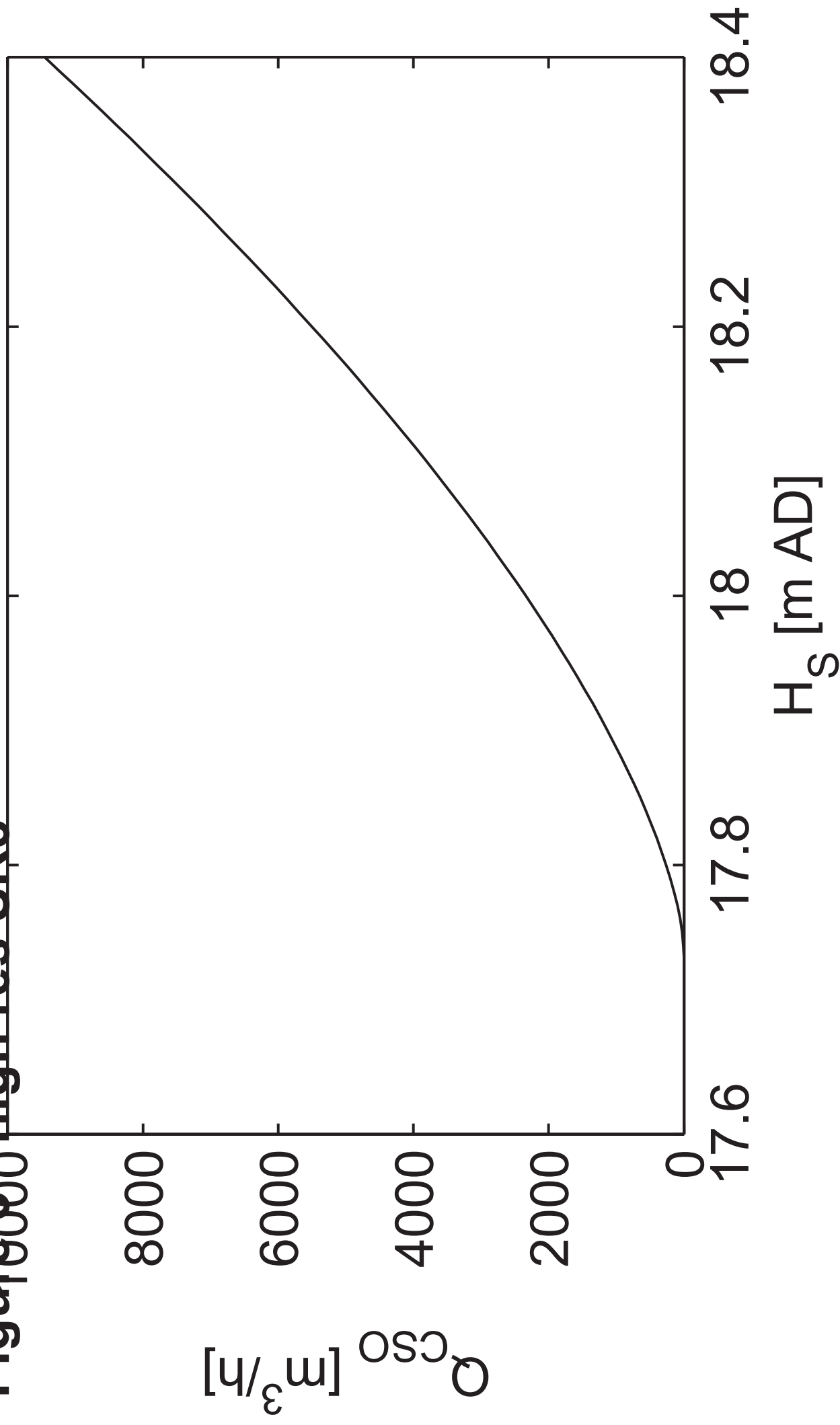


Figure 6 - total SR model Waalre with graphs SR4-SR10

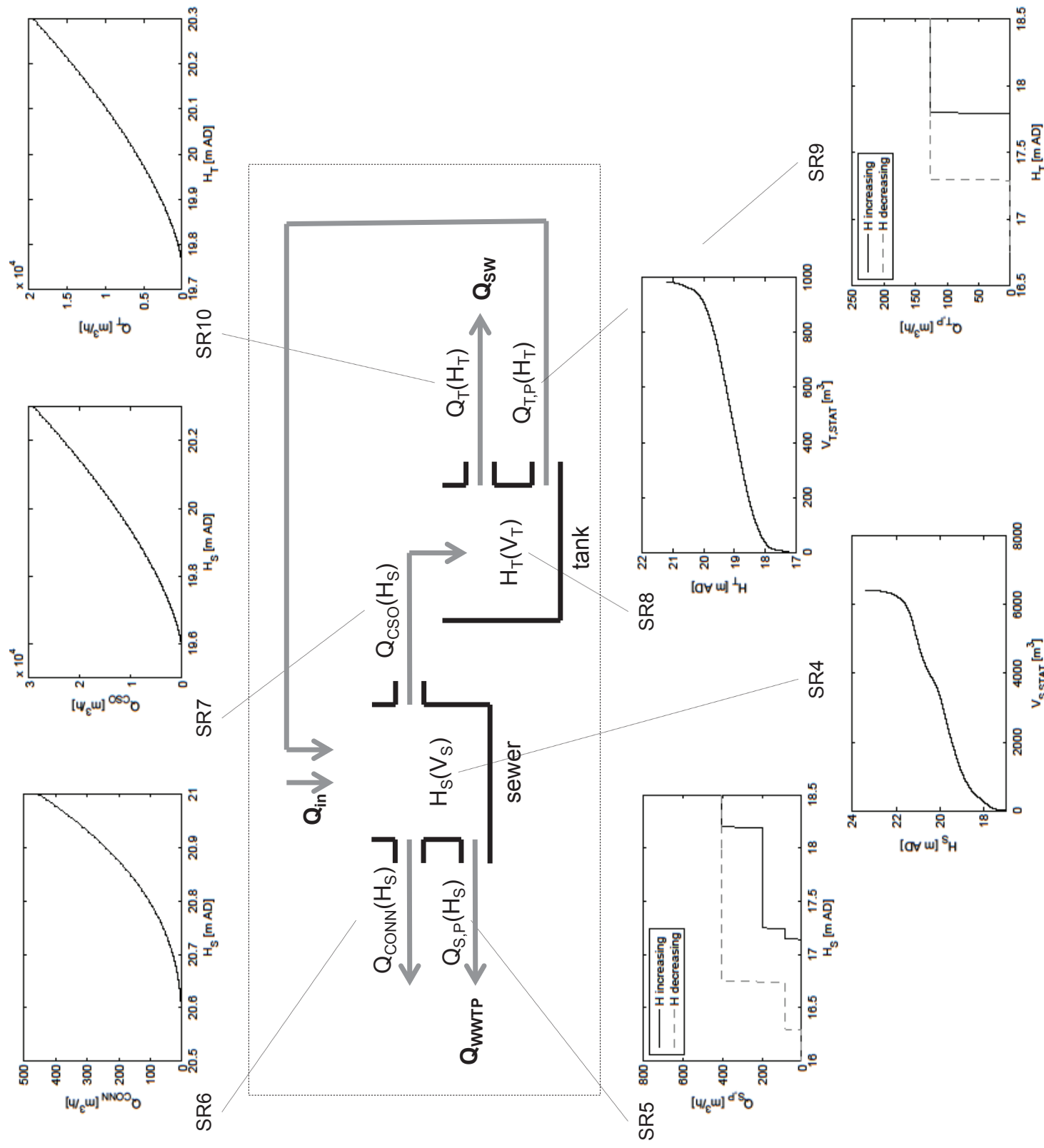


Figure 6 - high res SR4

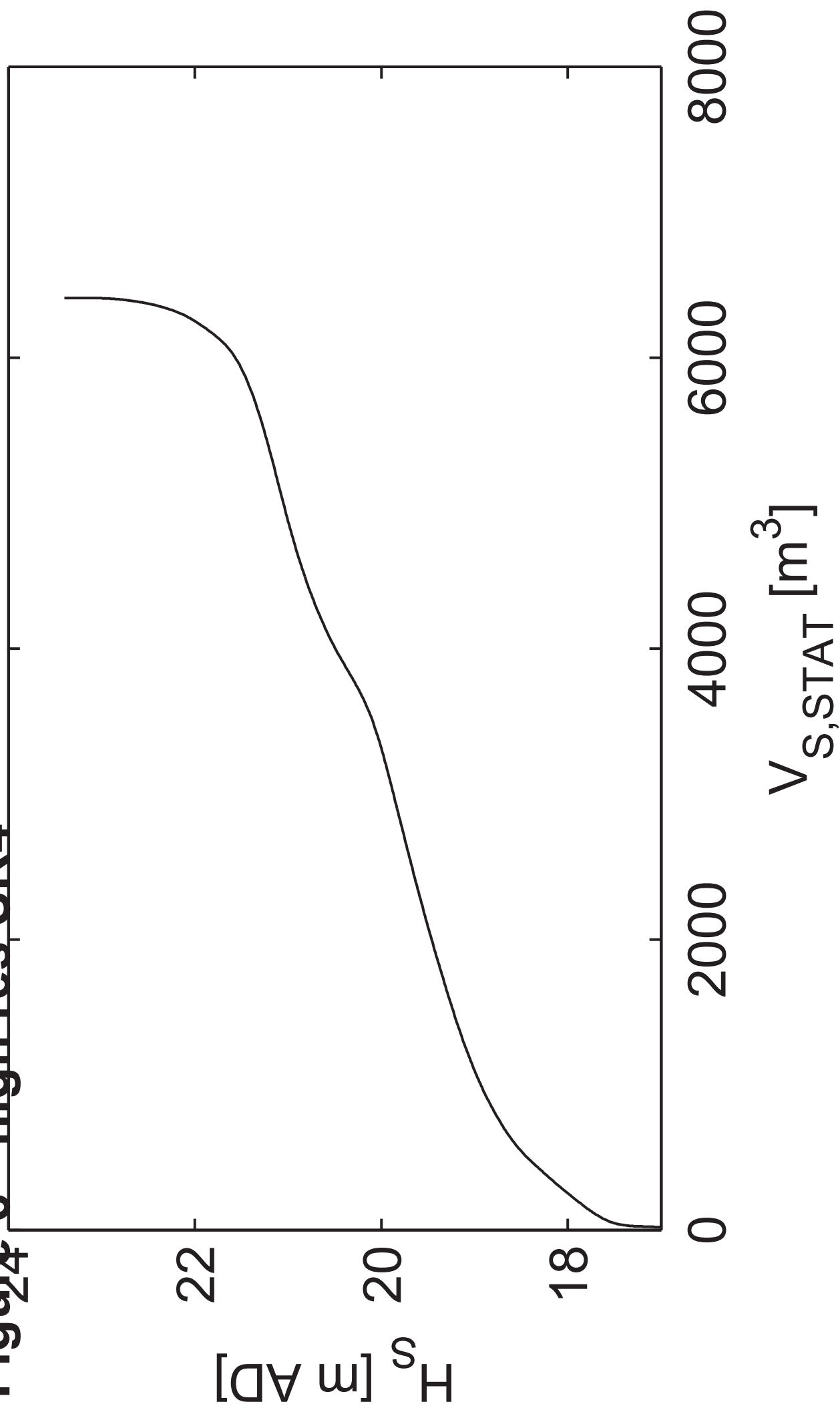


Figure 6 - high res SR5

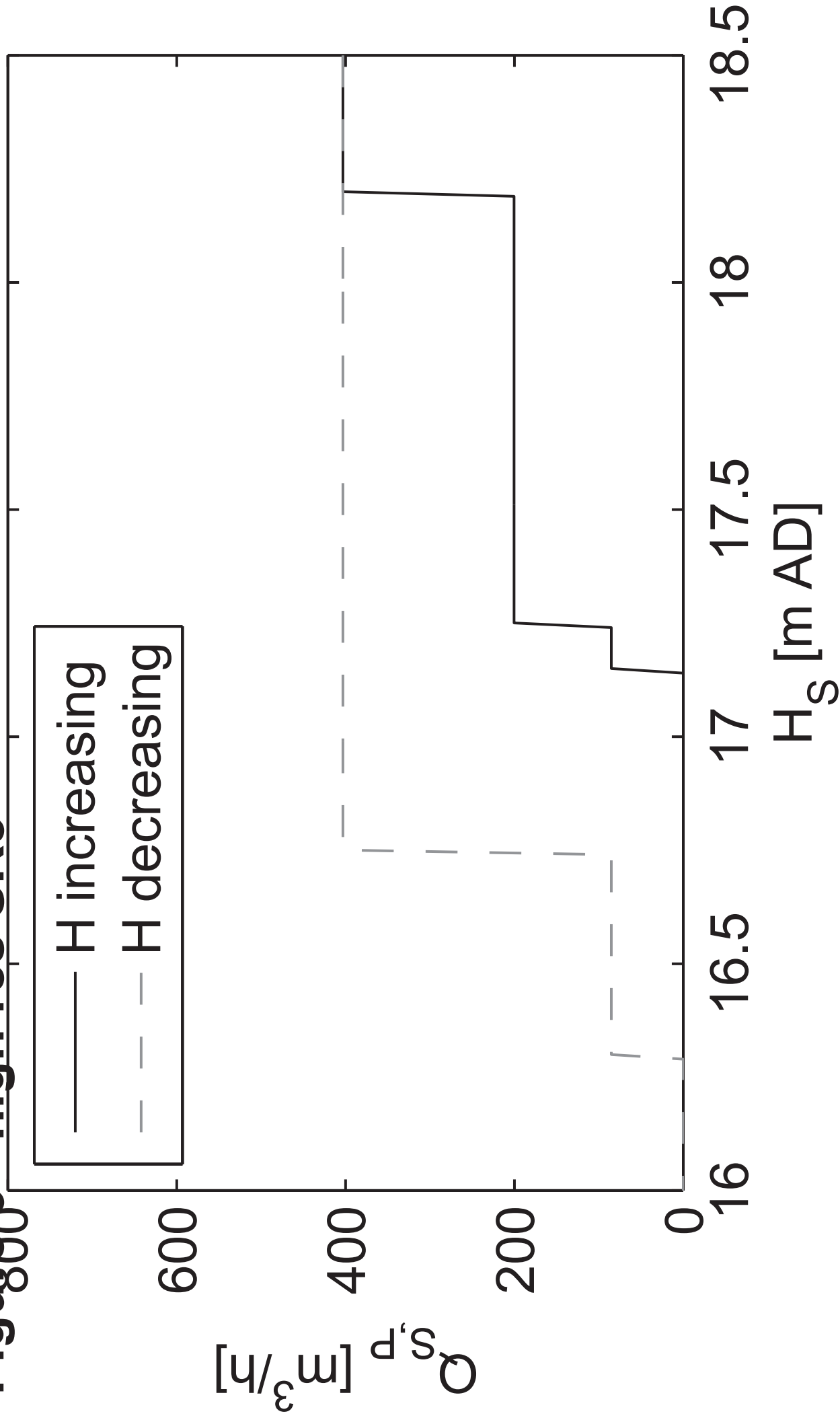


Figure 6 - high res SR6

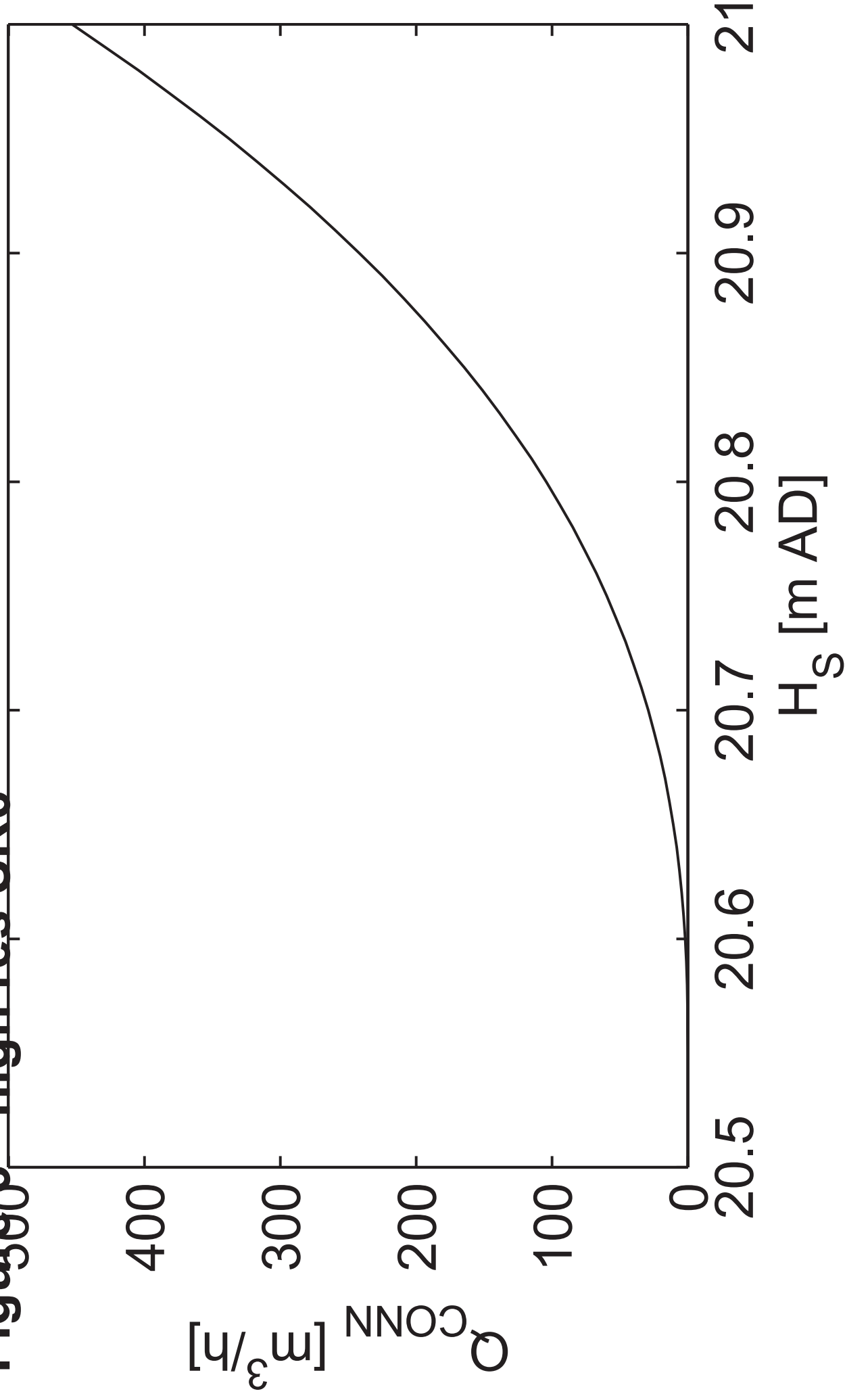


Figure 6-10⁴ high res SR7

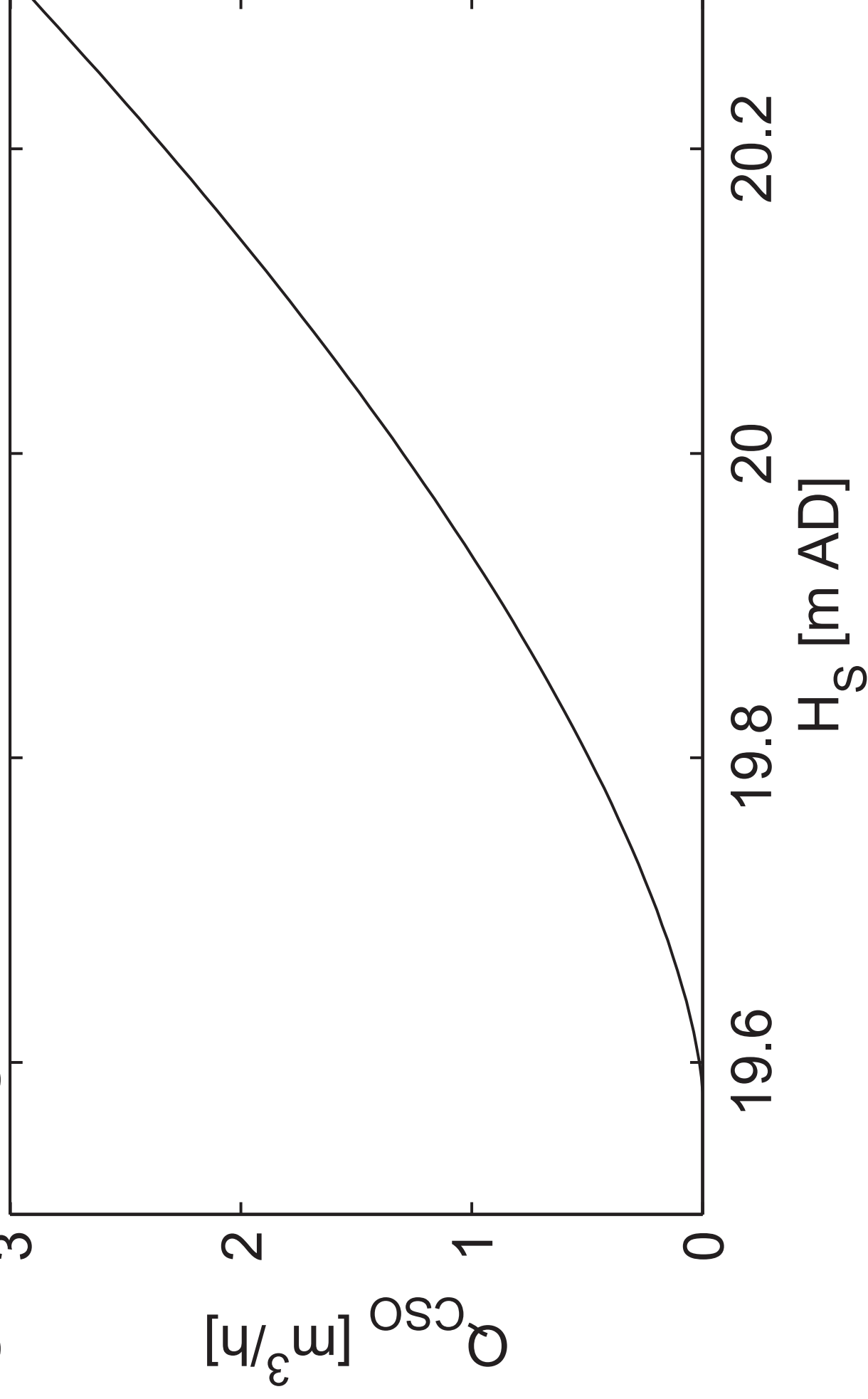


Figure 6 - high res SR8

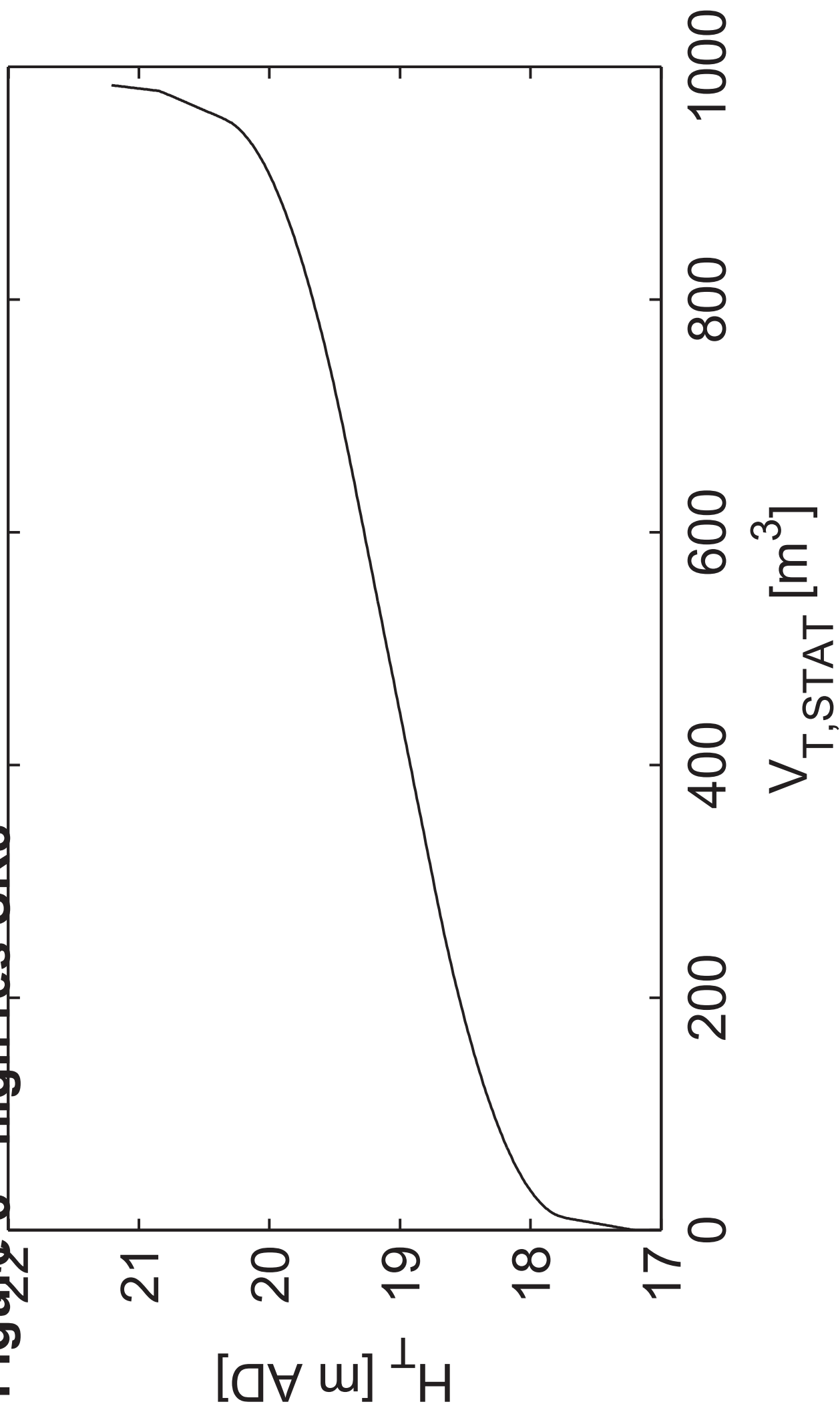


Figure 506 - high res SR9

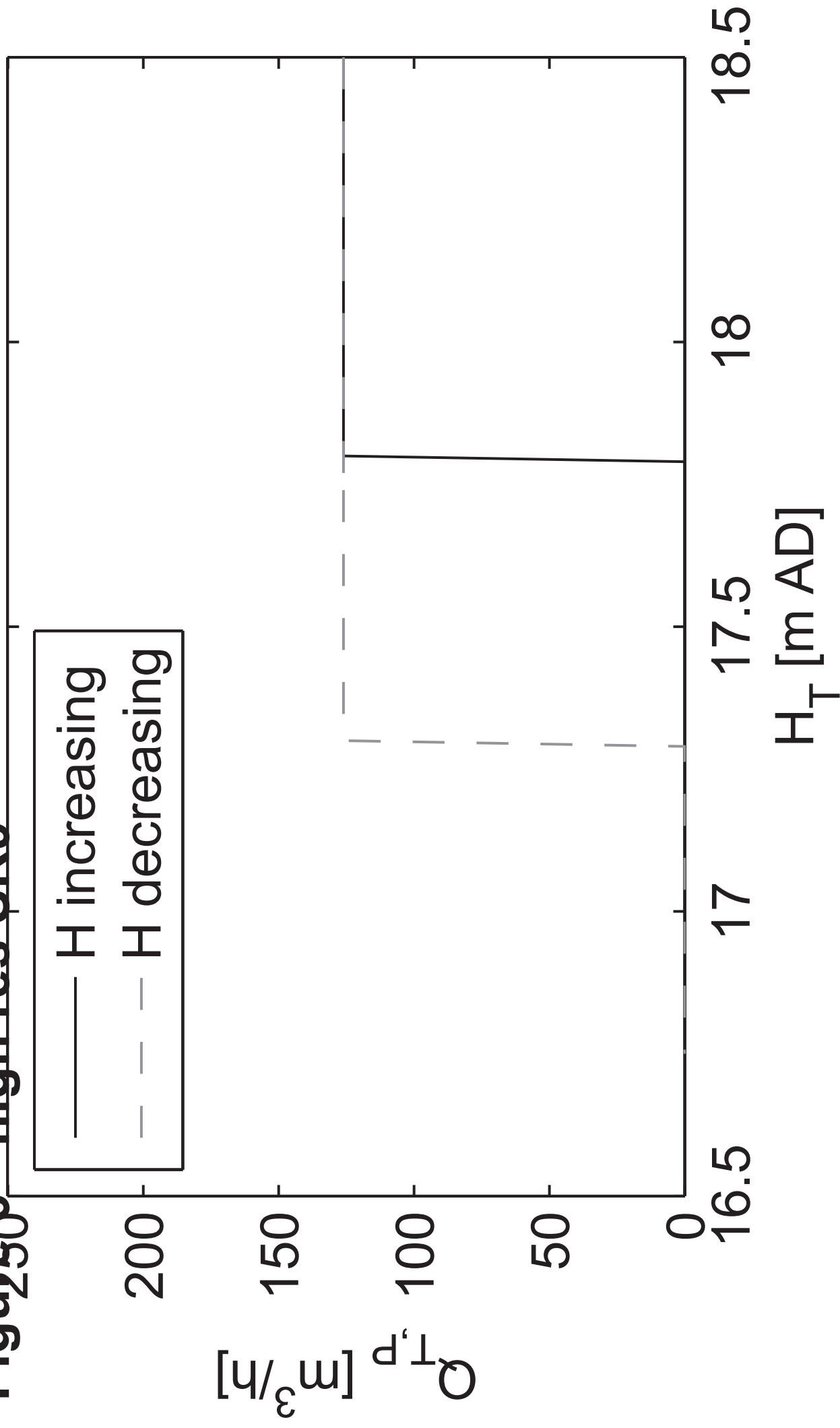


Figure 6-10⁴ high res SR10

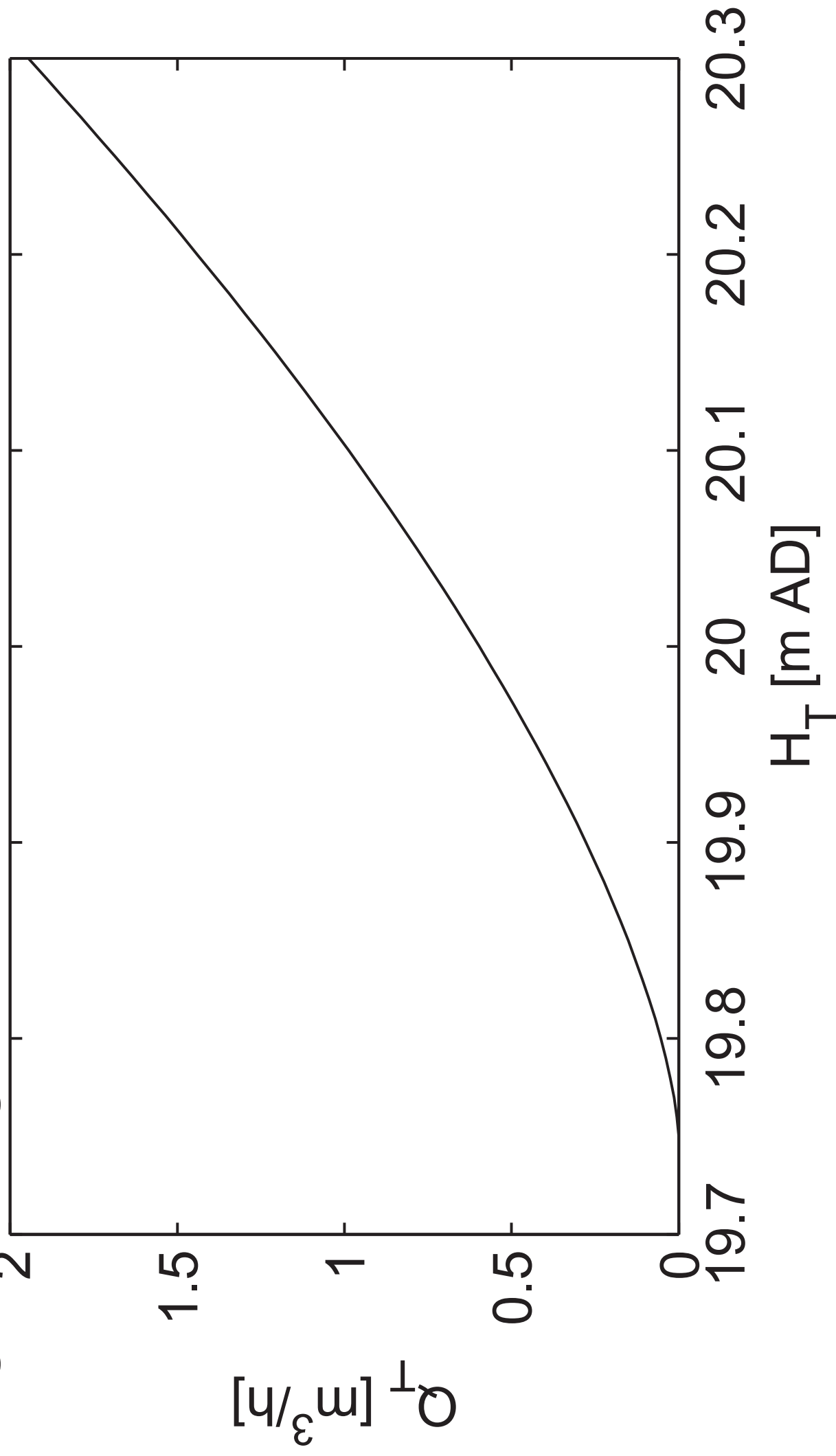


Figure 7 - total DR model Loenen with graphs DR1-DR4

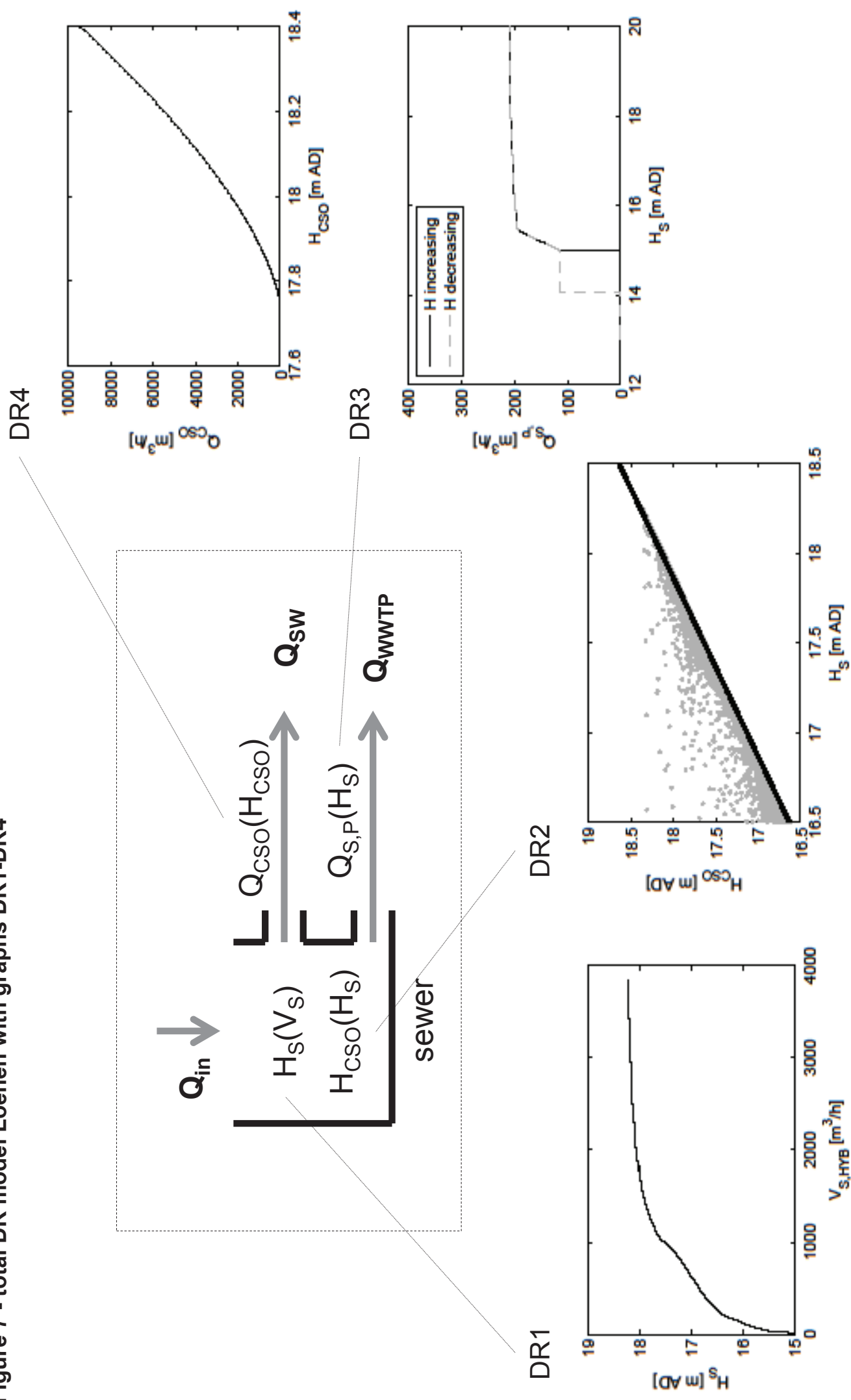


Figure 7 - high res DR1

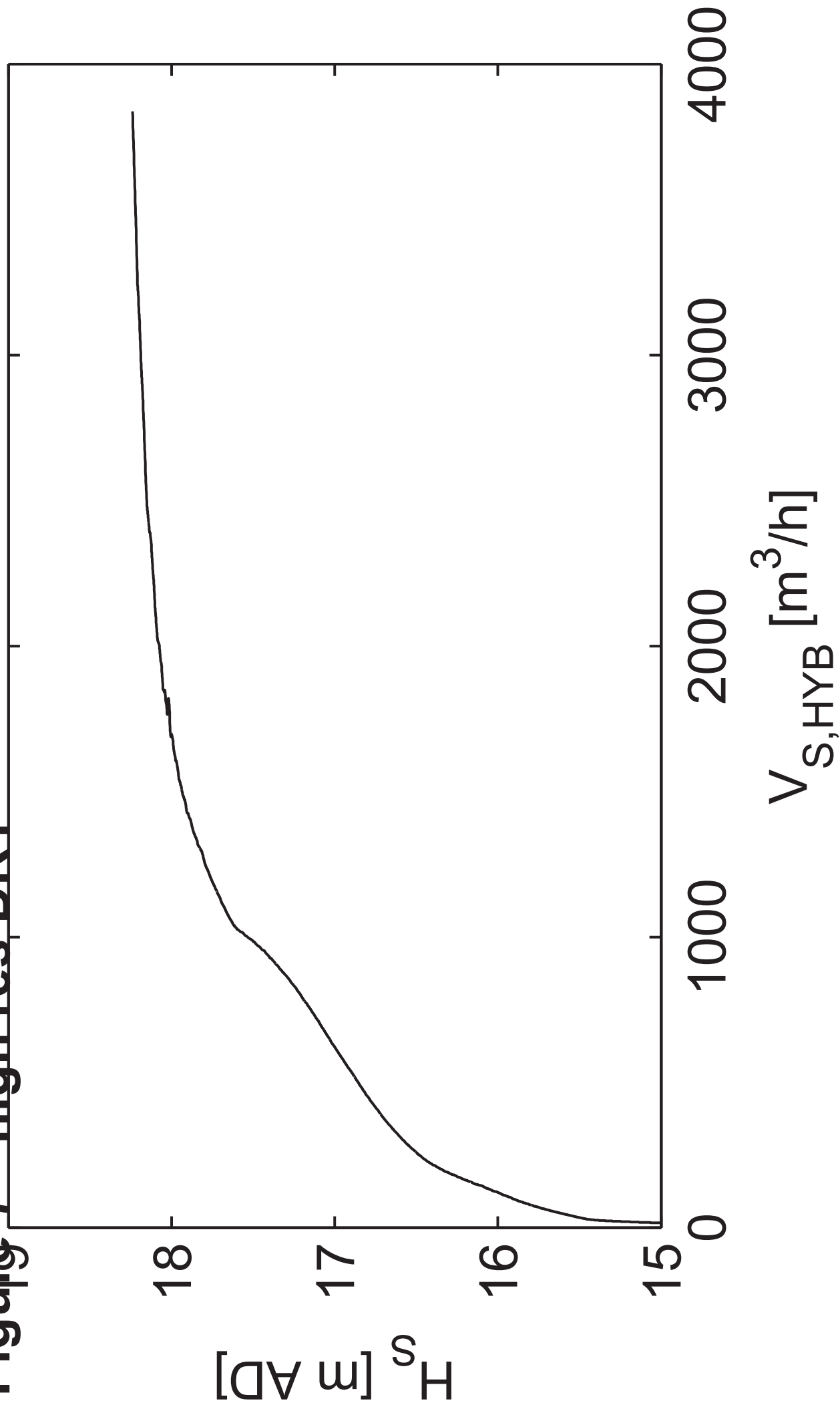


Figure 7 - high res DR2

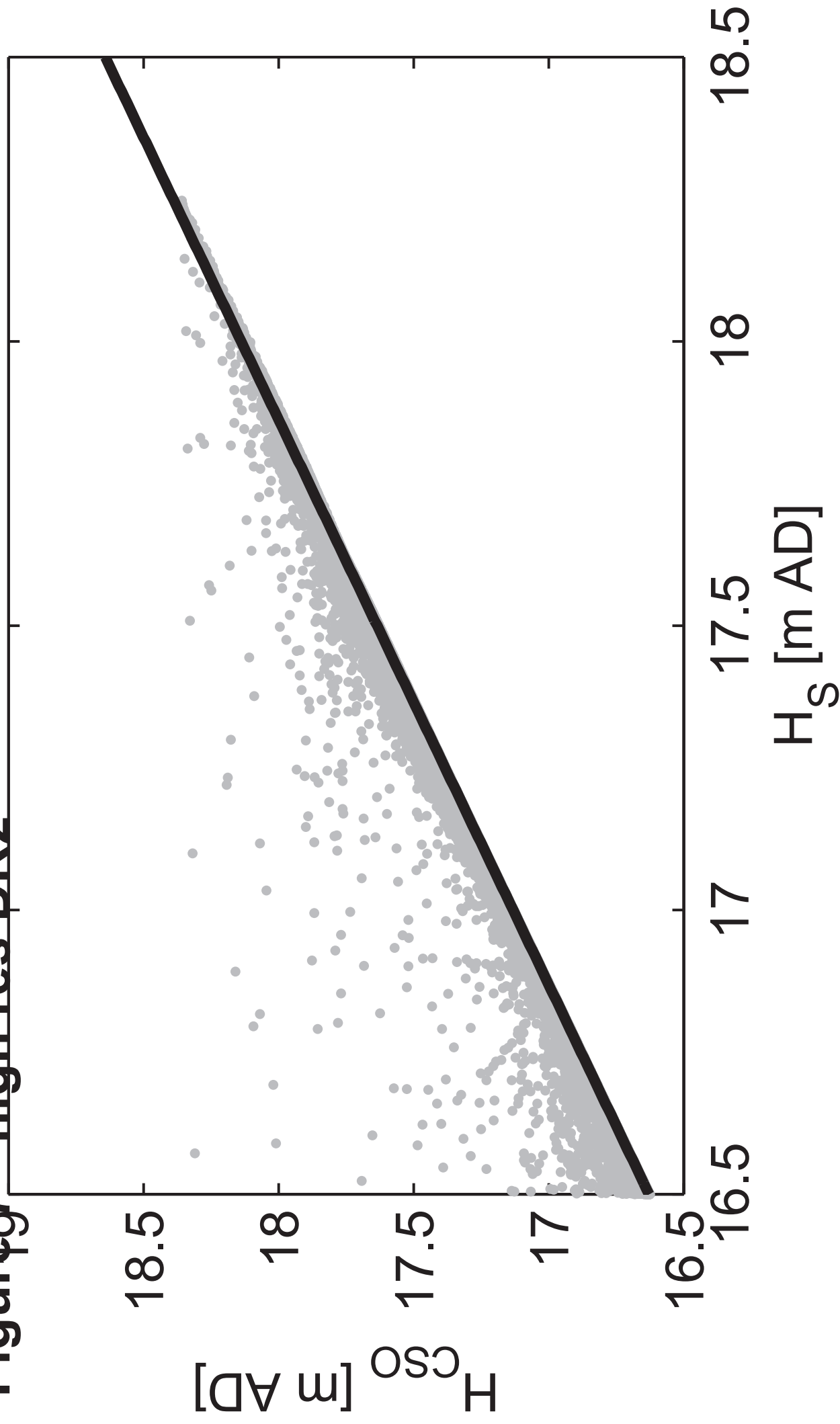


Figure 7 - high res DR3

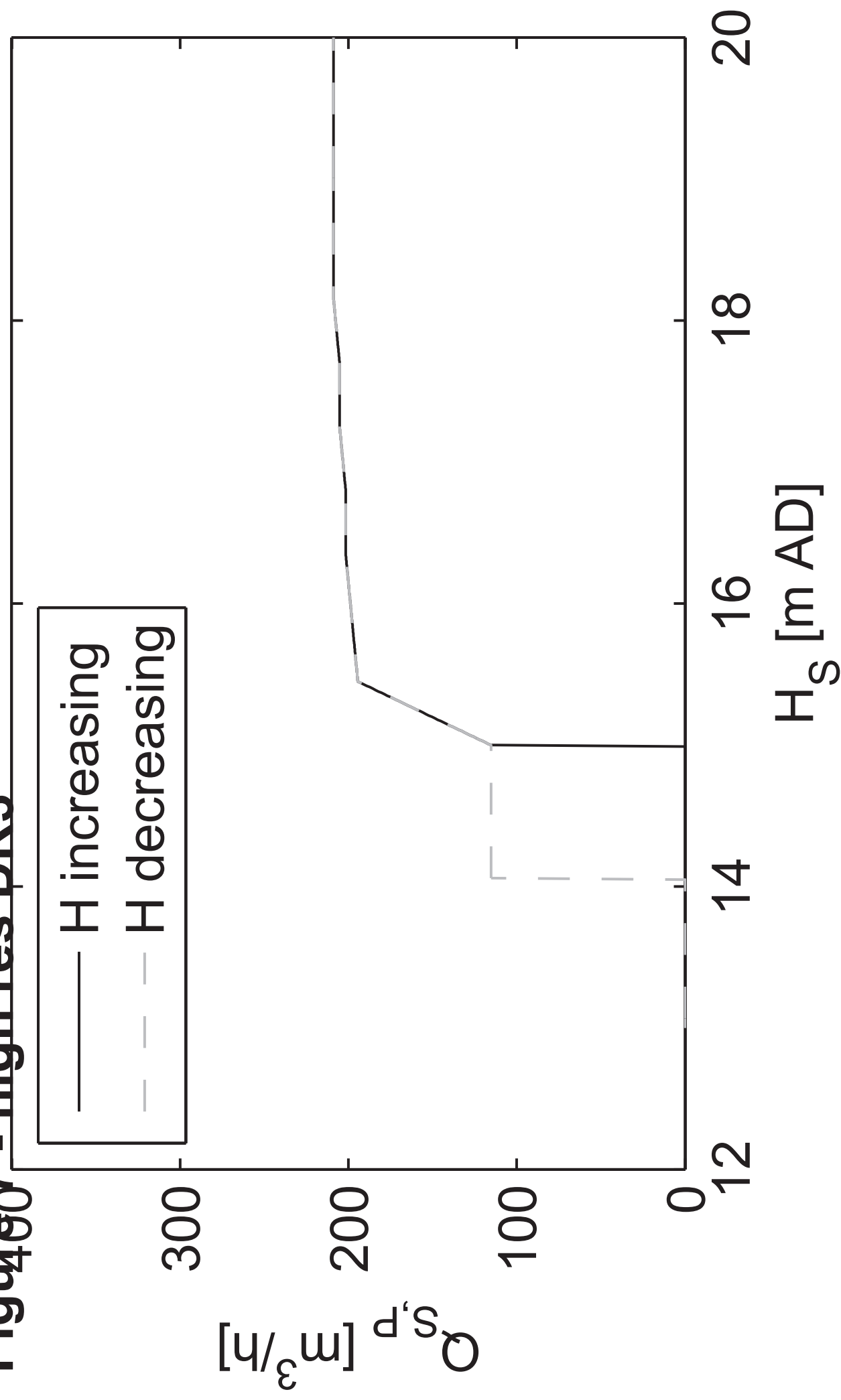


Figure 7 high res DR4

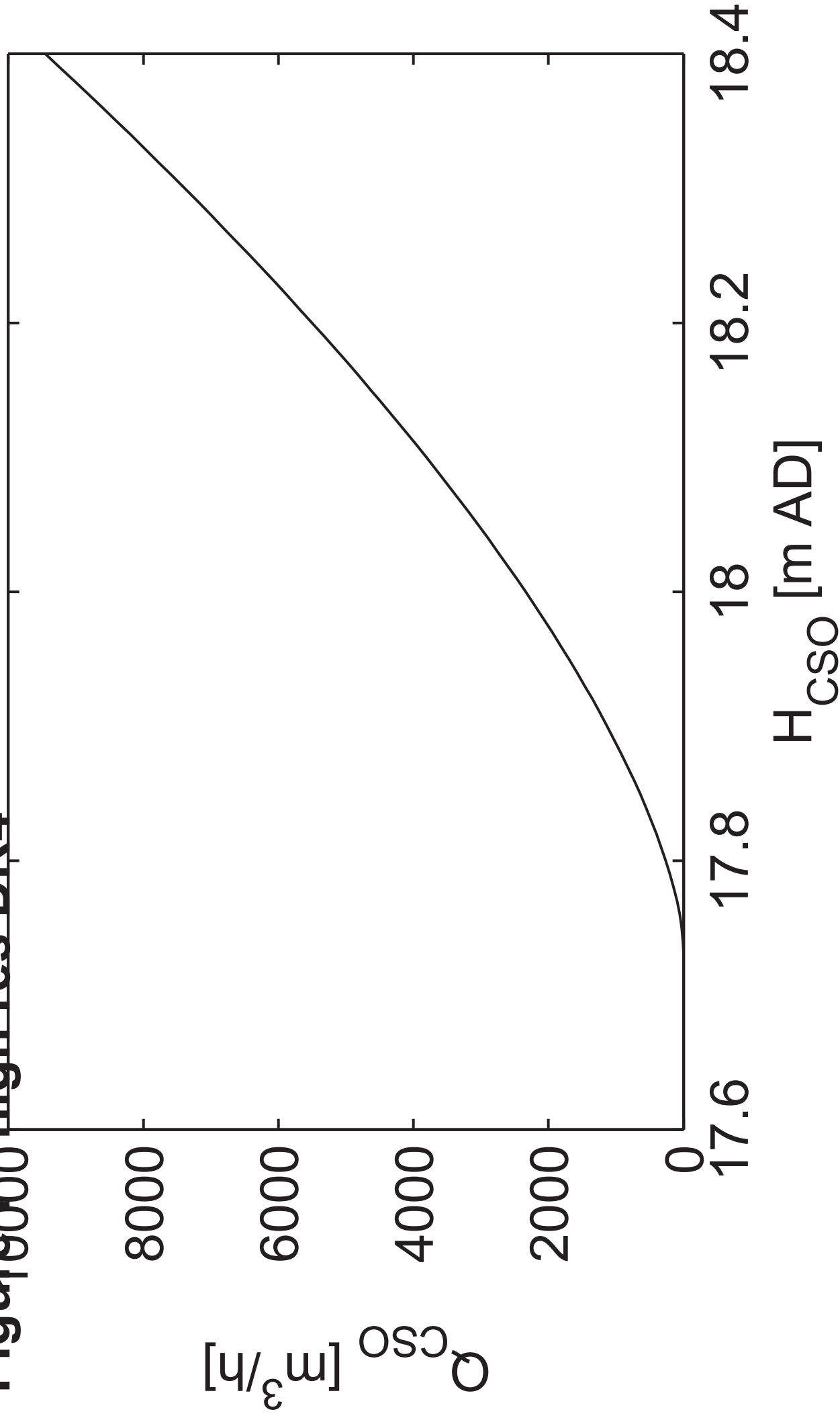


Figure 8 - left

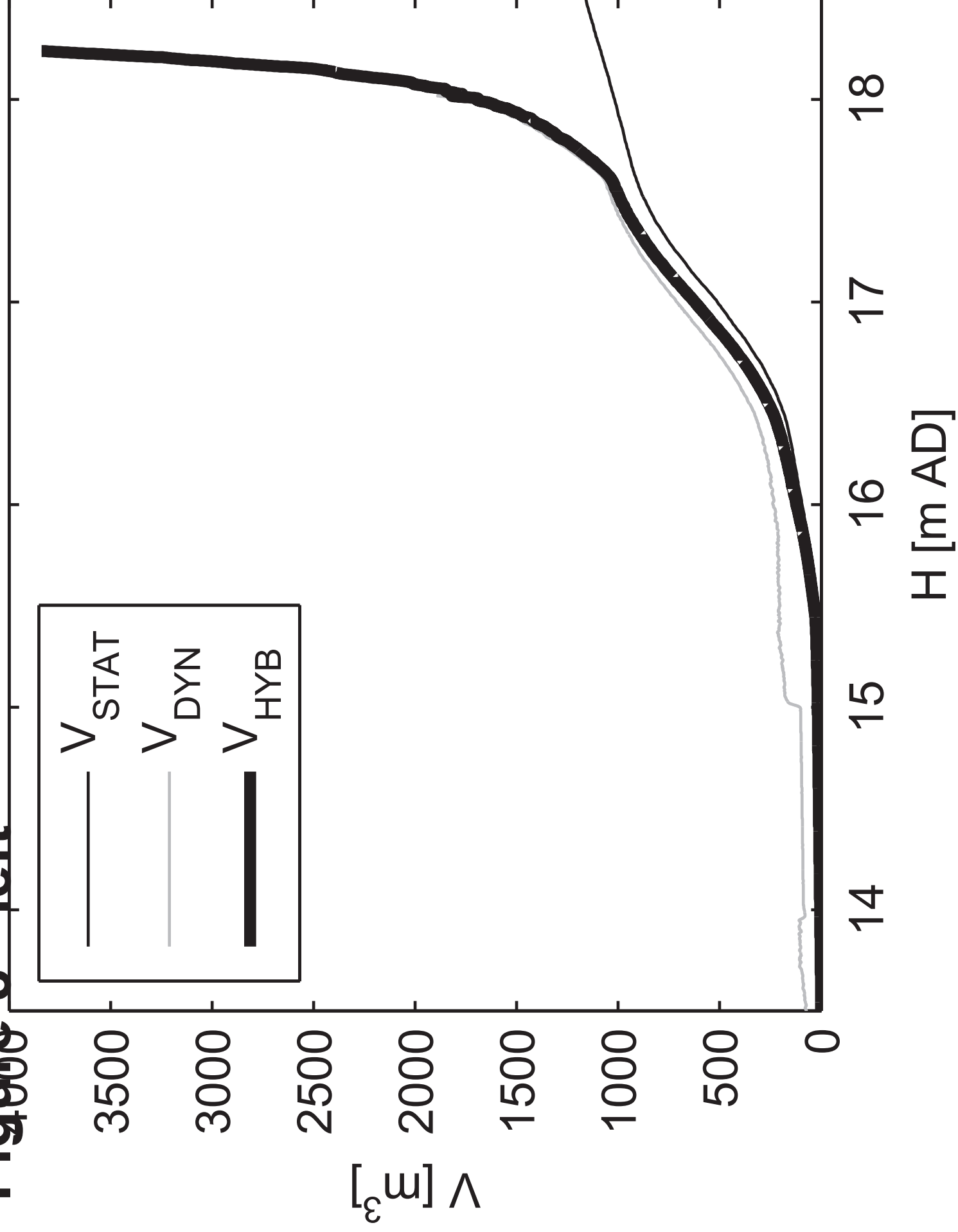


Figure 8 - right

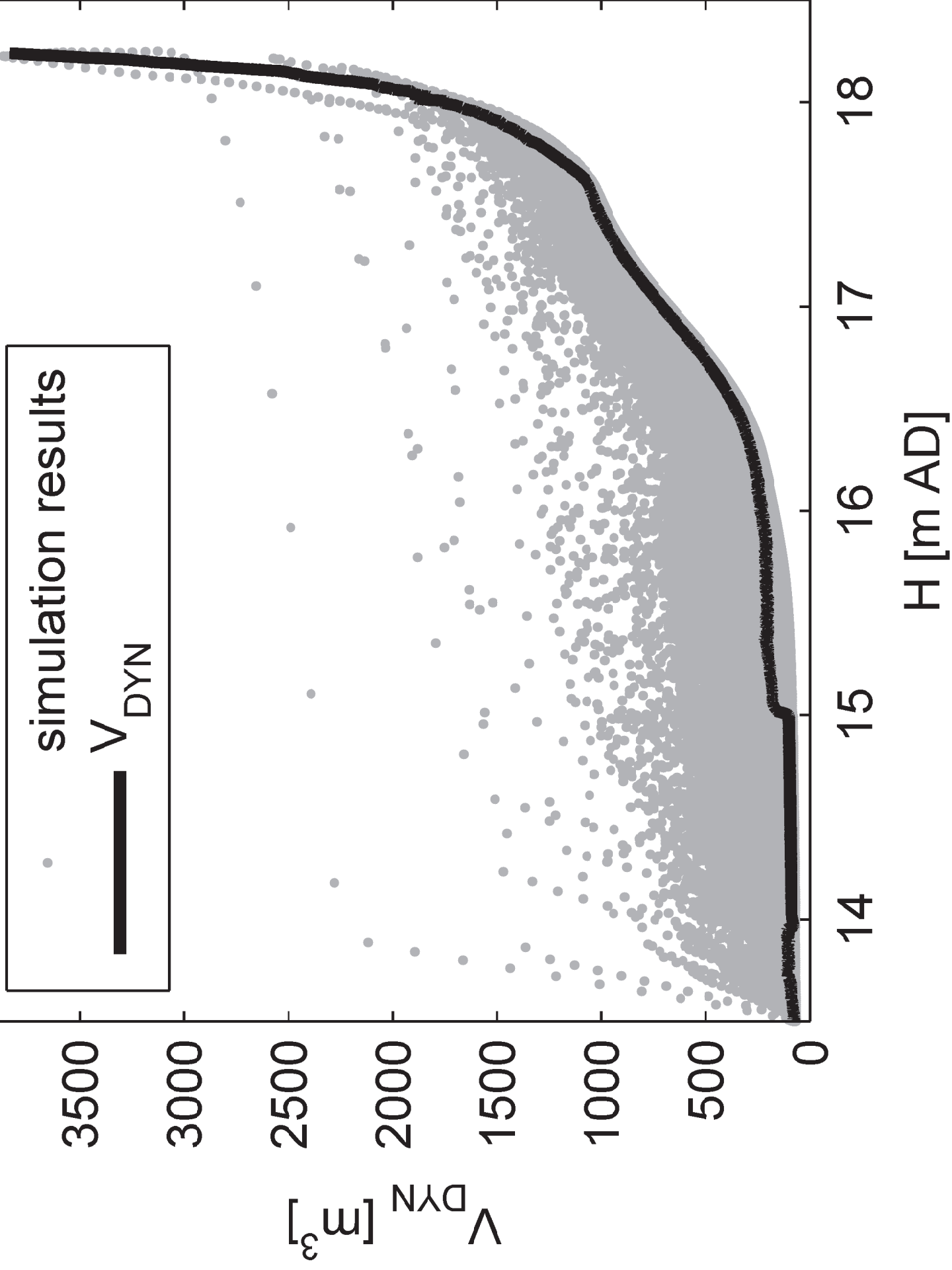


Figure 9 - total DR model Waalre with graphs DR5-DR13

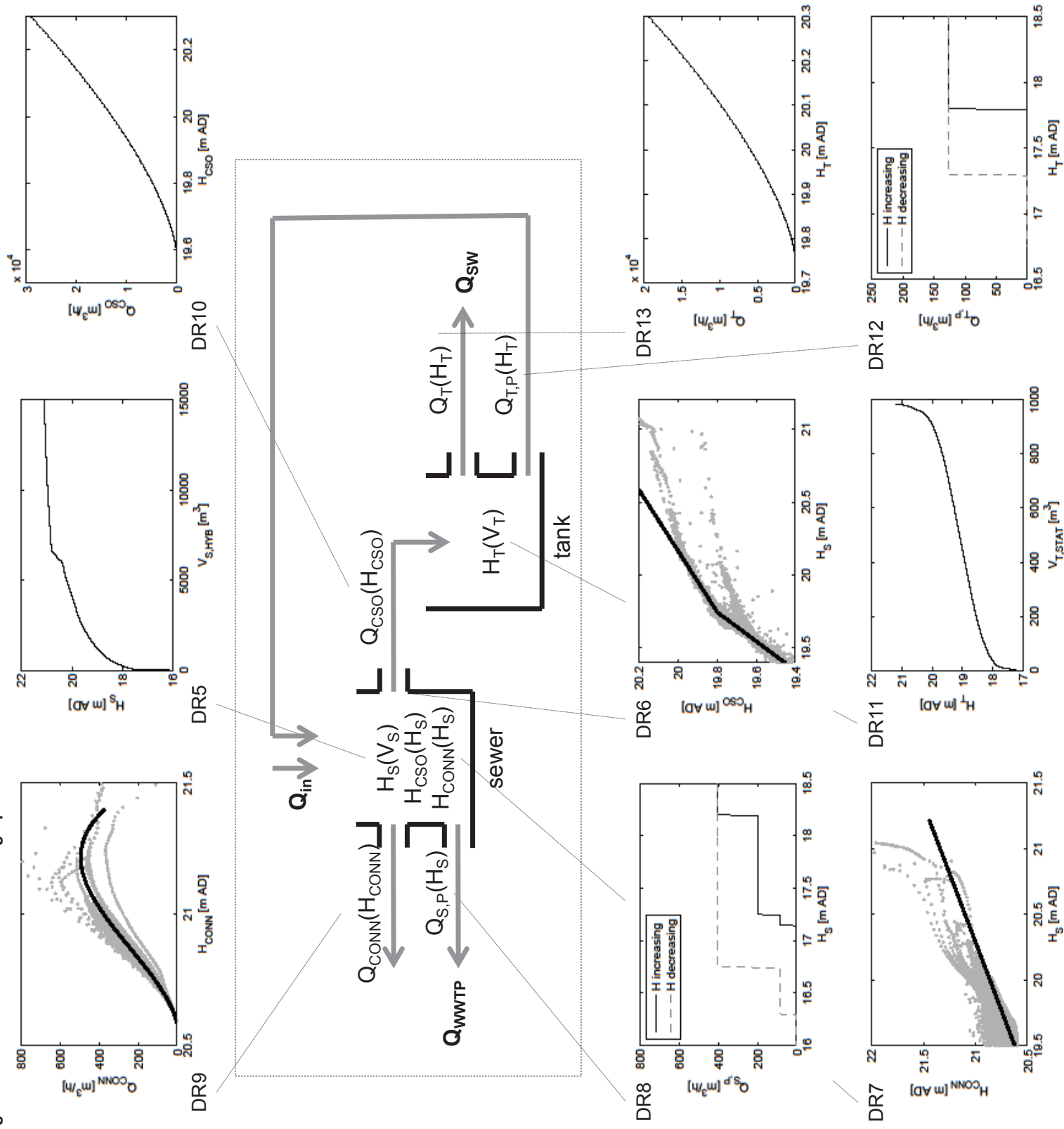


Figure 9 - high res DR5

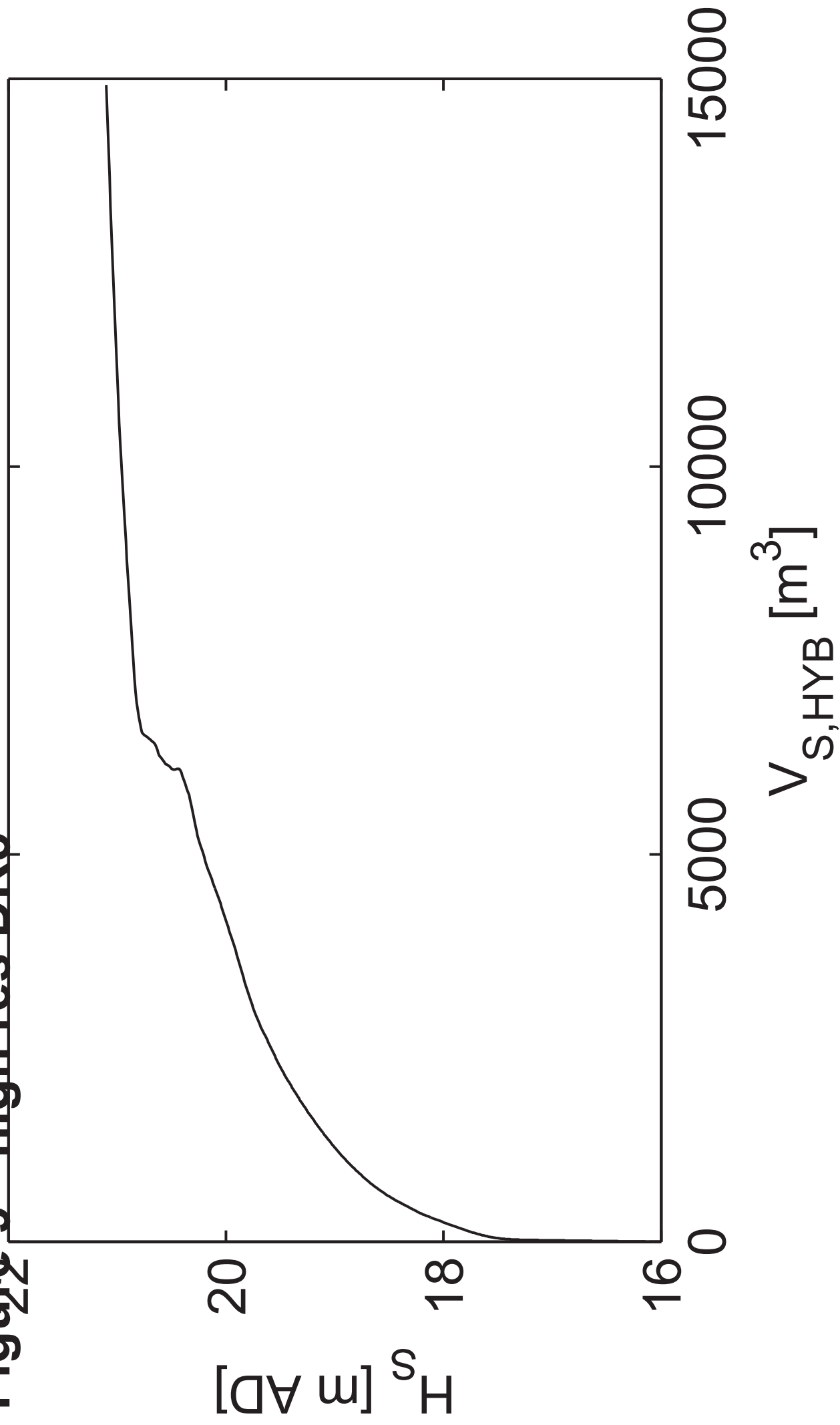


Figure 9 - high res DR6

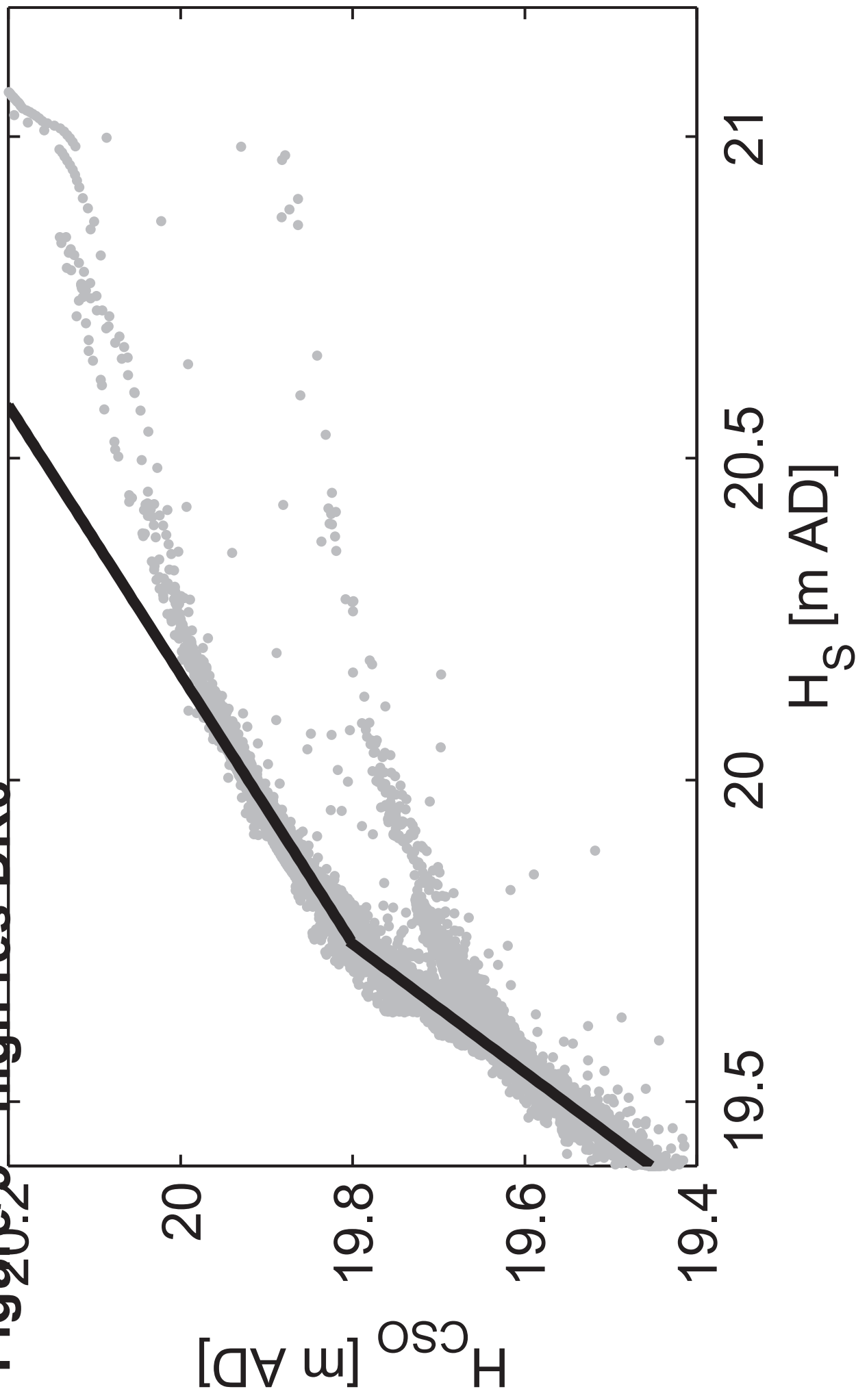


Figure 9 - high res DR7

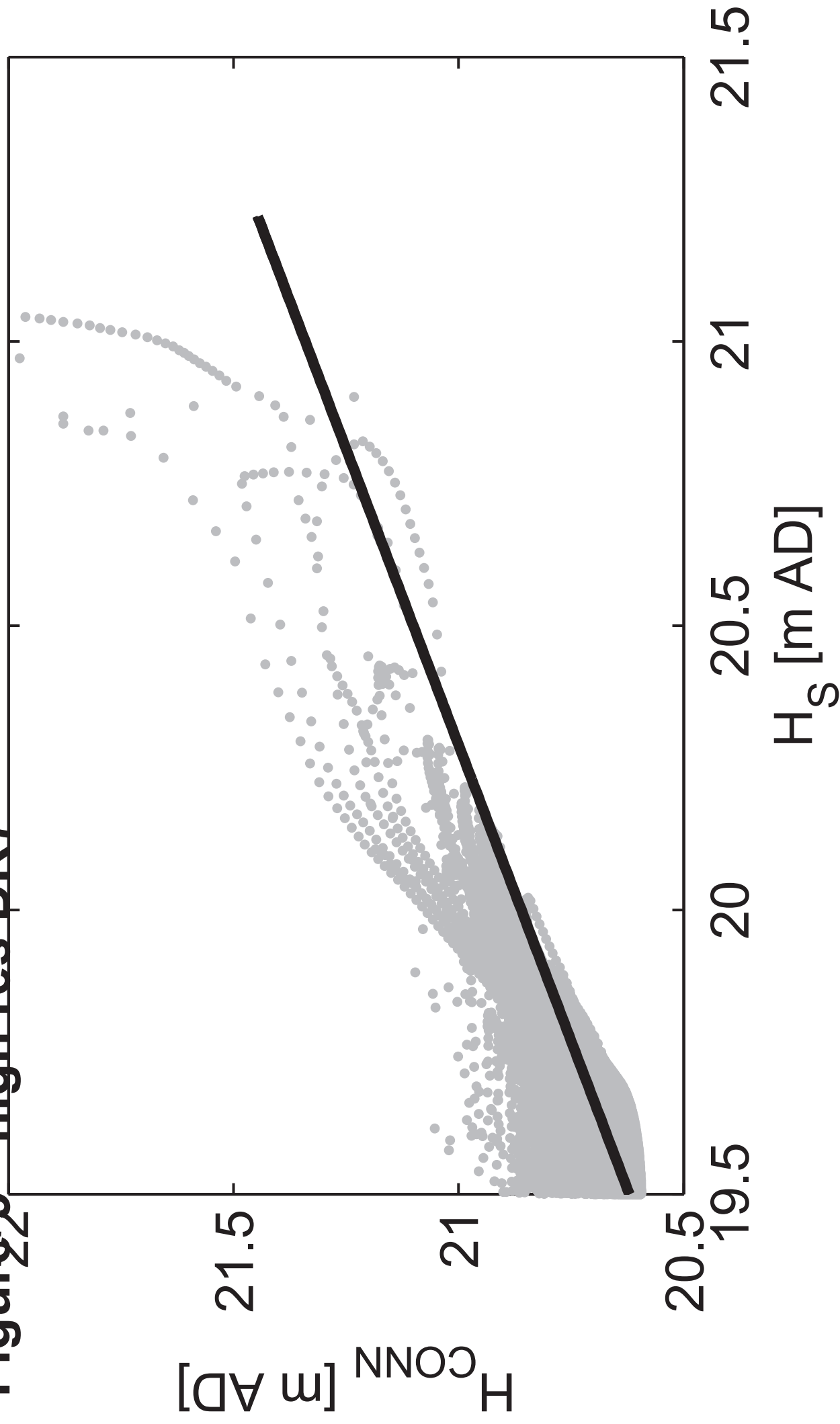


Figure 9 - high res DR8

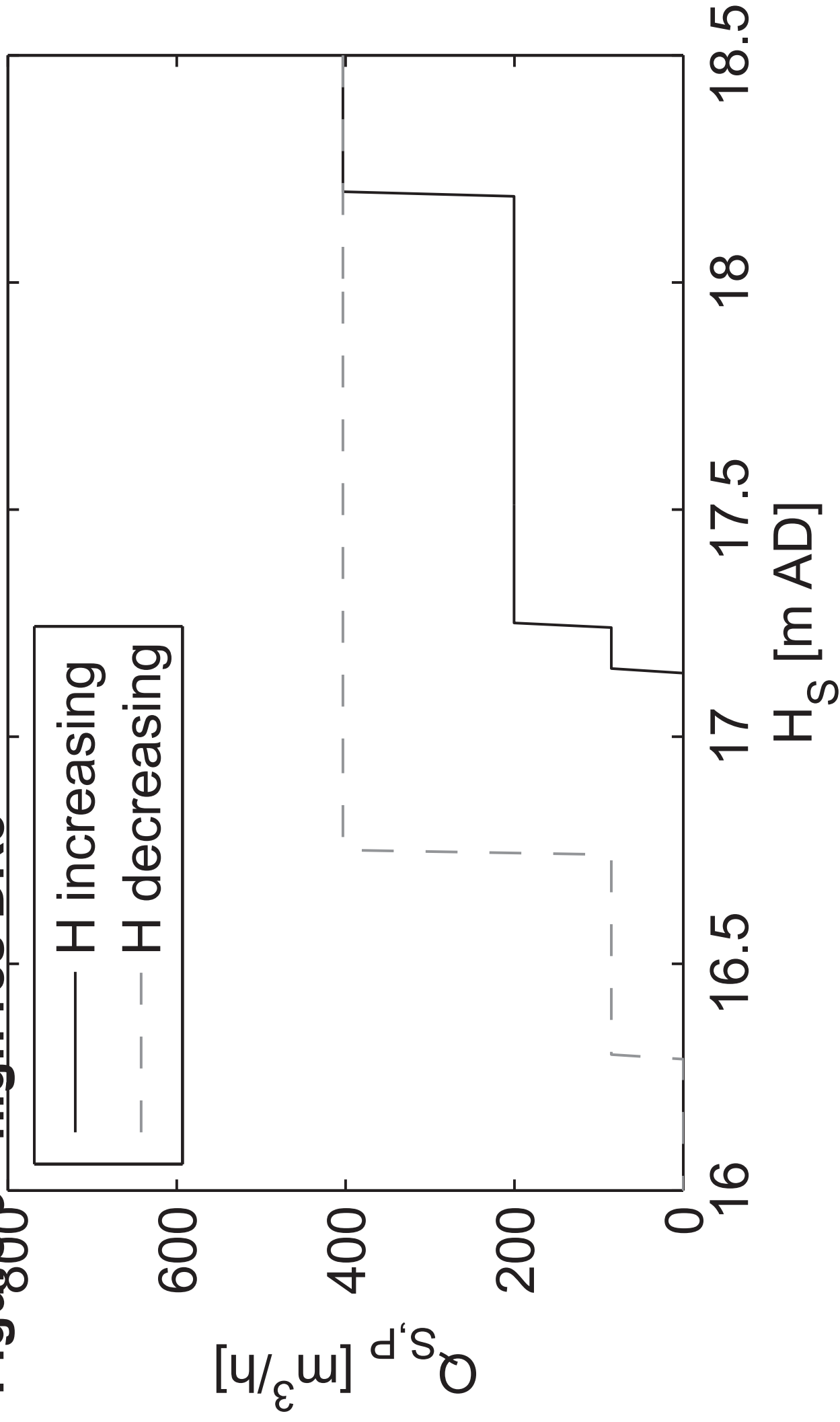


Figure 9-16⁴high res DR10

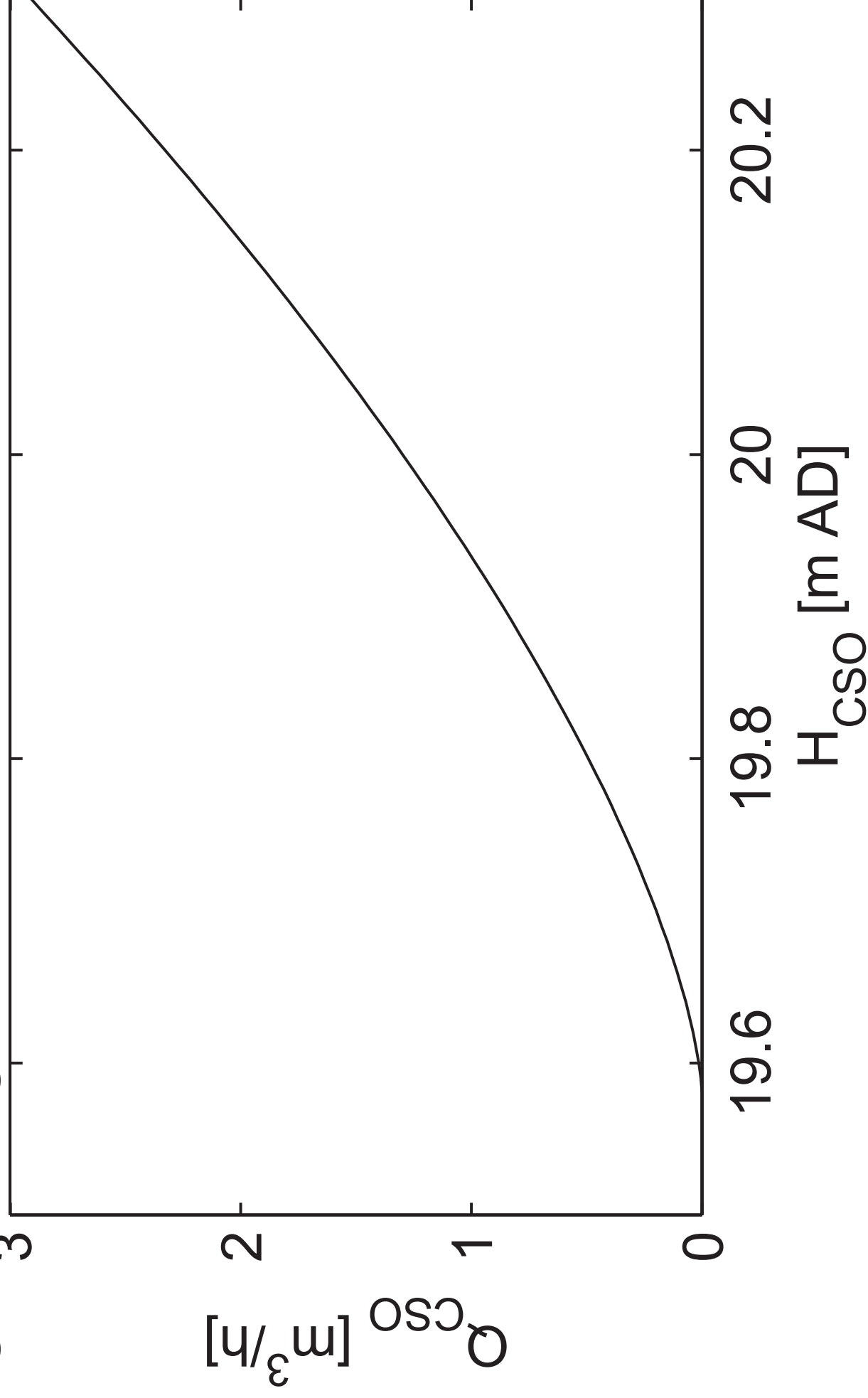


Figure 9 - high res DR9

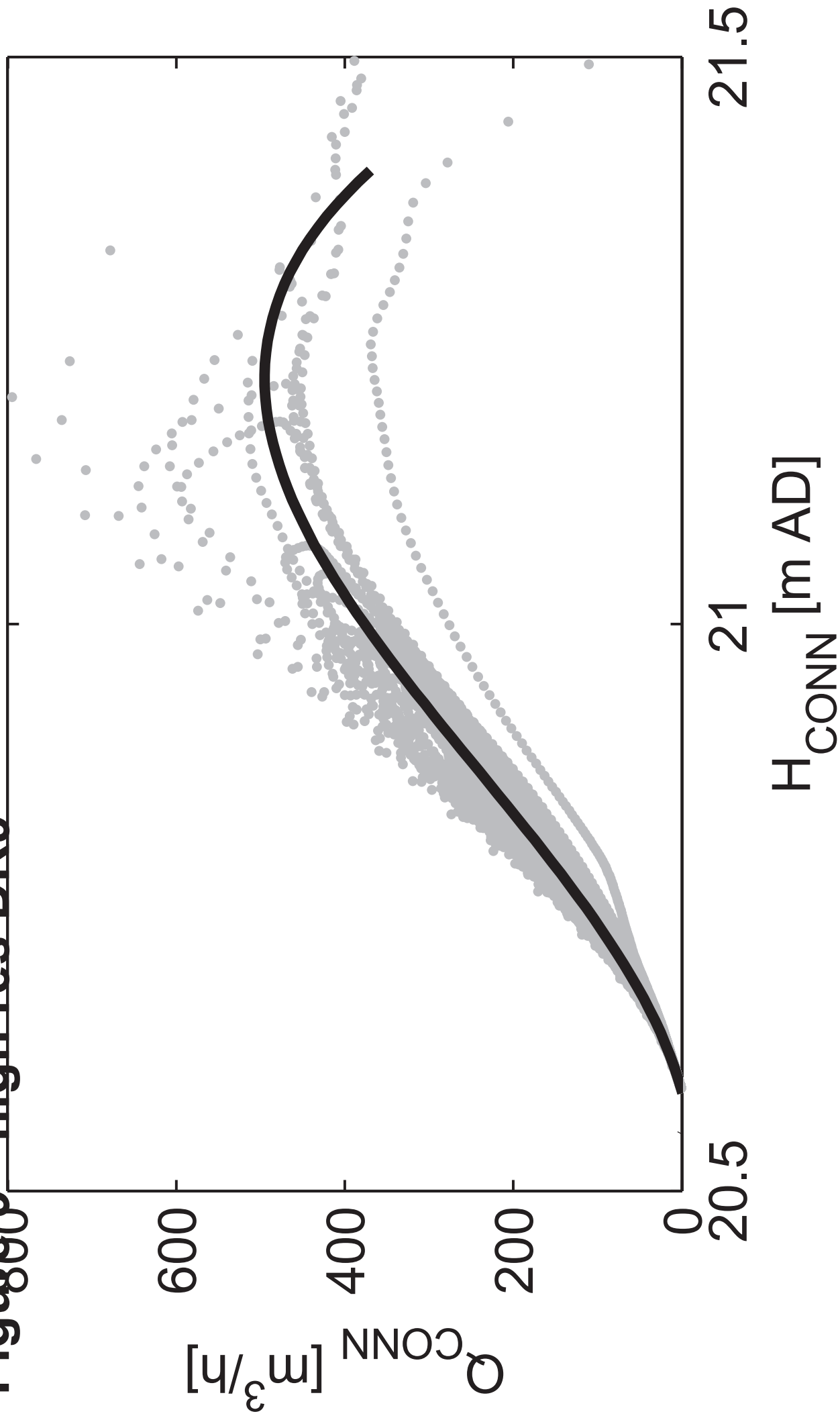


Figure 9 - high res DR11

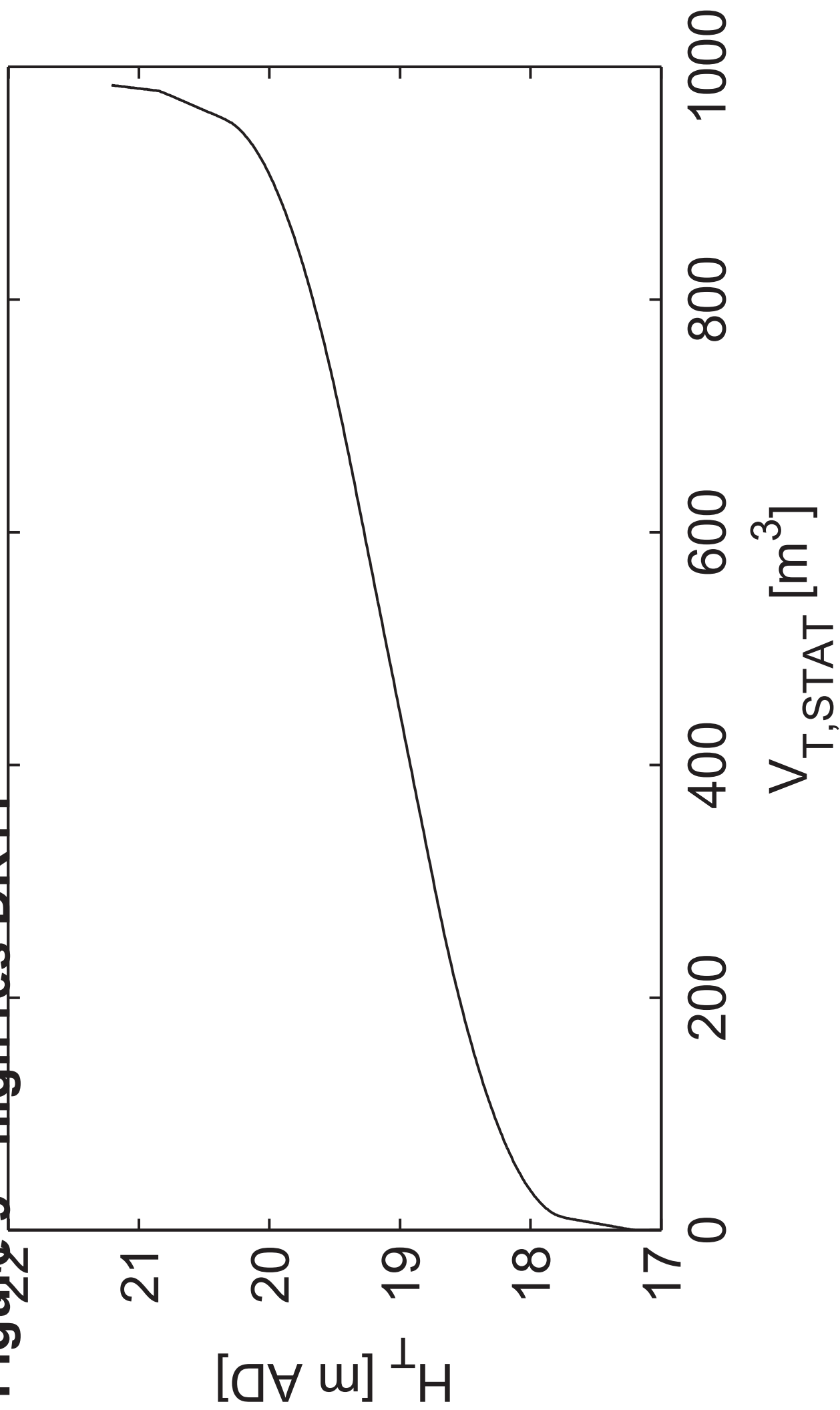


Figure 9 - high res DR12

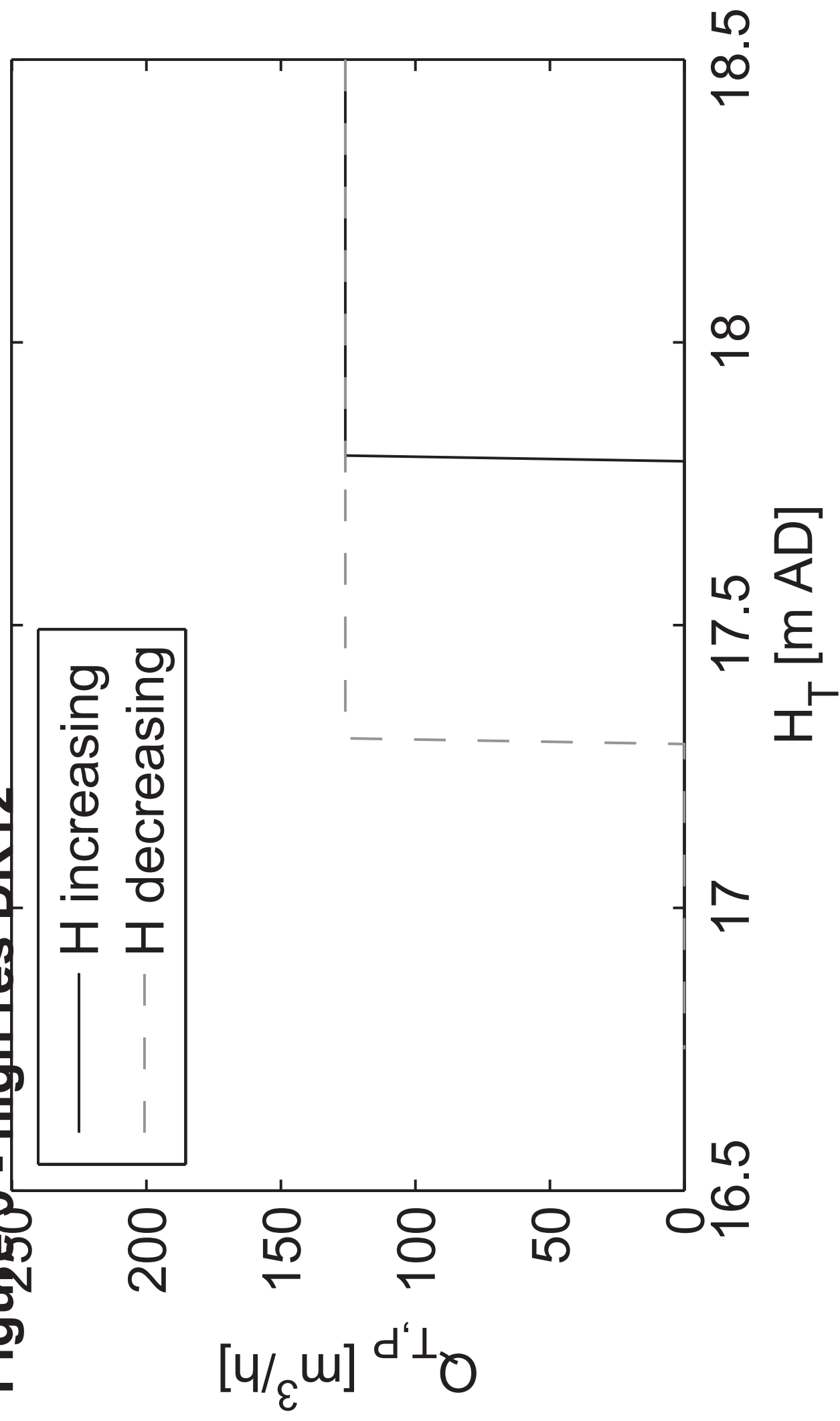


Figure 9-16⁴ high res DR13

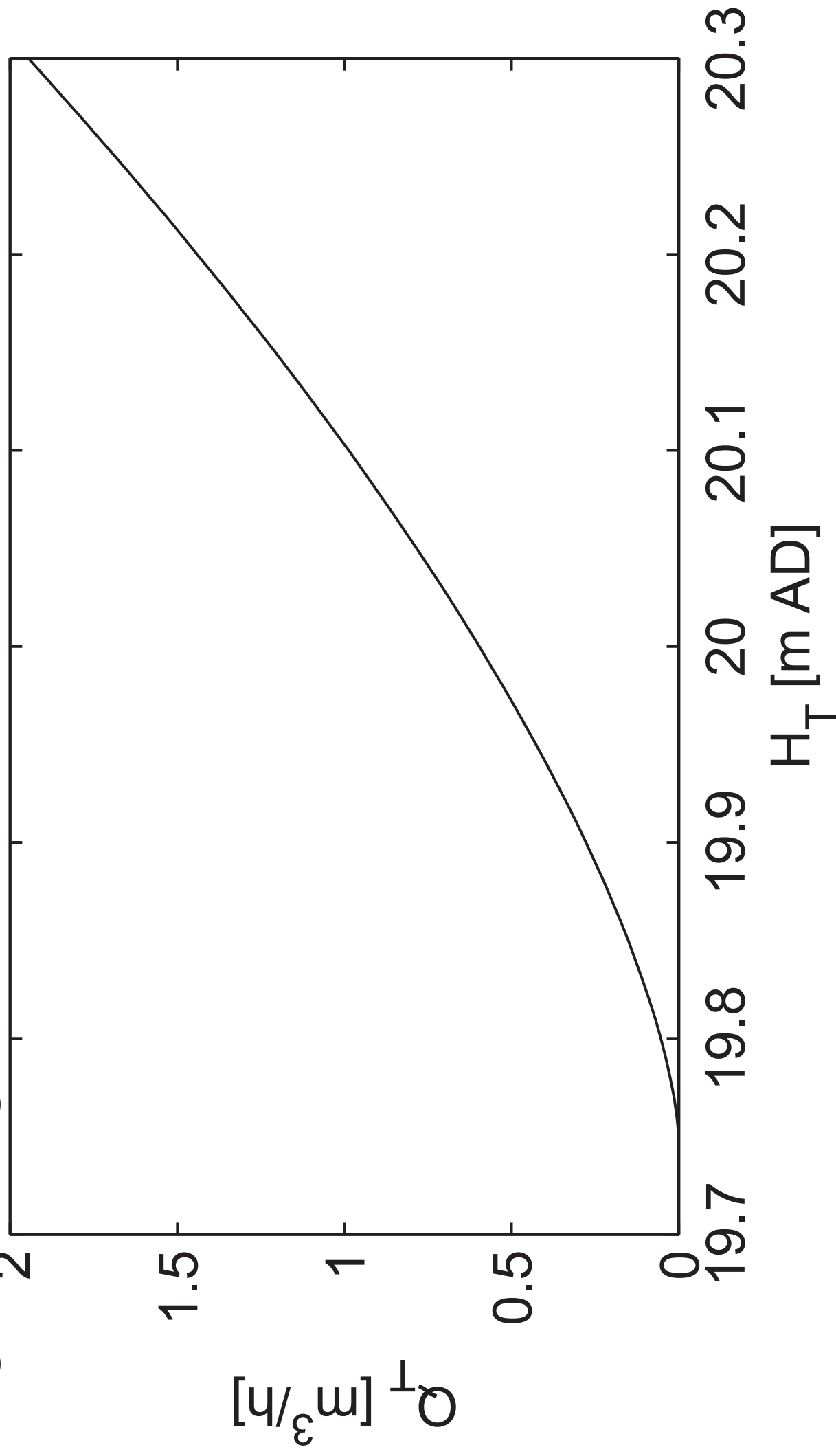


Figure 10 - left

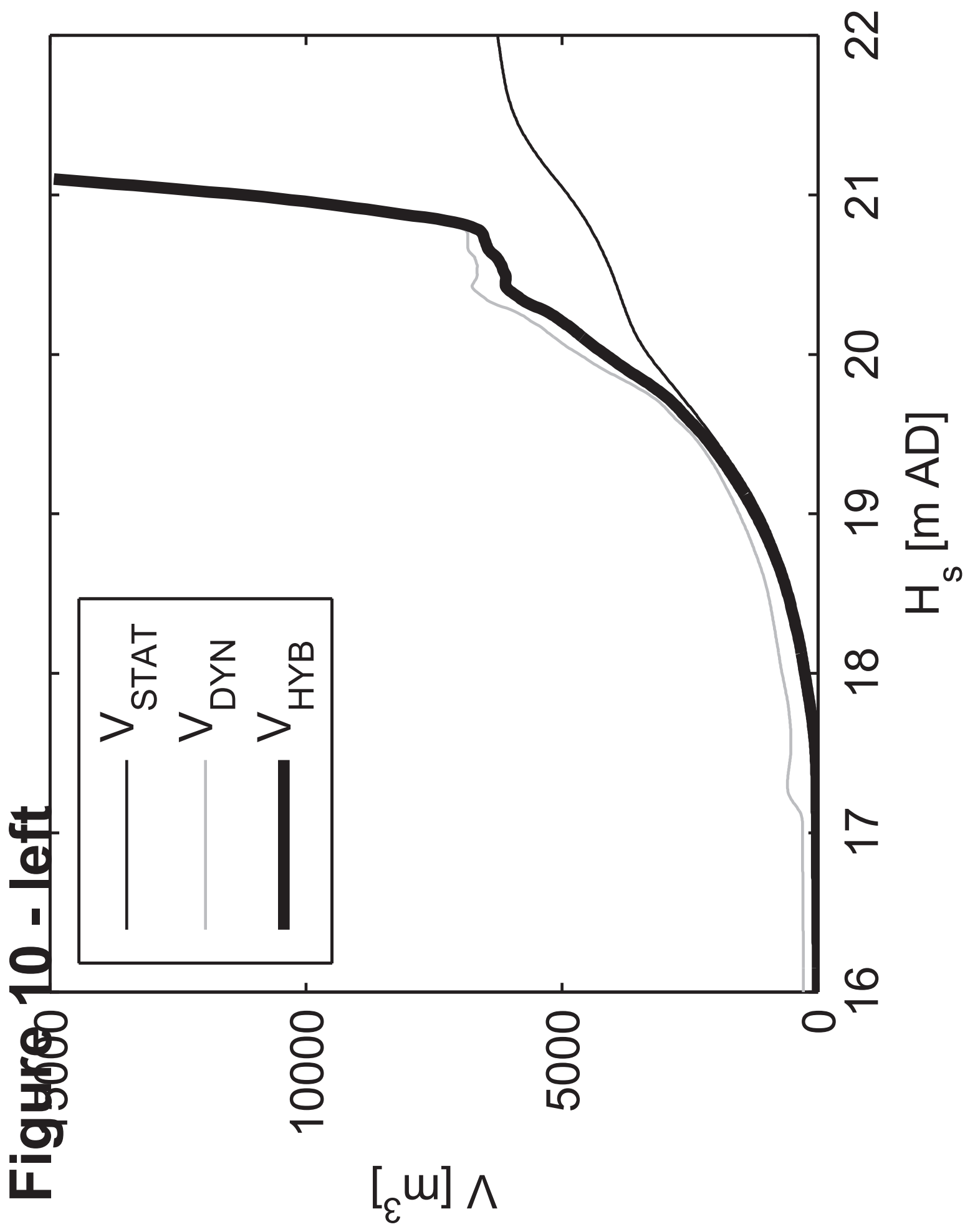


Figure 10 - right

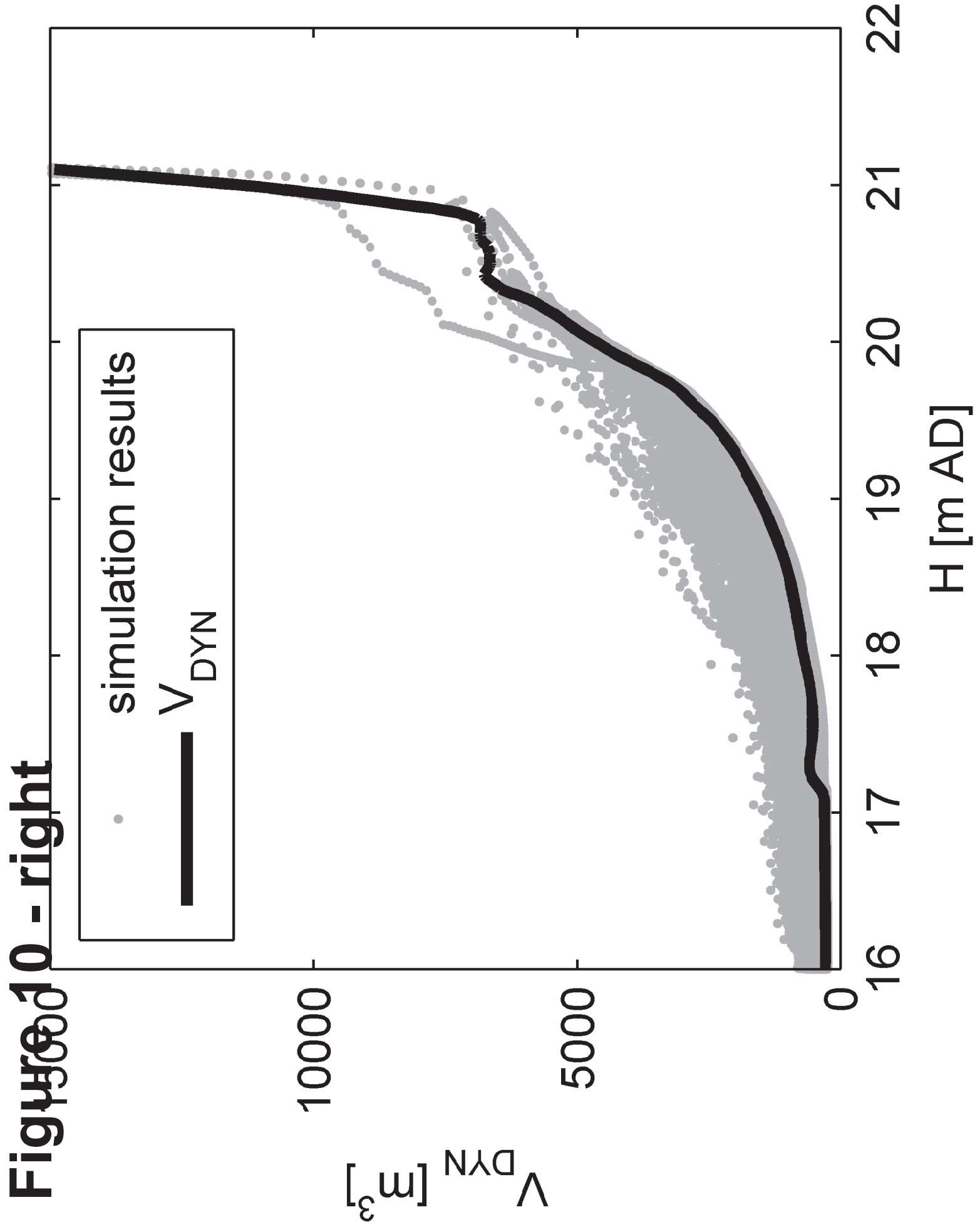


Figure 11

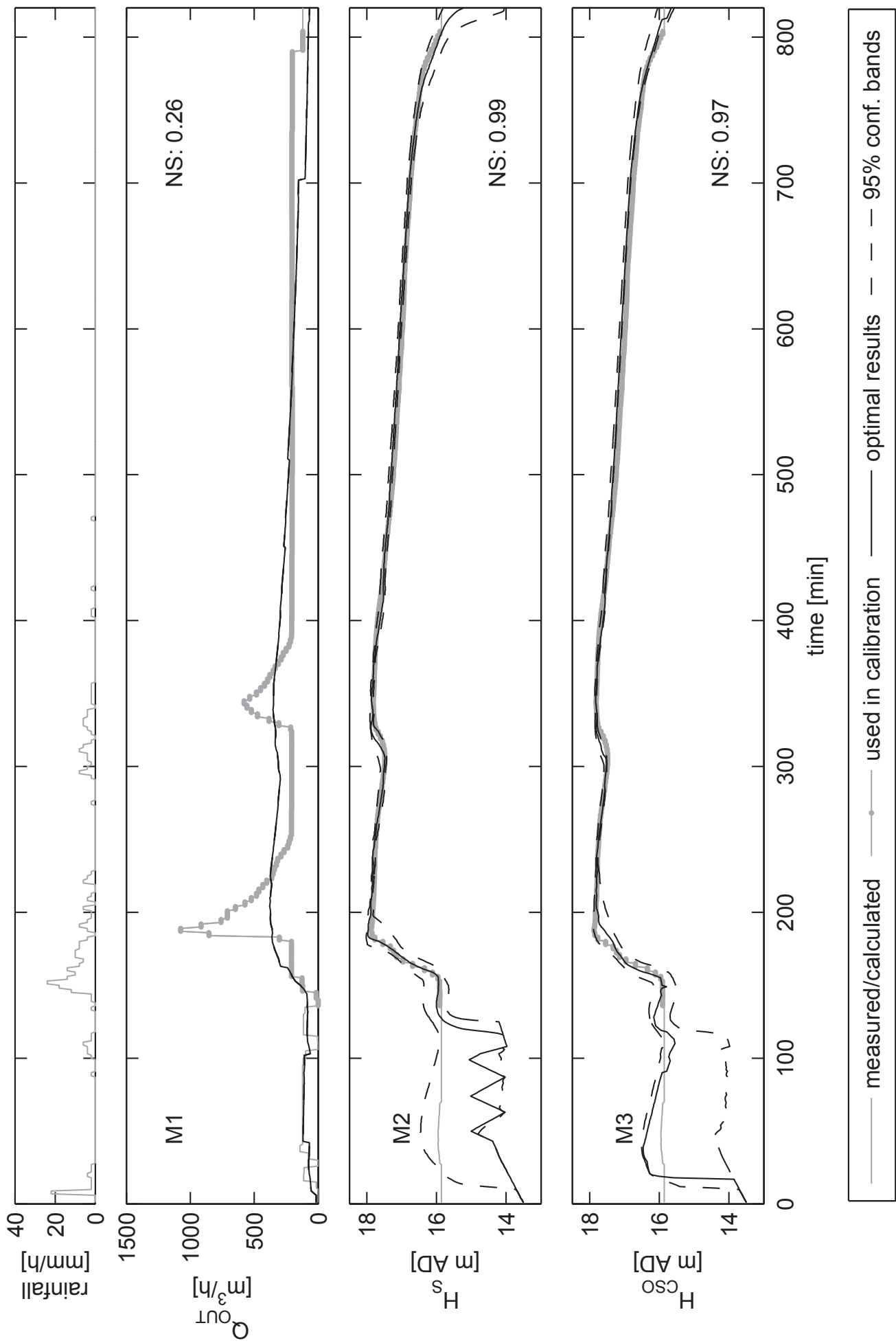


Figure 12

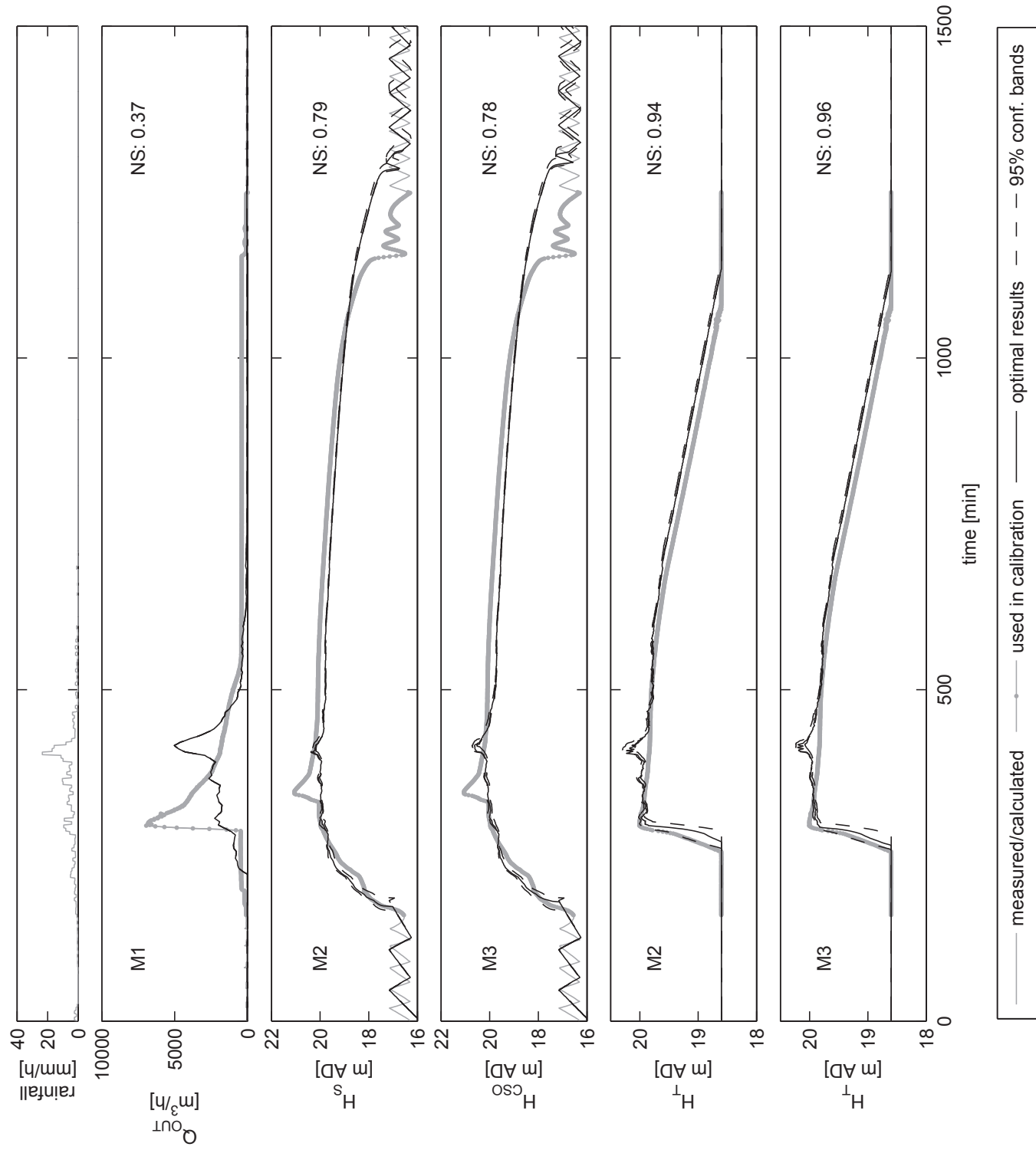


Figure 13

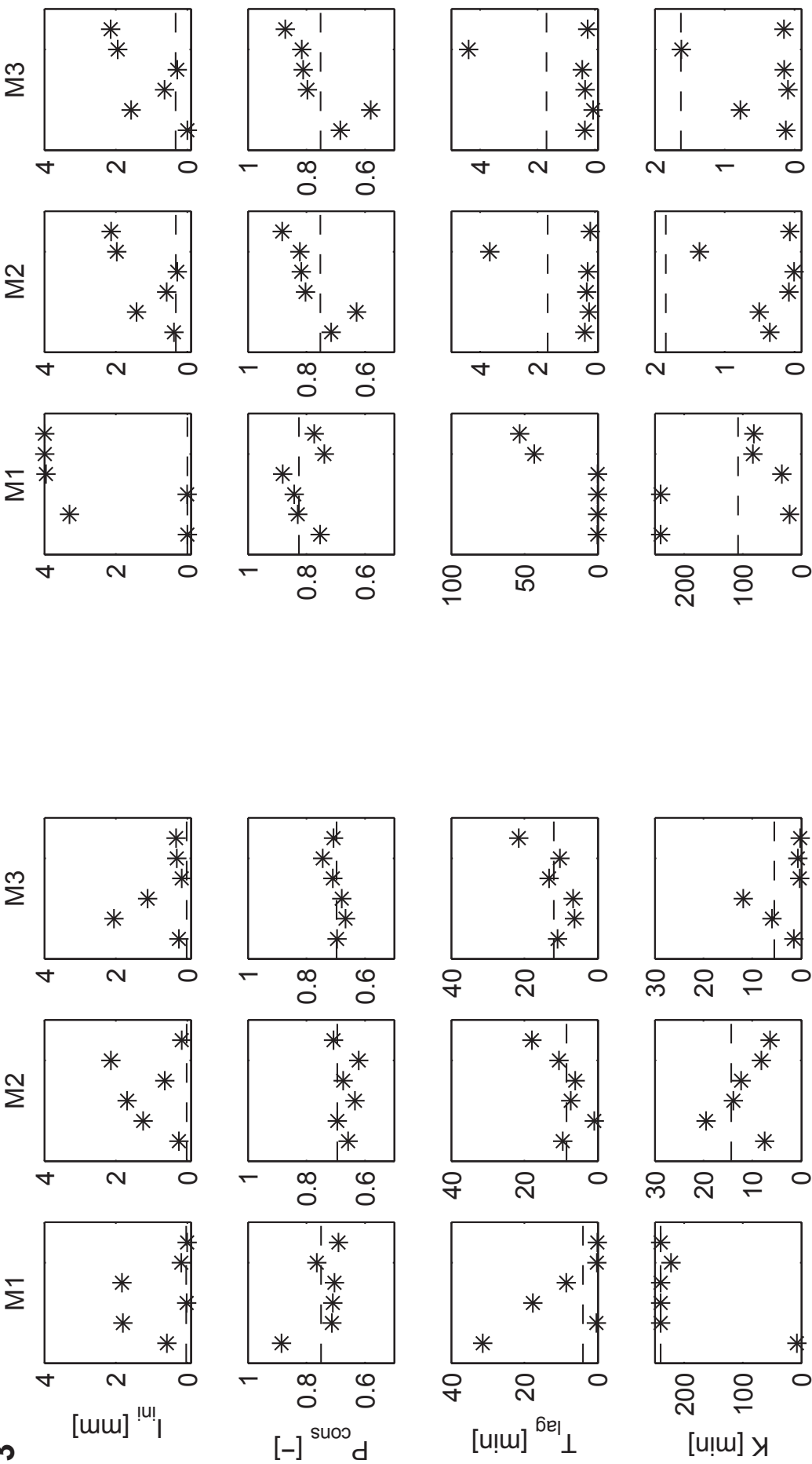


Figure 14

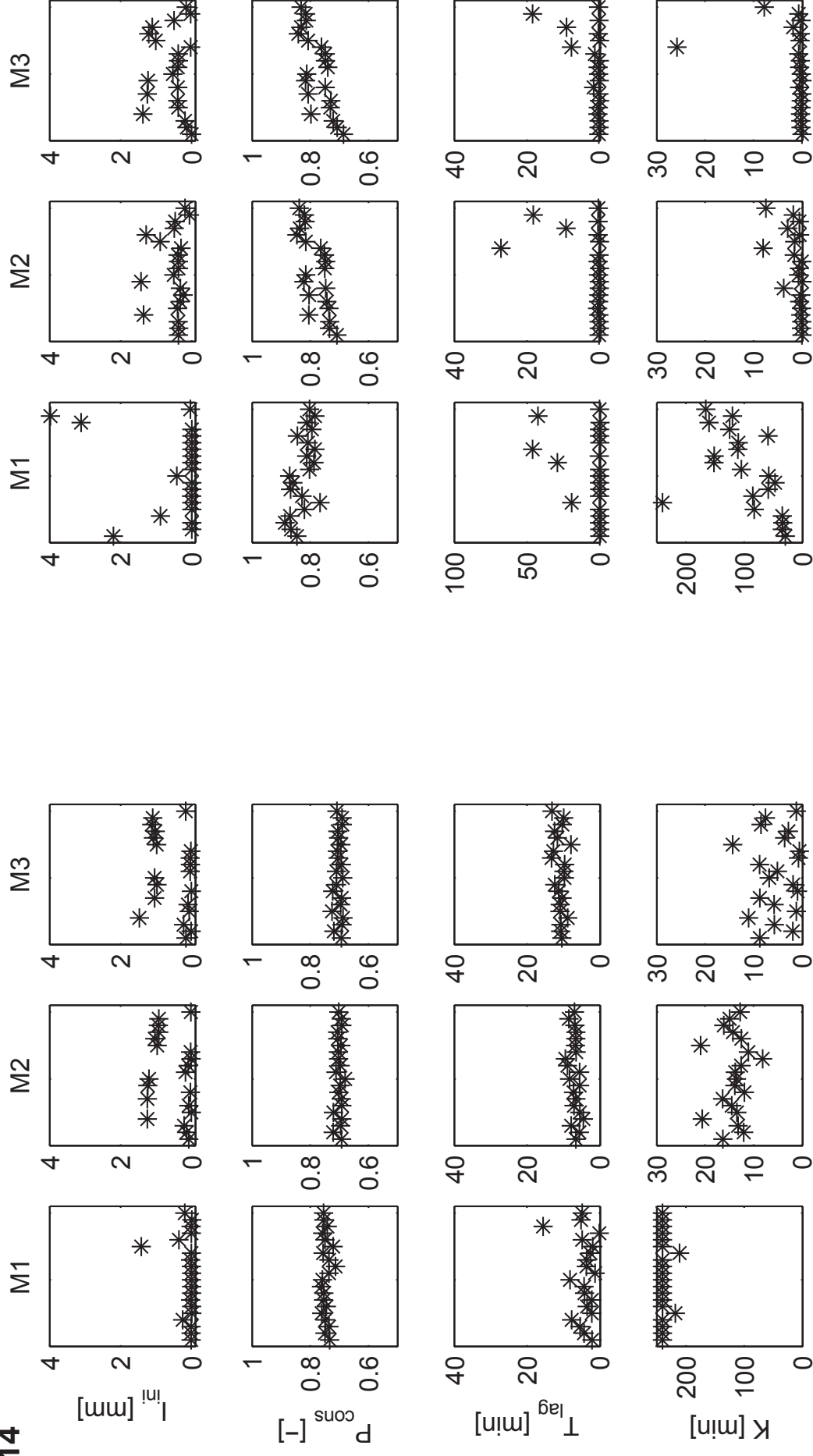


Figure 15

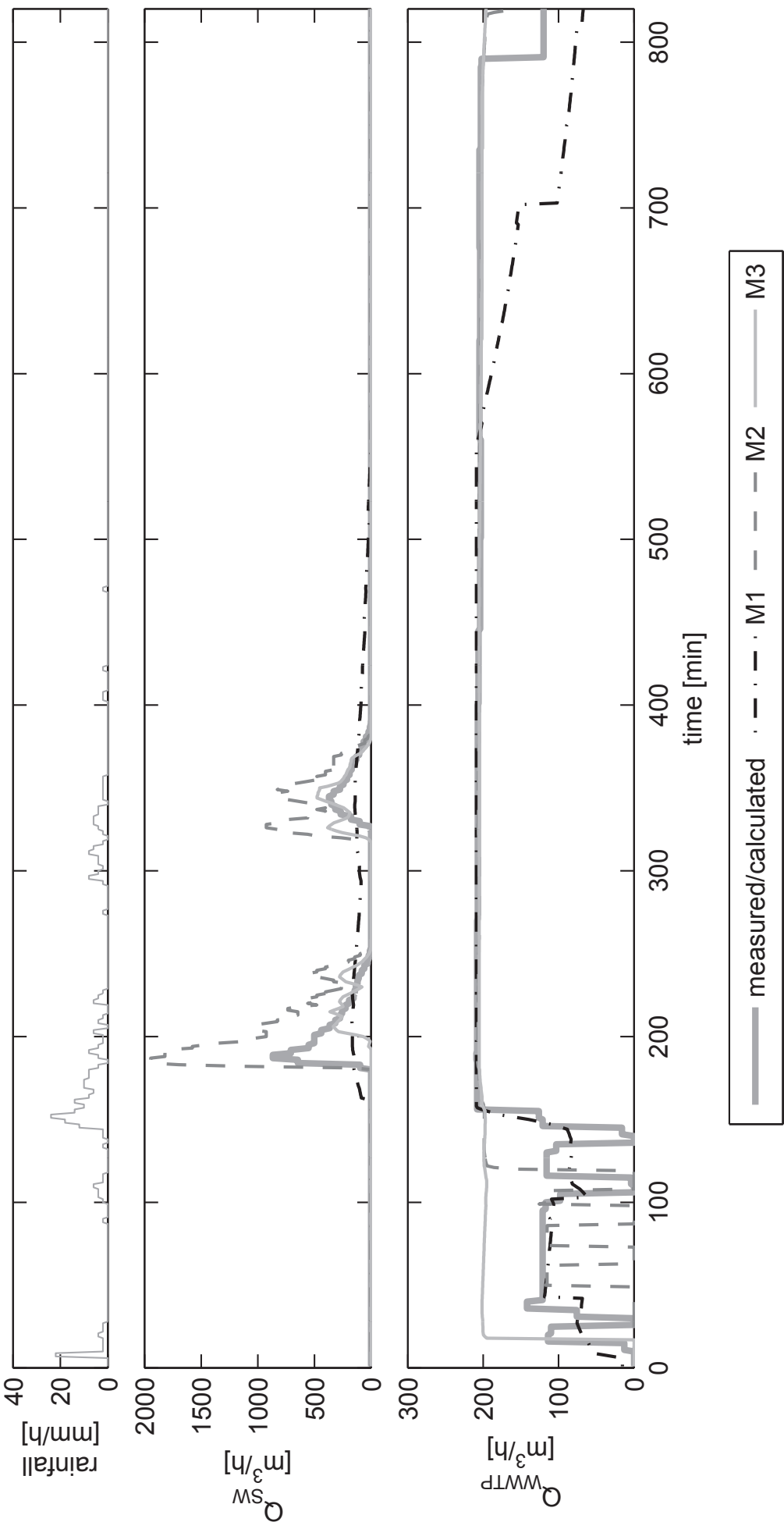


Figure 16

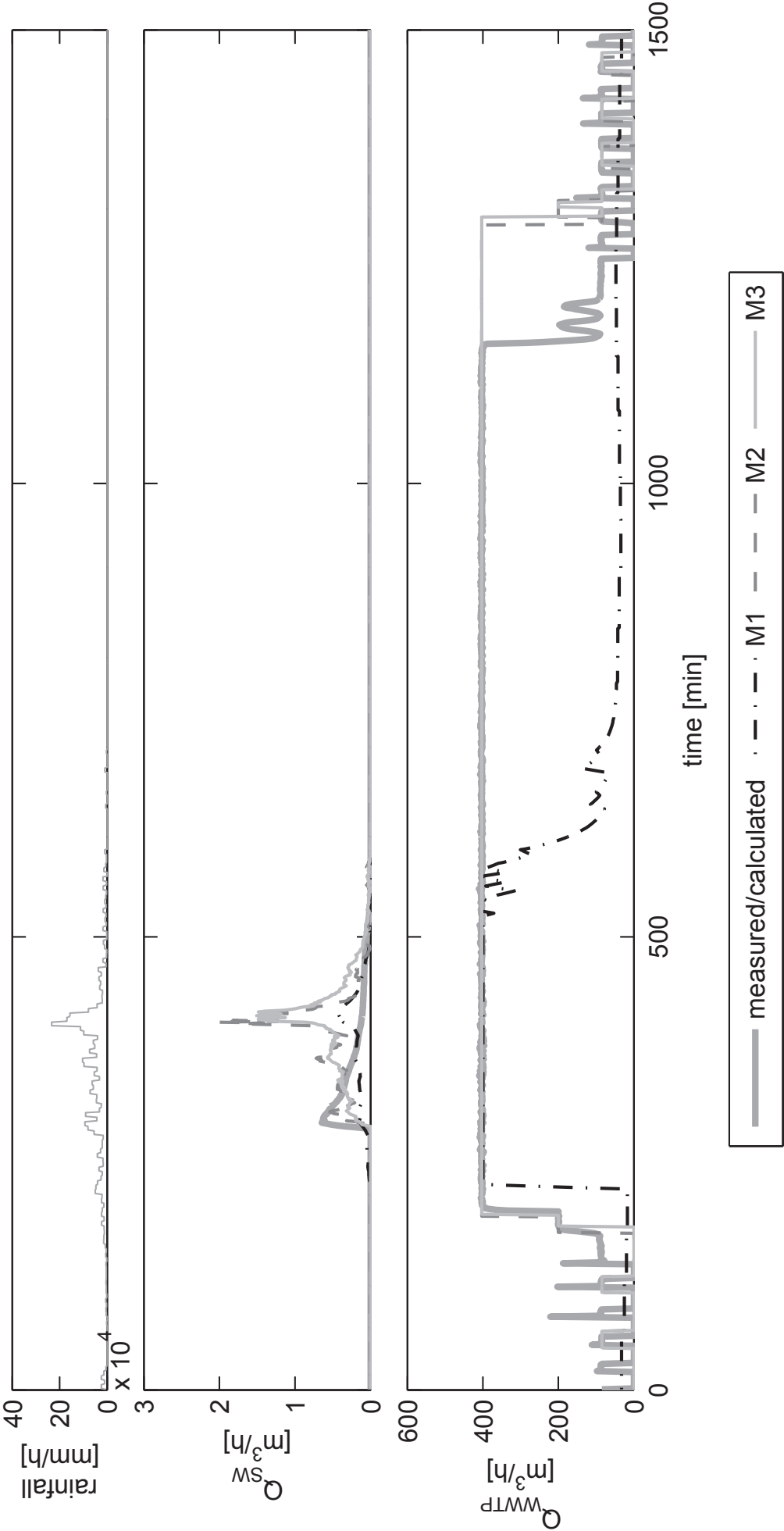


Figure 17

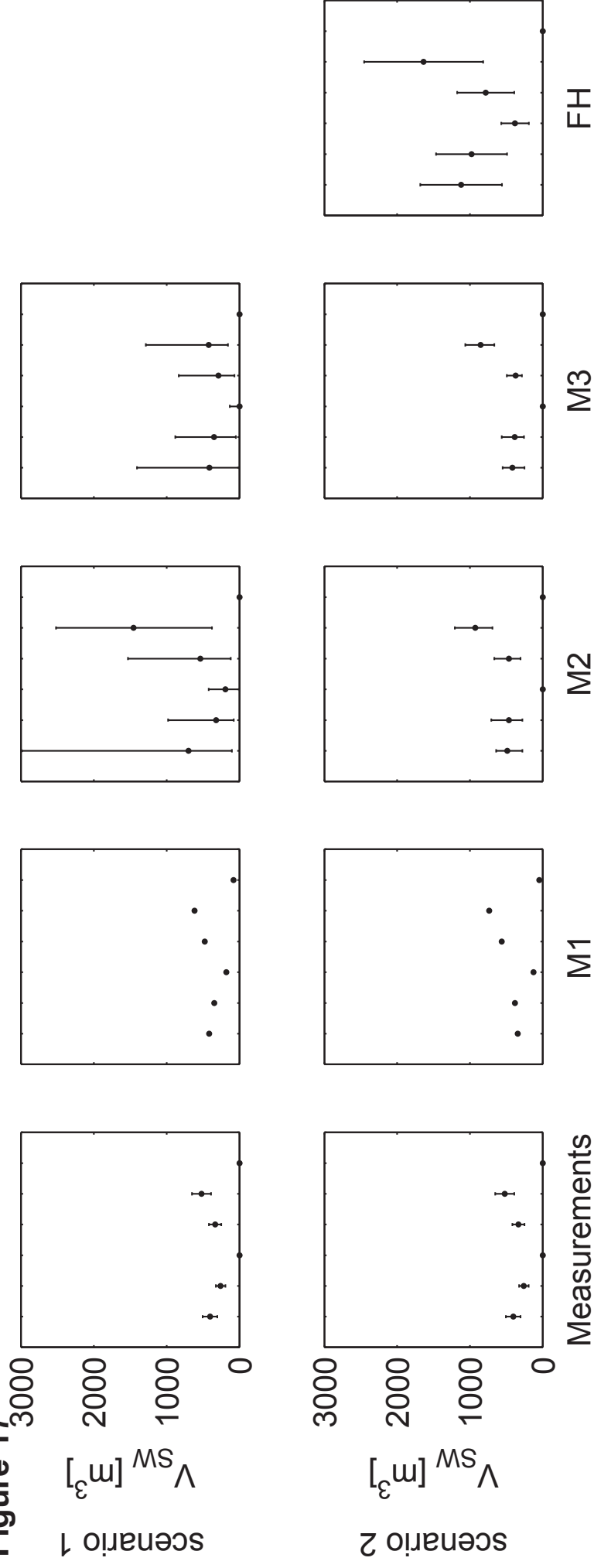
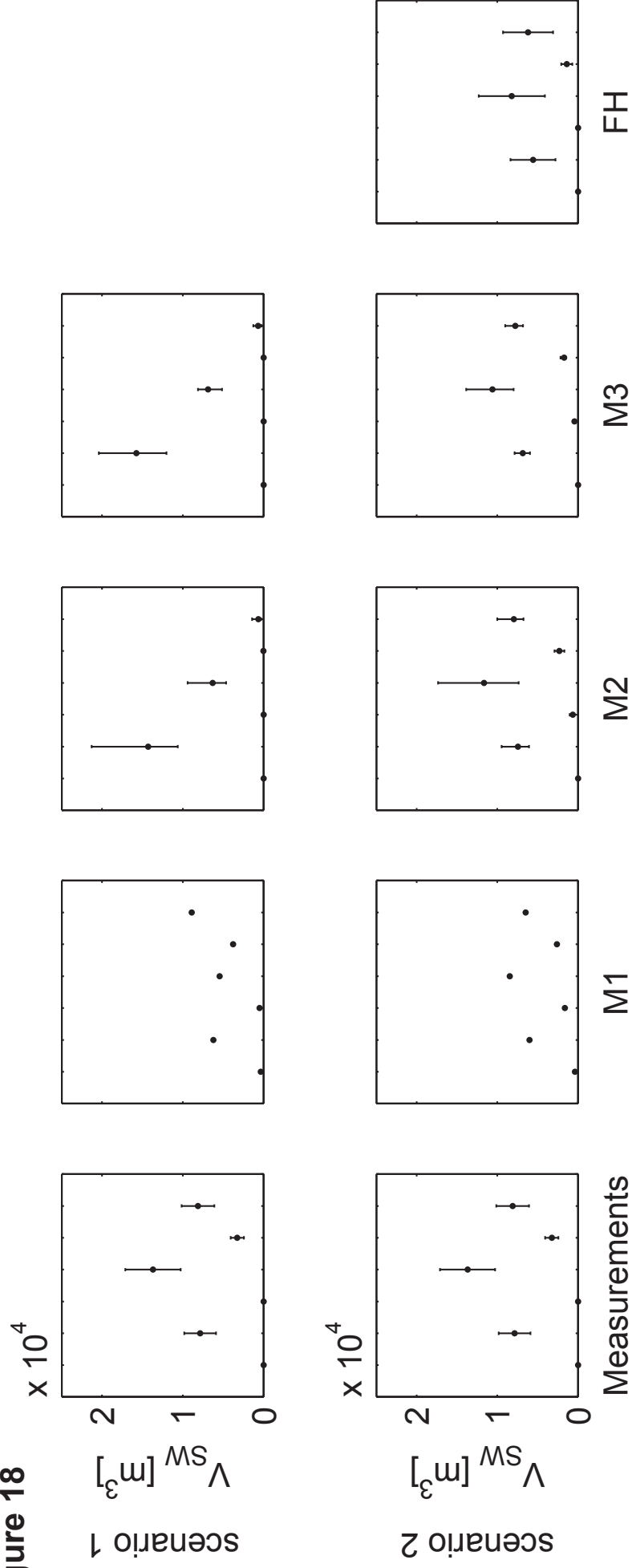


Figure 18



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

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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:

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

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.

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).

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,

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

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

281 SR7. Discharge sewer through CSO

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

285 SR8. Static storage-level curve settling tank

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

288 SR9. Discharge settling tank through pump

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

292 SR10. Discharge settling tank

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

294 **2.4.3. Dynamic reservoir (DR) model**

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

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

326 See SR2.

327 DR4. Discharge through CSO

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

329

330 A schematic representation of the DR model for Waalre is shown in figure 9 and can be

331 compared to the SR model in figure 6. Differences are expressed in the storage-level curve

332 applied (DR5-SR4), the water level applied in the CSO discharge (DR6-no equivalent in the SR

333 model) and the water level applied in and the calculation of the flow through the connection

334 (DR7-no equivalent in SR model, DR9-SR6).

335

336 The characteristics or relationships applied in the DR for Waalre are numbered DR5-DR13 in

337 figure 9. Their representation and derivation are explained as follows:

338 DR5. Hybrid storage-level curve sewer

339 A hybrid storage-level curve is used to convert V_s into H_s . The derivation follows DR1.

340 The resulting curves for Waalre are displayed in Figure 10: (left) the static, dynamic,

341 and hybrid storage curves, (right) the derivation of the dynamic storage-level curve

342 from the FH model simulation results.

343 DR6. Level sewer at CSO

344 Similar to DR2, a relationship has been derived between H_{CSO} and H_s . As Waalre is

345 equipped with the settling tank two linear segments that connect at the highest weir

346 crest level of the settling tank have been applied. Only elevated water levels (WWF

347 conditions) are taken into account.

348 DR7. Level sewer at connection

349 Similar to H_{CSO} in DR6, a relationship between the water level at the connection to the

350 neighbouring catchment (H_{CONN}) and H_s is derived from the FH model simulations. A

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

353 DR8. Discharge sewer through pump
354 See SR5.

355 DR9. Discharge sewer through connection
356 The discharge of the sewer through the connection to the neighbouring catchment
357 (Q_{CONN}) is based on H_{CONN} and a relationship derived from the FH model simulations.
358 The simulated water levels at the connection and the corresponding flow through the
359 connection were fitted with a third order polynomial equation. To prevent unrealistic
360 (negative) output a maximum value is set for H_{CONN} .

361 DR10. Discharge sewer through CSO
362 See SR7, where H_{CSO} is applied in the calculation of the discharge from the sewer.

363 DR11. Static storage-level curve settling tank
364 See SR8.

365 DR12. Discharge settling tank through pump
366 See SR9.

367 DR13. Discharge settling tank
368 See SR10.

369 **2.5. Calibration procedure**

370 **2.5.1. DREAM algorithm**

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

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

2.5.2. Parameter optimisation

The DREAM algorithm is applied to calibrate the parameters of the RRO model to find the minimal difference between the simplified model output and the measurements. Table 2 shows the parameters, units and the searching range for the calibration procedure.

The algorithm minimises the sum of squared errors (SSE) between the model output and measurements. Water level measurements are applied in the calibration as they are the actual 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 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

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.

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

favoured when high quality information is available (in this case Loenen), while the less detailed model M2, RRO with SR, suffices when the information is of lower quality (Waalre).

One main source of uncertainty for Waalre likely stems from the calibrated rain radar input. The rainfall in general seems reasonable with NS values for M2 or M3 > 0.6 . In detail the rainfall seems off in intensities and/or timing, an example of which can be found in figure 16. Judging from the rainfall, the models responses in Q_{SW} are in accordance (main peak in the outflow after main peak in the rainfall). However, in the measurements the main peak in the outflow occurs right at the beginning of the rain event. The other events display a similar mismatch between the rainfall and the outflow. This may also explain the very low values for the parameters T_{lag} and K , see figure 13, as the calibration procedure tries to correct the mismatch in the input data.

For V_{WWTP} the RMSE values in table 5 show that model M1 consistently performs worse than M2 and M3 for all scenarios and both catchments. M2 and M3 generally perform on a similar level, which is to be expected as the pumping regime in the SR and DR model structures is the same.

The NS values reported in section 3.1 are based on the calibration parameters for each time step, and the FP/FN in table 4 and RMSE in table 5 on V_{SW} . Each presents information on the performance of the model structure. NS indicates the quality of the description of the sewer systems behaviour in general, while the others are specific for CSO discharges. The difference between the best performing model structure based on these criteria, especially for Loenen, is striking. Model M2 and M3 have similar NS values > 0.9 , but M3 is much more accurate 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.

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.

678 – In case of detailed and trustworthy information available for the design and
679 calibration of the model (Loenen), M3 outperforms M2 for all scenarios. If the
680 available information is of lower quality (Waalre), M2 consistently performs
681 slightly better indicating that the derivation of the more detailed DR model is not
682 useful.

683 – For rainfall driven modelling trustworthy and local rain measurements remain
684 necessary despite the availability of rain radar data, to either apply as direct input
685 or the correction of radar data.

686 – M2 and M3 outperform the uncalibrated FH models based on the total discharge
687 to the surface water. In optimisation or RTC studies the application of suitable
688 calibrated simplified models is preferred over uncalibrated FH models.

689

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

695

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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	event	rainfall depth	max rain	duration	discharge to
area			intensity		surface water
	[dd-mm-yyyyy]	[mm]	[mm/h]	[hh:mm]	[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

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			
catchment / model structure	total FP	total FN	total FP	total FN	calibration mean FP	calibration mean FN	verification mean FP	verification 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				

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

RMSE [m ³]								
V_{SW}				V_{WWTP}				
catchment /			3	3			3	3
model	1	2	calibra-	verifica	1	2	calibra-	verifica
structure			tion	-tion			tion	-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		

811

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 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 ($209 \text{ m}^3/\text{h}$ 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.

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

54

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