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

3

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16

17

18 **Abstract**

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

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

33

34

35 **Keywords**

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

38

39 **1. Introduction**

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

55

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

63 to find appropriate calibration algorithms are described in e.g. (Krebs et al., 2014; Mair et al.,
64 2012; Vrugt et al., 2009; Wolfs et al., 2013).

65

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

78

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

87

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

105

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

112

113 **2. Materials and method**

114 **2.1. Catchment areas**

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

123

124 Waalre is located in the south of the Netherlands. The sewer system is looped with one
125 pumping station, a primary CSO equipped with a settling tank and a secondary CSO that rarely
126 discharges. Additionally Waalre is connected to a neighbouring catchment in the east.

127 Although water can flow both ways, it serves as a discharge for Waalre. Characteristics of the
128 sewer systems are listed in table 1, while figure 1 (right) displays the sewer system layout.

129 **2.2. Monitoring data**

130 For Loenen monitoring data is available at a one minute interval from June 2001 to January
131 2002, collected as part of a dedicated research project. Flow measurements are available at
132 the pumping station and an inflow into the pumping station from a neighbouring catchment.
133 Level measurements are available in the pumping chamber and at the CSO locations, as
134 displayed in figure 1 (left). Additionally, two rain gauges were installed in the catchment. Due
135 to various reasons no continuous data set is available for the measuring period.

136

137 For Waalre monitoring data at the sewer system edges is available at a one minute interval.

138 Flow is measured at the pumping station. Level measurements are available in the pumping

139 chamber, inside the settling tank and at the secondary CSO location. The measuring locations

140 are indicated in figure 1 (right). Additional one minute interval rain gauge measurements are

141 performed at several locations approximately 10 km around Waalre. All measurements are

142 recorded permanently. Data validation was performed applying the algorithms described in

143 (Van Bijnen and Korving, 2008). Rain radar data with a five minute interval and pixel size of one

144 square kilometre are available from the Royal Netherlands Meteorological Institute (KNMI).

145 The radar data is calibrated against the rain gauge measurements using a procedure based on

146 conditional merging as described in (De Niet et al., 2013). The rain radar calibration was

147 performed only during wet weather days and when the rain gauges functioned in the period of

148 April 2011 to January 2012.

149

150 **Dry Weather Flow (DWF)**

151 Daily dry weather flow (DWF) profiles have been derived from the monitoring data for both

152 catchments. For Waalre it was based on the pump flow measurements in 2011. The mean

153 hourly pumped discharge at DWF days was used to represent a typical daily DWF profile. DWF

154 days are defined as having received less than 0.05 mm of precipitation after exponential

155 smoothing (80% accounted to the current day and 20% to the following day) to prevent false

156 detection of DWF days due to the absence of rain gauges inside the catchment. Unrealistic

157 measurements and periods with snowfall have been manually discarded. The DWF profile for

158 Loenen was previously derived by (Langeveld, 2004) based on the pump flow measurements

159 using a similar strategy. The resulting profiles can be found in figure 2.

160 **2.3. Full hydrodynamic (FH) models**

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

174

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

184

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

191 **2.4. Model structures**

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

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

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

204

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

206

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

219 **2.4.2. Static reservoir (SR) model**

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

226

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

229 SR1. Static storage-level curve

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

234 SR2. Discharge through pump

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

239 SR3. Discharge through CSO

240 The discharge through the CSO (Q_{CSO}) is taken to be only caused by the primary CSO.

241 The discharge is calculated through H_s and the standard weir equations for frontal
242 weirs:

243

$$244 \quad Q_{free} = c_1 h^{c_2} \quad (2)$$

245

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

248

$$249 \quad Q_{sub} = c_3 h_{DS} \sqrt{2g(h_{US} - h_{DS})} \quad (3)$$

250

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

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

256

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

263

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

266 SR4. Static storage-level curve sewer

267 See SR1, and excluding the settling tank.

268 SR5. Discharge sewer through pump

269 The discharge through the pump ($Q_{S,p}$) is calculated through the water level in the
270 sewer (H_s) and the pump characteristic. The pump characteristic is derived from
271 analysis of the water level and flow measurements at the pumping station, and (Van
272 Daal-Rombouts, 2012). The DWF and maximum capacity are 85 and 400 m³/h
273 respectively. The switch on level is 17.15 m AD, the switch off level 16.30 m AD.

274 SR6. Discharge sewer through connection

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

279

280
$$Q = c_1 \tan (\theta/2) h^{5/2}, \quad (4)$$

281

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

286 SR7. Discharge sewer through CSO

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

290 SR8. Static storage-level curve settling tank

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

293 SR9. Discharge settling tank through pump

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

297 SR10. Discharge settling tank

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

299 **2.4.3. Dynamic reservoir (DR) model**

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

303 and can be compared to the SR model in figure 5. Differences are expressed in the storage-
304 level curve applied (SR1 - DR1) and the water level applied in the CSO discharge (DR2 - no
305 equivalent in the SR model).

306

307 The characteristics or relationships applied in the DR model are numbered DR1-DR4 in figure 7.

308 Their representation and derivation are explained below:

309 DR1. Hybrid storage-level curve

310 A so called hybrid storage-level curve is used to convert the sewer volume (V_s) into the
311 water level in the sewer (H_s). The hybrid curve follows the static storage-level curve
312 (see SR1) for low water levels to correctly model DWF circumstances and pumping
313 behaviour, and gradually turns to the dynamic storage-level curve for high water levels
314 (with possibly pressurised flow conditions) to take the dynamic properties of the sewer
315 system under wet weather flow (WWF) conditions and CSO discharges into account.

316 Figure 8 (left) displays the static, dynamic, and hybrid storage curves for Loenen.

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

325 DR2. Level at CSO

326 H_s is converted into the water level at the primary CSO location (H_{CSO}). The relationship
327 is based on FH model simulations, where a linear relation is fitted through the

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**

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

392 **2.5.2. Parameter optimisation**

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

396

397 The algorithm minimises the sum of squared errors (SSE) between the model output and
398 measurements. Water level measurements are applied in the calibration as they are the actual
399 monitoring data available, containing all information on the sewer systems behaviour. For

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

410

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

419

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

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

426 **2.5.3. Events**

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

432

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

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

442 **2.6. Performance evaluation**

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

447 the WWTP and the surface water. As the RRO models are calibrated, i.e. all calibration
448 parameters are related to rainfall, the focus of the performance evaluation will be on the CSO
449 discharges to the surface water. As the discharge to the WWTP is also relevant for integrated
450 studies it will be reported for completeness.

451

452 Common sense dictates that the impact of CSO events depends foremost on the occurrence of
453 such events, with the absolute discharged flows of secondary consequence. This is supported
454 by literature stating that impact based RTC can influence the systems performance for small
455 and moderate events, contrary to large events on which it has no influence (Langeveld et al.,
456 2013), and that up to a certain point overflow frequency is a good indicator of receiving water
457 impact (Lau et al., 2002). Therefore the first evaluation criterion for the simplified sewer
458 models is the correct determination of CSO event occurrences. The second evaluation criterion
459 is the correct determination of the total discharged volume.

460

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

467

468 CSO event occurrences are analysed through false positives (FP) and false negatives (FN). A FP
469 is defined as a CSO event occurrence ($V_{SW} > 0$) in the model output but not in the
470 measurements, a FN as a CSO event occurrence in the measurements but not in the model
471 output. For the comparison of discharged volumes, differences in V_{SW} (and V_{WWTP}) between the

472 model output and the measurements are calculated and listed for each event and scenario.

473 Cumulative results for each scenario are determined by taking the root mean squared errors

474 (RMSE) over all events.

475

476 For comparison purposes the selected rain events have also been simulated using the FH

477 models. The comparison between simplified models with calibrated inflow parameters and FH

478 models with uncalibrated inflow parameters is relevant since the FH models simulate the

479 sewer systems behaviour in greatest detail and hence are deemed to be most accurate (Ferreri

480 et al., 2010; Meirlaen et al., 2001; Rubinato et al., 2013). This might hold true for calibrated FH

481 models but not for the much more commonly applied uncalibrated models, as proper

482 calibration of FH models is very time consuming and requires a very large monitoring data set.

483

484 Finally, the simulation time needed by different simplified model structures and the FH model

485 will be compared.

486

487 3. Results and discussion

488 3.1. Calibration

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

495

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

503

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

510 sewer storage. The response to rainfall is therefore more smoothed, which is best
511 demonstrated in figure 11. NS values < 0.4 are found.
512
513 For both catchments and all model structures the 95% confidence bands are mostly $< 1\%$.
514 Logically, the influence of the (inflow) calibration parameters on water levels in sewer systems
515 is most apparent at the onset of a rain event or during temporal changes, resulting in
516 confidence bands up to 10% for M2 and M3, while they stay $< 1\%$ for M1.
517
518 For all scenarios for Loenen NS values for M2 and M3 > 0.90 . For M1, values differ strongly
519 from -8.52 to 0.44. For Waalre for M2 and M3 in scenario 1, NS values range between 0.61 and
520 0.96, with one event around zero. In scenario 2 the values drop to 0.5 to 0.6. The NS values for
521 M1 again differ strongly between events and scenarios from -9.42 to 0.82.
522
523 Figure 13 shows the optimal parameter values for Loenen (left) and Waalre (right) for all
524 model structures. In asterisks the results for scenario 1 (calibration on single rain events) are
525 given, the line indicates the parameter values for scenario 2 (all events together). Results for
526 all twenty possible combinations of three calibration events in scenario 3 can be found in
527 figure 14. The optimal parameter values reflect the results for the water levels and NS values:
528 the parameters for M2 and M3 show much resemblance within a catchment, while M1
529 deviates. Especially the difference in K stands out, as the RRO model in M1 has to account for
530 the surface and in-sewer storage, while in M2 and M3 only for the surface storage. The
531 optimal parameter values between scenarios 2 (line in figure 13) and 3 (figure 14) are
532 consistent, indicating that the exact split in a calibration and verification set does not have a
533 major impact on the outcome.

534 **3.2. Performance evaluation**

535 **3.2.1. Model discharge**

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

539

540 Optimal Q_{SW} and Q_{WWTP} for all model structures for the calibration of the single events of 2001-
541 08-27 (Loenen) and 2011-08-14 (Waalre) are displayed in figures 15 and 16 as well as the
542 discharges determined from the measurements. The difference between M1 and M2/M3
543 observed in the calibration results are also clear from these figures, as Q_{SW} for M1 tends to be
544 more smoothed because of the higher value for K.

545 **3.2.2. Determination of CSO events**

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

550

551 Based on the FPs and FNs in table 4, M1 can be immediately discarded for these catchments.
552 For each scenario and catchment two FPs were recorded, the exact number of rain events that
553 did not lead to a CSO event. This is easily explained since a rain event leading to a significant
554 rise in water level in a pumped sewer system will likely contain rain intensities higher than the
555 pumping capacity of the sewer system reserved for WWF (design guideline in the Netherlands:
556 0.7 mm/h). In M1 all rainfall in excess of this capacity has to be discharged to the surface
557 water, leading to a CSO event. The calibration algorithm unsuccessfully tries to overcome this

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

568 **3.2.3. Determination of discharged volumes**

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

582

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

587

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

598

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

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

609

610 One main source of uncertainty for Waalre likely stems from the calibrated rain radar input.

611 The rainfall in general seems reasonable with NS values for M2 or M3 > 0.6. In detail the

612 rainfall seems off in intensities and/or timing, an example of which can be found in figure 16.

613 Judging from the rainfall, the models responses in Q_{SW} are in accordance (main peak in the

614 outflow after main peak in the rainfall). However, in the measurements the main peak in the

615 outflow occurs right at the beginning of the rain event. The other events display a similar

616 mismatch between the rainfall and the outflow. This may also explain the very low values for

617 the parameters T_{lag} and K , see figure 13, as the calibration procedure tries to correct the

618 mismatch in the input data.

619

620 For V_{WWTP} the RMSE values in table 5 show that model M1 consistently performs worse than

621 M2 and M3 for all scenarios and both catchments. M2 and M3 generally perform on a similar

622 level, which is to be expected as the pumping regime in the SR and DR model structures is the

623 same.

624

625 The NS values reported in section 3.1 are based on the calibration parameters for each time

626 step, and the FP/FN in table 4 and RMSE in table 5 on V_{SW} . Each presents information on the

627 performance of the model structure. NS indicates the quality of the description of the sewer

628 systems behaviour in general, while the others are specific for CSO discharges. The difference

629 between the best performing model structure based on these criteria, especially for Loenen,

630 is striking. Model M2 and M3 have similar NS values > 0.9, but M3 is much more accurate

631 based on FP/FN and RMSE. Simplified sewer models are calibrated on measurements,

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

635 **3.2.4. Uncalibrated FH models**

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

640

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

644

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

651

652 The simulation time for the FH models takes 1,000-5,000 times longer than for M2/M3 or
653 250,000-475,000 times longer than for M1.

654

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

659 **4. Conclusions and future research**

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

666

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

673

674 From this research the following conclusions can be drawn:

- 675 – Model M1 simulates > 100,000 times faster than the FH model; models M2/M3
676 are > 1,000 times faster than the FH model.
- 677 – M1 is unsuitable to correctly predict CSO occurrences for pumped catchments.
678 The model structure is unable to retain rain intensities higher than the pumping
679 capacity reserved for WWF, resulting in too many CSO discharges.
- 680 – M2 and M3 are able to describe the behaviour of pumped sewer systems.
- 681 – Performance indicators for the selection of the most appropriate model structure
682 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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1 **DESIGN AND PERFORMANCE EVALUATION OF A SIMPLIFIED DYNAMIC MODEL FOR**
2 **COMBINED SEWER OVERFLOWS IN PUMPED SEWER SYSTEMS**

3

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16

17

18 **Abstract**

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

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

33

34

35 **Keywords**

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

38

39 **1. Introduction**

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

55

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

63 to find appropriate calibration algorithms are described in e.g. (Krebs et al., 2014; Mair et al.,
64 2012; Vrugt et al., 2009; Wolfs et al., 2013).

65

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

78

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

87

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

105

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

112

113 **2. Materials and method**

114 **2.1. Catchment areas**

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

123

124 Waalre is located in the south of the Netherlands. The sewer system is looped with one
125 pumping station, a primary CSO equipped with a settling tank and a secondary CSO that rarely
126 discharges. Additionally Waalre is connected to a neighbouring catchment in the east.

127 Although water can flow both ways, it serves as a discharge for Waalre. Characteristics of the
128 sewer systems are listed in table 1, while figure 1 (right) displays the sewer system layout.

129 **2.2. Monitoring data**

130 For Loenen monitoring data is available at a one minute interval from June 2001 to January
131 2002, collected as part of a dedicated research project. Flow measurements are available at
132 the pumping station and an inflow into the pumping station from a neighbouring catchment.
133 Level measurements are available in the pumping chamber and at the CSO locations, as
134 displayed in figure 1 (left). Additionally, two rain gauges were installed in the catchment. Due
135 to various reasons no continuous data set is available for the measuring period.

136

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

149

150 **Dry Weather Flow (DWF)**

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

160 **2.3. Full hydrodynamic (FH) models**

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

174

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

184

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

191 **2.4. Model structures**

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

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

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

204

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

206

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

219 **2.4.2. Static reservoir (SR) model**

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

226

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

229 SR1. Static storage-level curve

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

234 SR2. Discharge through pump

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

239 SR3. Discharge through CSO

240 The discharge through the CSO (Q_{CSO}) is taken to be only caused by the primary CSO.

241 The discharge is calculated through H_s and the standard weir equations for frontal
242 weirs:

243

$$244 \quad Q_{free} = c_1 h^{c_2} \quad (2)$$

245

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

248

$$249 \quad Q_{sub} = c_3 h_{DS} \sqrt{2g(h_{US} - h_{DS})} \quad (3)$$

250

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

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

256

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

263

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

266 SR4. Static storage-level curve sewer

267 See SR1, and excluding the settling tank.

268 SR5. Discharge sewer through pump

269 The discharge through the pump ($Q_{S,p}$) is calculated through the water level in the
270 sewer (H_s) and the pump characteristic. The pump characteristic is derived from
271 analysis of the water level and flow measurements at the pumping station, and (Van
272 Daal-Rombouts, 2012). The DWF and maximum capacity are 85 and 400 m³/h
273 respectively. The switch on level is 17.15 m AD, the switch off level 16.30 m AD.

274 SR6. Discharge sewer through connection

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

279

280
$$Q = c_1 \tan (\theta/2) h^{5/2}, \quad (4)$$

281

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

286 SR7. Discharge sewer through CSO

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

290 SR8. Static storage-level curve settling tank

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

293 SR9. Discharge settling tank through pump

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

297 SR10. Discharge settling tank

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

299 **2.4.3. Dynamic reservoir (DR) model**

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

303 and can be compared to the SR model in figure 5. Differences are expressed in the storage-
304 level curve applied (SR1 - DR1) and the water level applied in the CSO discharge (DR2 - no
305 equivalent in the SR model).

306

307 The characteristics or relationships applied in the DR model are numbered DR1-DR4 in figure 7.

308 Their representation and derivation are explained below:

309 DR1. Hybrid storage-level curve

310 A so called hybrid storage-level curve is used to convert the sewer volume (V_s) into the
311 water level in the sewer (H_s). The hybrid curve follows the static storage-level curve
312 (see SR1) for low water levels to correctly model DWF circumstances and pumping
313 behaviour, and gradually turns to the dynamic storage-level curve for high water levels
314 (with possibly pressurised flow conditions) to take the dynamic properties of the sewer
315 system under wet weather flow (WWF) conditions and CSO discharges into account.

316 Figure 8 (left) displays the static, dynamic, and hybrid storage curves for Loenen.

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

325 DR2. Level at CSO

326 H_s is converted into the water level at the primary CSO location (H_{CSO}). The relationship
327 is based on FH model simulations, where a linear relation is fitted through the

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**

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

392 **2.5.2. Parameter optimisation**

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

396

397 The algorithm minimises the sum of squared errors (SSE) between the model output and
398 measurements. Water level measurements are applied in the calibration as they are the actual
399 monitoring data available, containing all information on the sewer systems behaviour. For

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

410

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

419

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

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

426 **2.5.3. Events**

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

432

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

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

442 **2.6. Performance evaluation**

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

447 the WWTP and the surface water. As the RRO models are calibrated, i.e. all calibration
448 parameters are related to rainfall, the focus of the performance evaluation will be on the CSO
449 discharges to the surface water. As the discharge to the WWTP is also relevant for integrated
450 studies it will be reported for completeness.

451

452 Common sense dictates that the impact of CSO events depends foremost on the occurrence of
453 such events, with the absolute discharged flows of secondary consequence. This is supported
454 by literature stating that impact based RTC can influence the systems performance for small
455 and moderate events, contrary to large events on which it has no influence (Langeveld et al.,
456 2013), and that up to a certain point overflow frequency is a good indicator of receiving water
457 impact (Lau et al., 2002). Therefore the first evaluation criterion for the simplified sewer
458 models is the correct determination of CSO event occurrences. The second evaluation criterion
459 is the correct determination of the total discharged volume.

460

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

467

468 CSO event occurrences are analysed through false positives (FP) and false negatives (FN). A FP
469 is defined as a CSO event occurrence ($V_{SW} > 0$) in the model output but not in the
470 measurements, a FN as a CSO event occurrence in the measurements but not in the model
471 output. For the comparison of discharged volumes, differences in V_{SW} (and V_{WWTP}) between the

472 model output and the measurements are calculated and listed for each event and scenario.

473 Cumulative results for each scenario are determined by taking the root mean squared errors

474 (RMSE) over all events.

475

476 For comparison purposes the selected rain events have also been simulated using the FH

477 models. The comparison between simplified models with calibrated inflow parameters and FH

478 models with uncalibrated inflow parameters is relevant since the FH models simulate the

479 sewer systems behaviour in greatest detail and hence are deemed to be most accurate (Ferreri

480 et al., 2010; Meirlaen et al., 2001; Rubinato et al., 2013). This might hold true for calibrated FH

481 models but not for the much more commonly applied uncalibrated models, as proper

482 calibration of FH models is very time consuming and requires a very large monitoring data set.

483

484 Finally, the simulation time needed by different simplified model structures and the FH model

485 will be compared.

486

487 **3. Results and discussion**

488 **3.1. Calibration**

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

495

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

503

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

510 sewer storage. The response to rainfall is therefore more smoothed, which is best
511 demonstrated in figure 11. NS values < 0.4 are found.
512
513 For both catchments and all model structures the 95% confidence bands are mostly $< 1\%$.
514 Logically, the influence of the (inflow) calibration parameters on water levels in sewer systems
515 is most apparent at the onset of a rain event or during temporal changes, resulting in
516 confidence bands up to 10% for M2 and M3, while they stay $< 1\%$ for M1.
517
518 For all scenarios for Loenen NS values for M2 and M3 > 0.90 . For M1, values differ strongly
519 from -8.52 to 0.44. For Waalre for M2 and M3 in scenario 1, NS values range between 0.61 and
520 0.96, with one event around zero. In scenario 2 the values drop to 0.5 to 0.6. The NS values for
521 M1 again differ strongly between events and scenarios from -9.42 to 0.82.
522
523 Figure 13 shows the optimal parameter values for Loenen (left) and Waalre (right) for all
524 model structures. In asterisks the results for scenario 1 (calibration on single rain events) are
525 given, the line indicates the parameter values for scenario 2 (all events together). Results for
526 all twenty possible combinations of three calibration events in scenario 3 can be found in
527 figure 14. The optimal parameter values reflect the results for the water levels and NS values:
528 the parameters for M2 and M3 show much resemblance within a catchment, while M1
529 deviates. Especially the difference in K stands out, as the RRO model in M1 has to account for
530 the surface and in-sewer storage, while in M2 and M3 only for the surface storage. The
531 optimal parameter values between scenarios 2 (line in figure 13) and 3 (figure 14) are
532 consistent, indicating that the exact split in a calibration and verification set does not have a
533 major impact on the outcome.

534 **3.2. Performance evaluation**

535 **3.2.1. Model discharge**

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

539

540 Optimal Q_{SW} and Q_{WWTP} for all model structures for the calibration of the single events of 2001-
541 08-27 (Loenen) and 2011-08-14 (Waalre) are displayed in figures 15 and 16 as well as the
542 discharges determined from the measurements. The difference between M1 and M2/M3
543 observed in the calibration results are also clear from these figures, as Q_{SW} for M1 tends to be
544 more smoothed because of the higher value for K.

545 **3.2.2. Determination of CSO events**

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

550

551 Based on the FPs and FNs in table 4, M1 can be immediately discarded for these catchments.
552 For each scenario and catchment two FPs were recorded, the exact number of rain events that
553 did not lead to a CSO event. This is easily explained since a rain event leading to a significant
554 rise in water level in a pumped sewer system will likely contain rain intensities higher than the
555 pumping capacity of the sewer system reserved for WWF (design guideline in the Netherlands:
556 0.7 mm/h). In M1 all rainfall in excess of this capacity has to be discharged to the surface
557 water, leading to a CSO event. The calibration algorithm unsuccessfully tries to overcome this

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

568 **3.2.3. Determination of discharged volumes**

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

582

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

587

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

598

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

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

609

610 One main source of uncertainty for Waalre likely stems from the calibrated rain radar input.

611 The rainfall in general seems reasonable with NS values for M2 or M3 > 0.6. In detail the

612 rainfall seems off in intensities and/or timing, an example of which can be found in figure 16.

613 Judging from the rainfall, the models responses in Q_{SW} are in accordance (main peak in the

614 outflow after main peak in the rainfall). However, in the measurements the main peak in the

615 outflow occurs right at the beginning of the rain event. The other events display a similar

616 mismatch between the rainfall and the outflow. This may also explain the very low values for

617 the parameters T_{lag} and K , see figure 13, as the calibration procedure tries to correct the

618 mismatch in the input data.

619

620 For V_{WWTP} the RMSE values in table 5 show that model M1 consistently performs worse than

621 M2 and M3 for all scenarios and both catchments. M2 and M3 generally perform on a similar

622 level, which is to be expected as the pumping regime in the SR and DR model structures is the

623 same.

624

625 The NS values reported in section 3.1 are based on the calibration parameters for each time

626 step, and the FP/FN in table 4 and RMSE in table 5 on V_{SW} . Each presents information on the

627 performance of the model structure. NS indicates the quality of the description of the sewer

628 systems behaviour in general, while the others are specific for CSO discharges. The difference

629 between the best performing model structure based on these criteria, especially for Loenen,

630 is striking. Model M2 and M3 have similar NS values > 0.9, but M3 is much more accurate

631 based on FP/FN and RMSE. Simplified sewer models are calibrated on measurements,

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

635 **3.2.4. Uncalibrated FH models**

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

640

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

644

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

651

652 The simulation time for the FH models takes 1,000-5,000 times longer than for M2/M3 or
653 250,000-475,000 times longer than for M1.

654

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

659 **4. Conclusions and future research**

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

666

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

673

674 From this research the following conclusions can be drawn:

- 675 – Model M1 simulates > 100,000 times faster than the FH model; models M2/M3
676 are > 1,000 times faster than the FH model.
- 677 – M1 is unsuitable to correctly predict CSO occurrences for pumped catchments.
678 The model structure is unable to retain rain intensities higher than the pumping
679 capacity reserved for WWF, resulting in too many CSO discharges.
- 680 – M2 and M3 are able to describe the behaviour of pumped sewer systems.
- 681 – Performance indicators for the selection of the most appropriate model structure
682 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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720

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

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

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

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

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

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

5

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

7

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

11

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

14

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

17

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

20

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

23

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

26

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

29

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

32

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

35

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

38

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

42

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

46

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

48

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

50

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

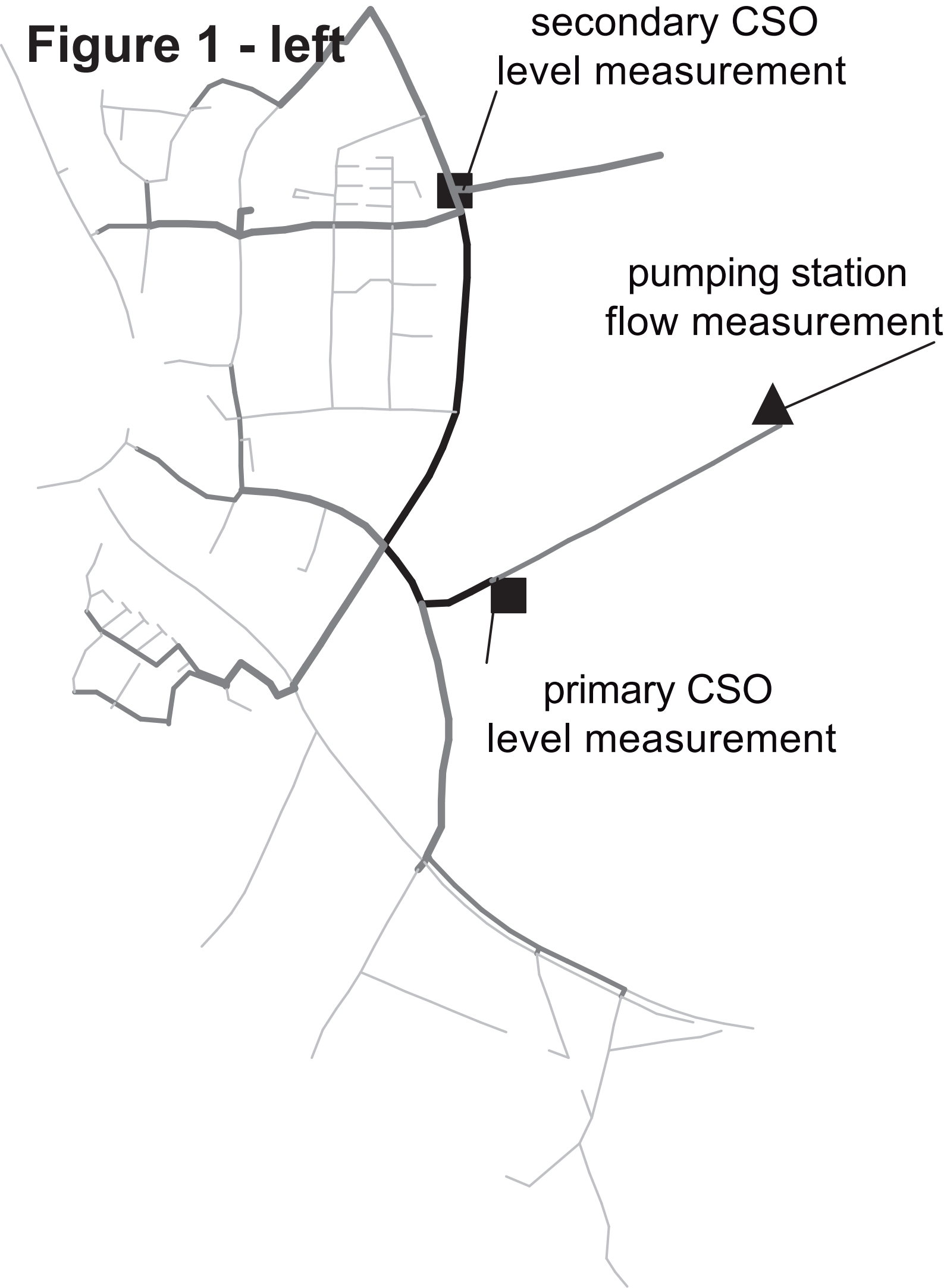


Figure 1 - right

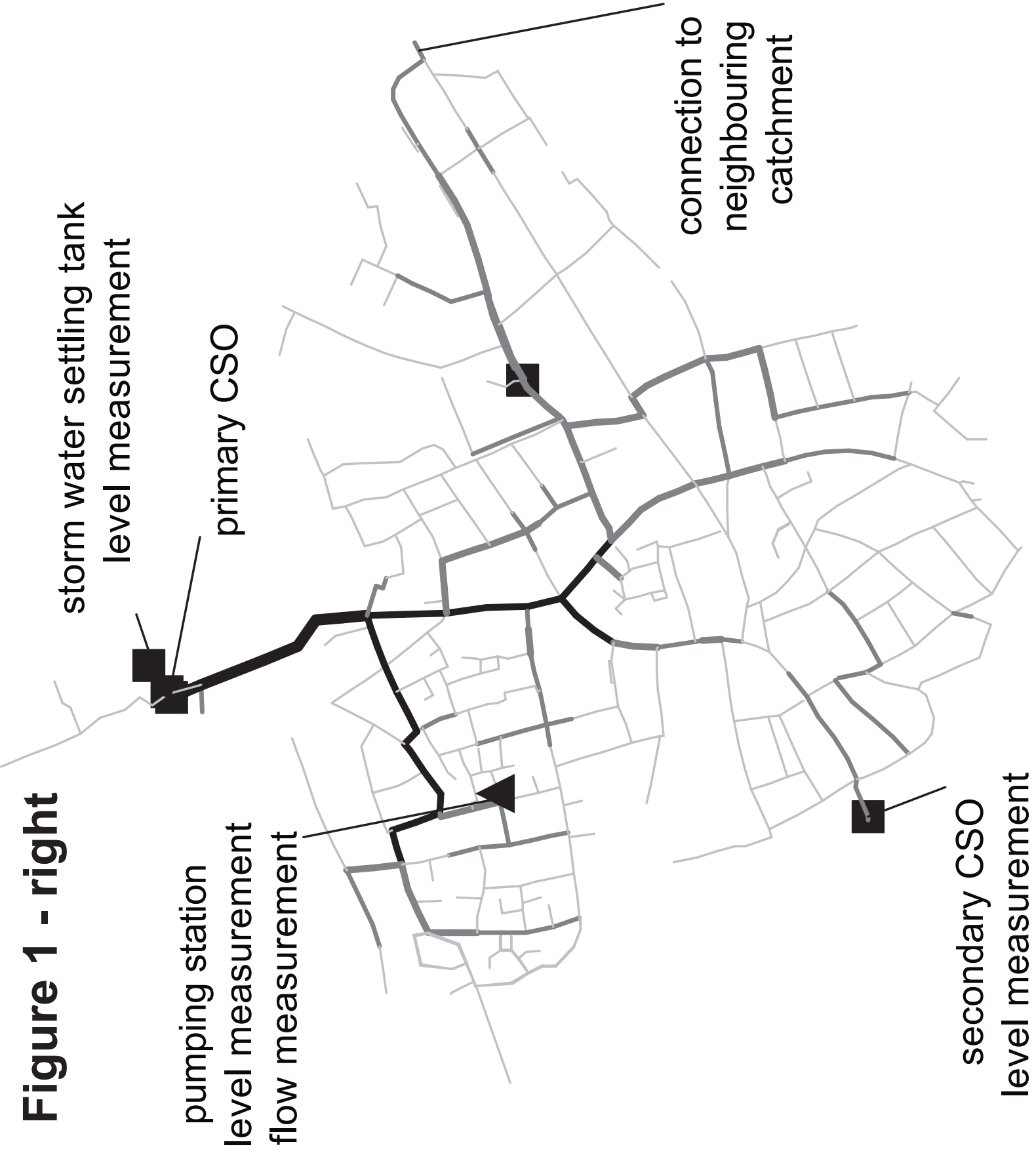


Figure 2

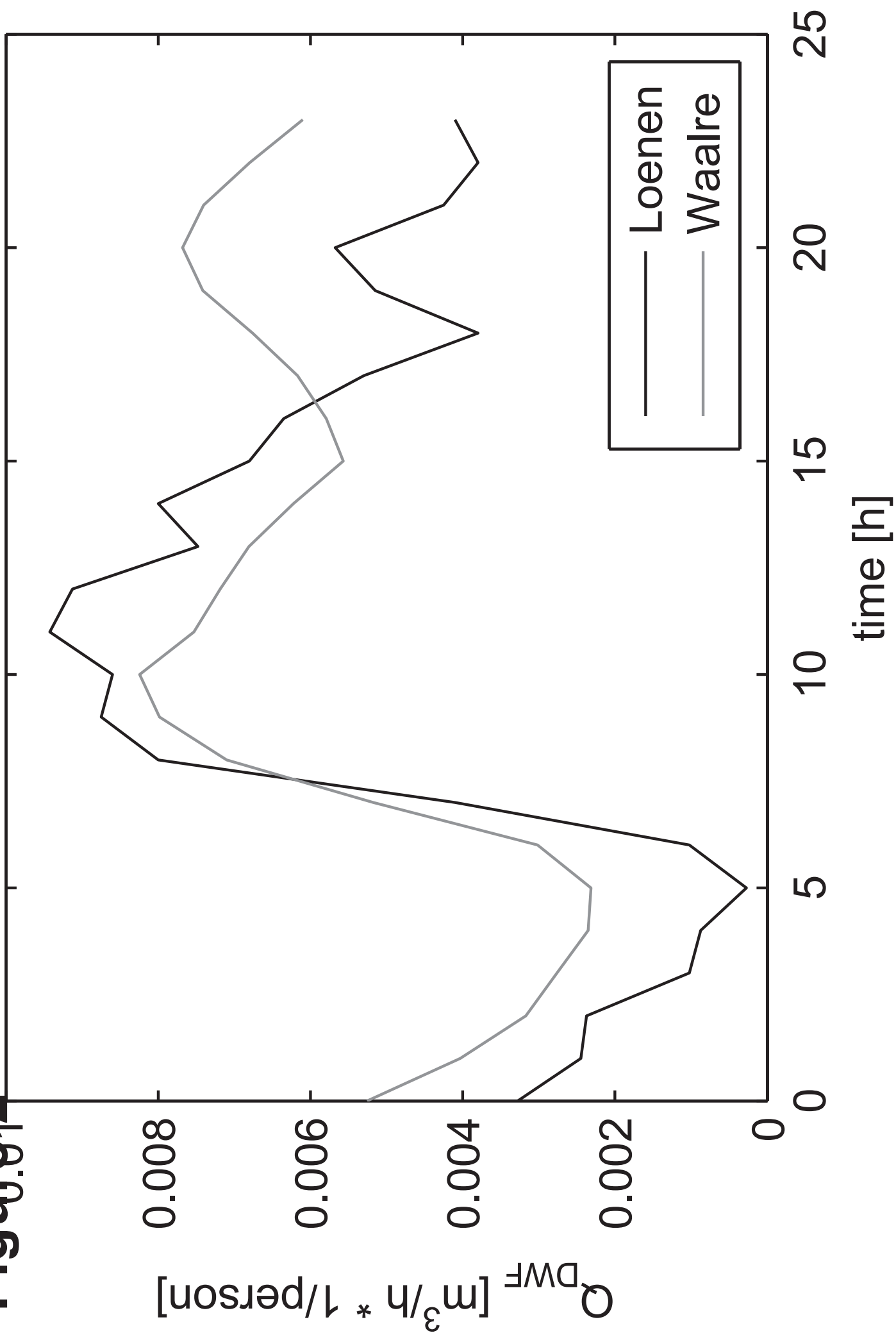


Figure 3

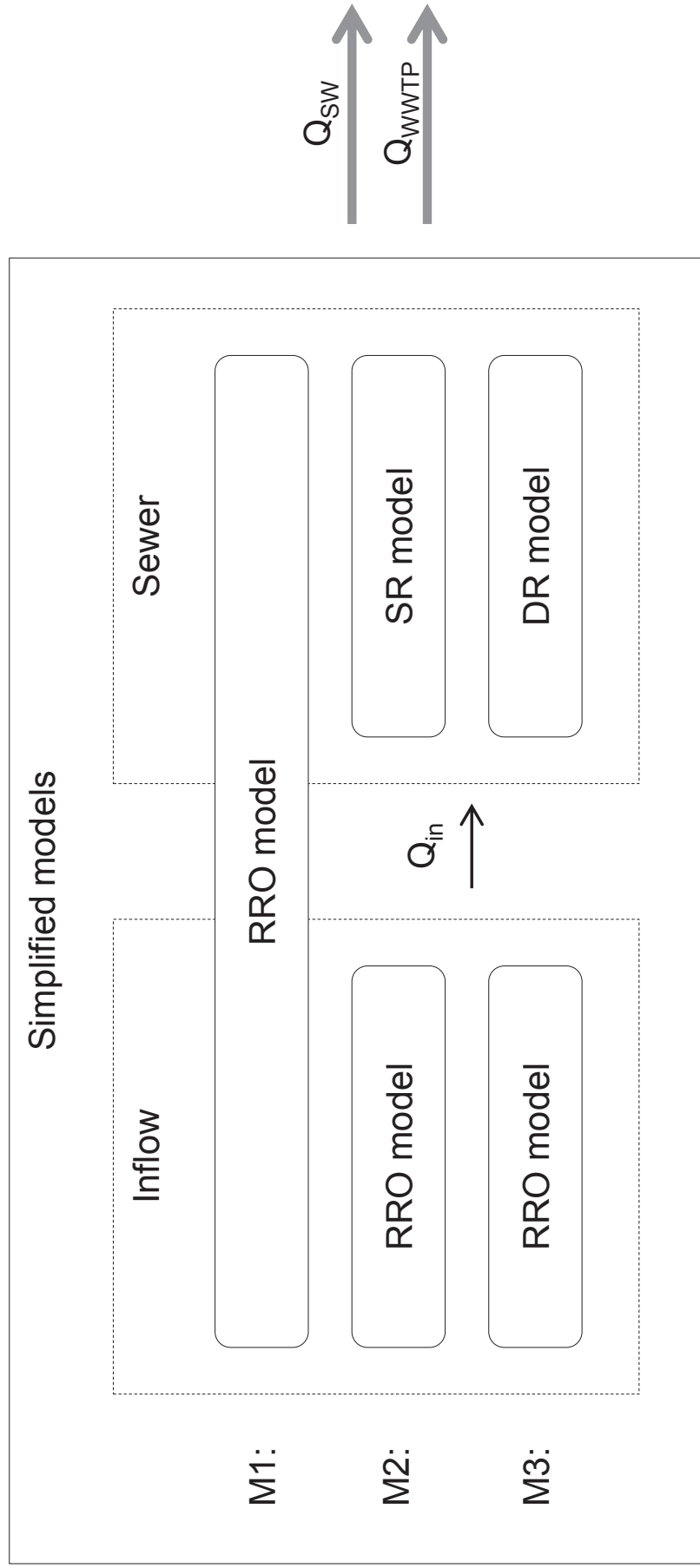


Figure 4

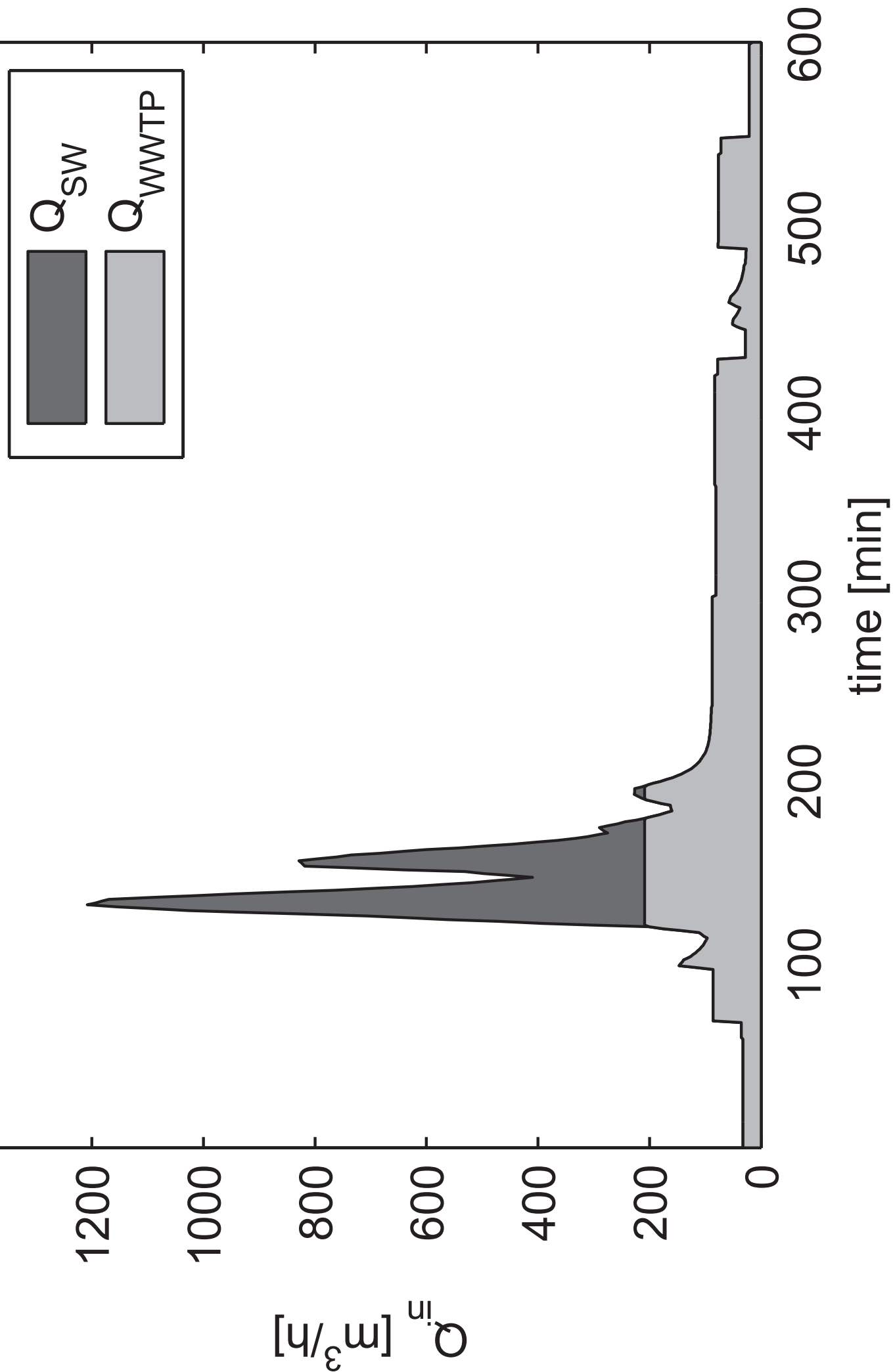


Figure 5 - total SR model Loenen with graphs SR1-SR3

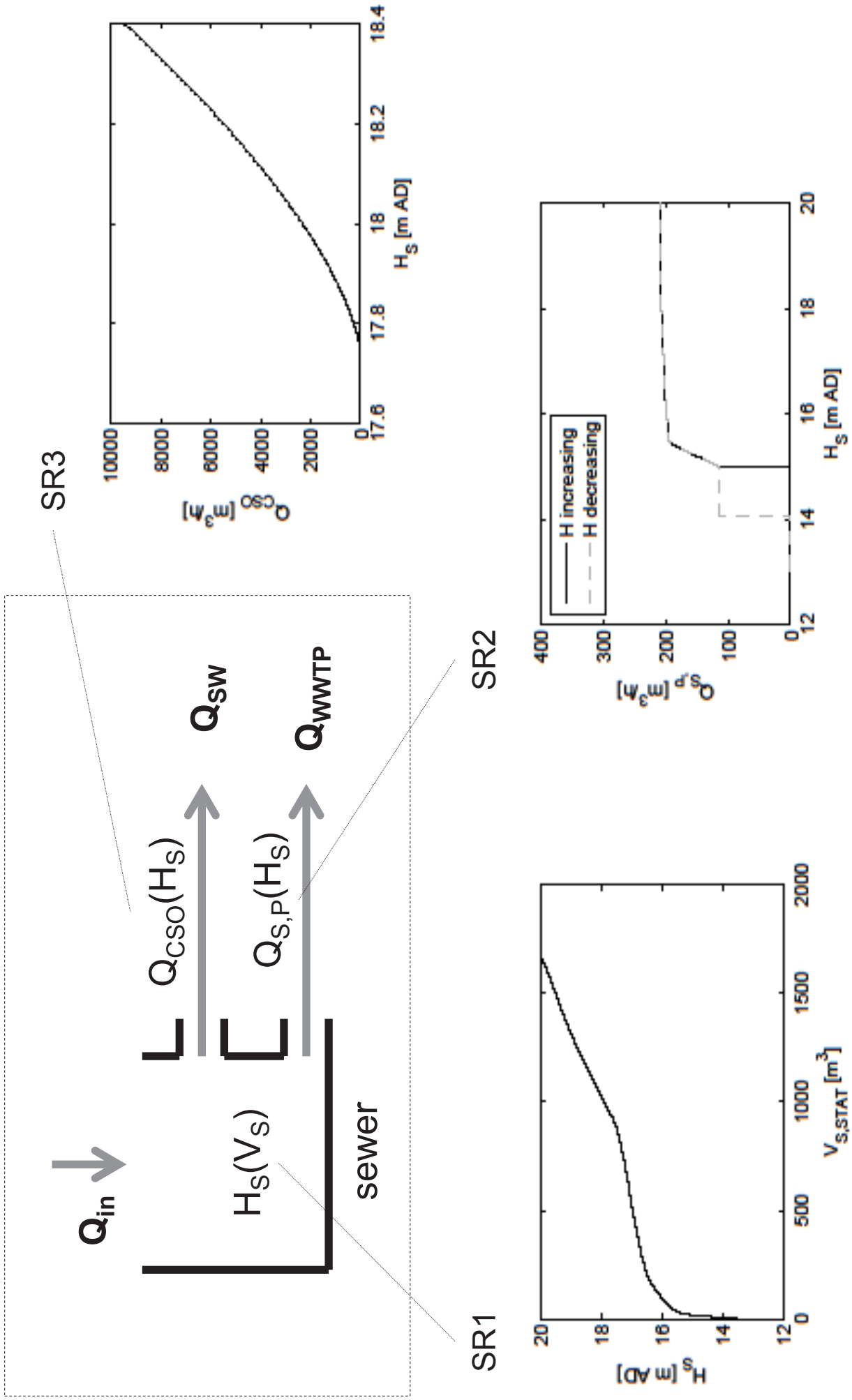


Figure 5 - high res SR1

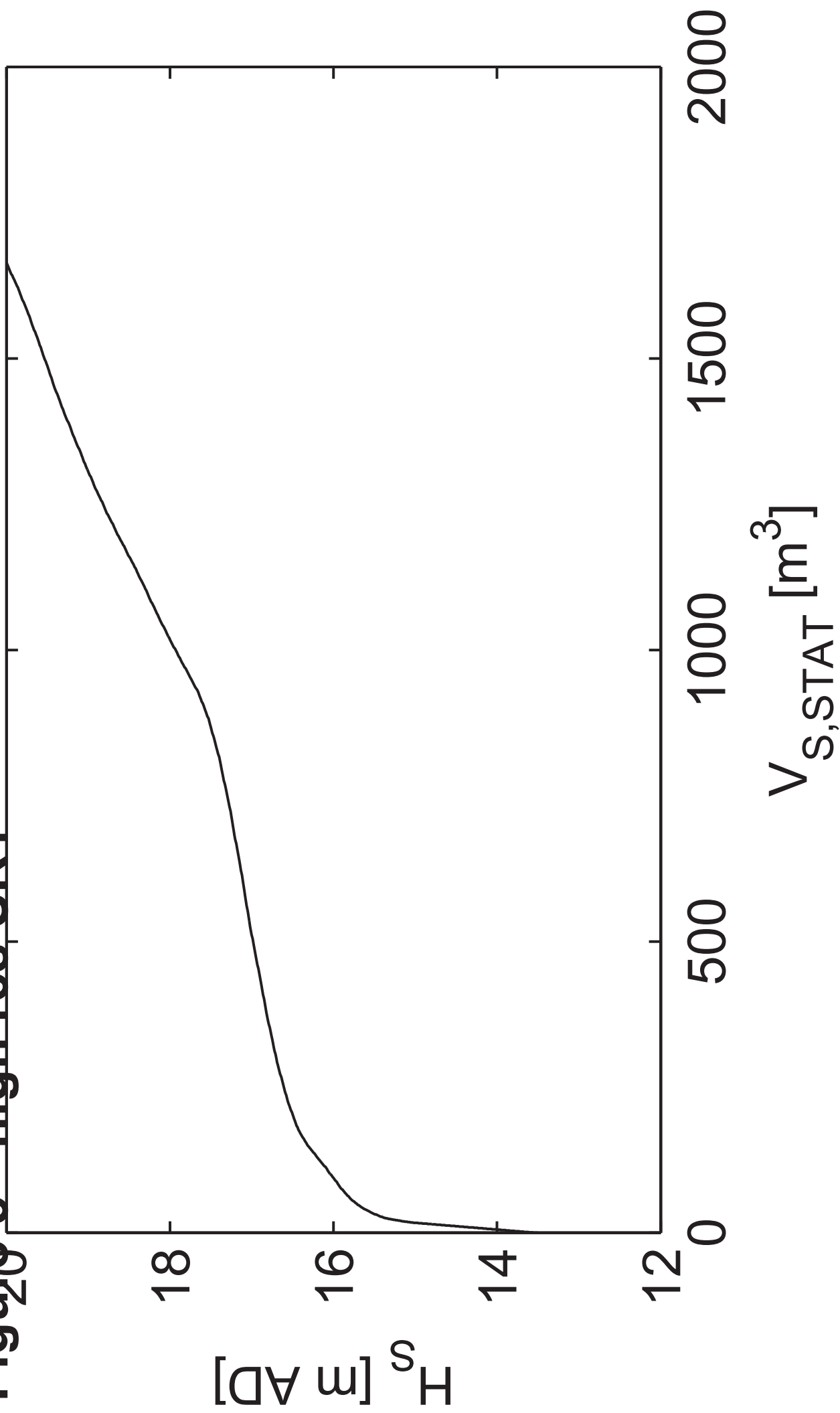


Figure 5 - high res SR2

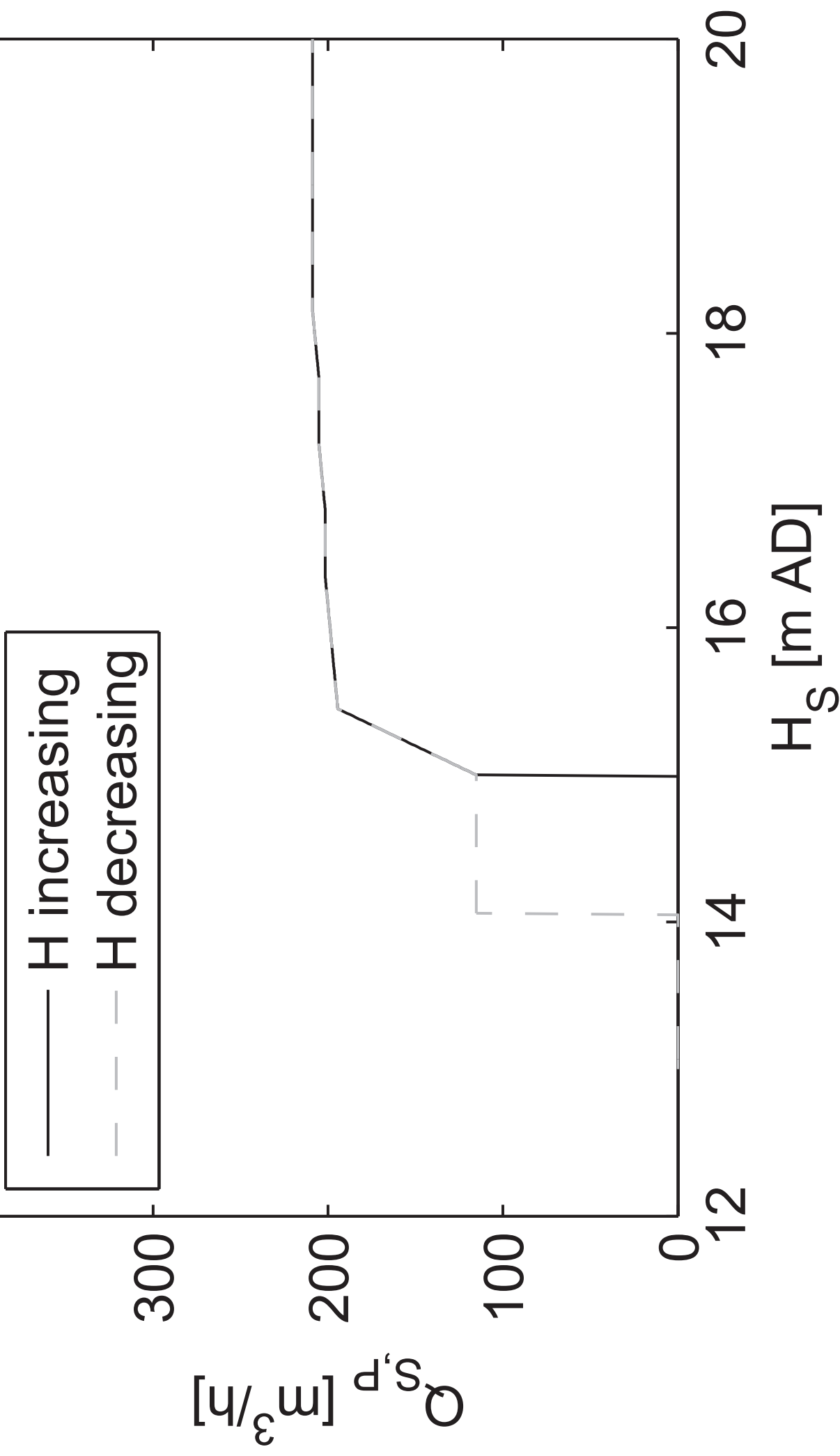


Figure 500 high res SR3

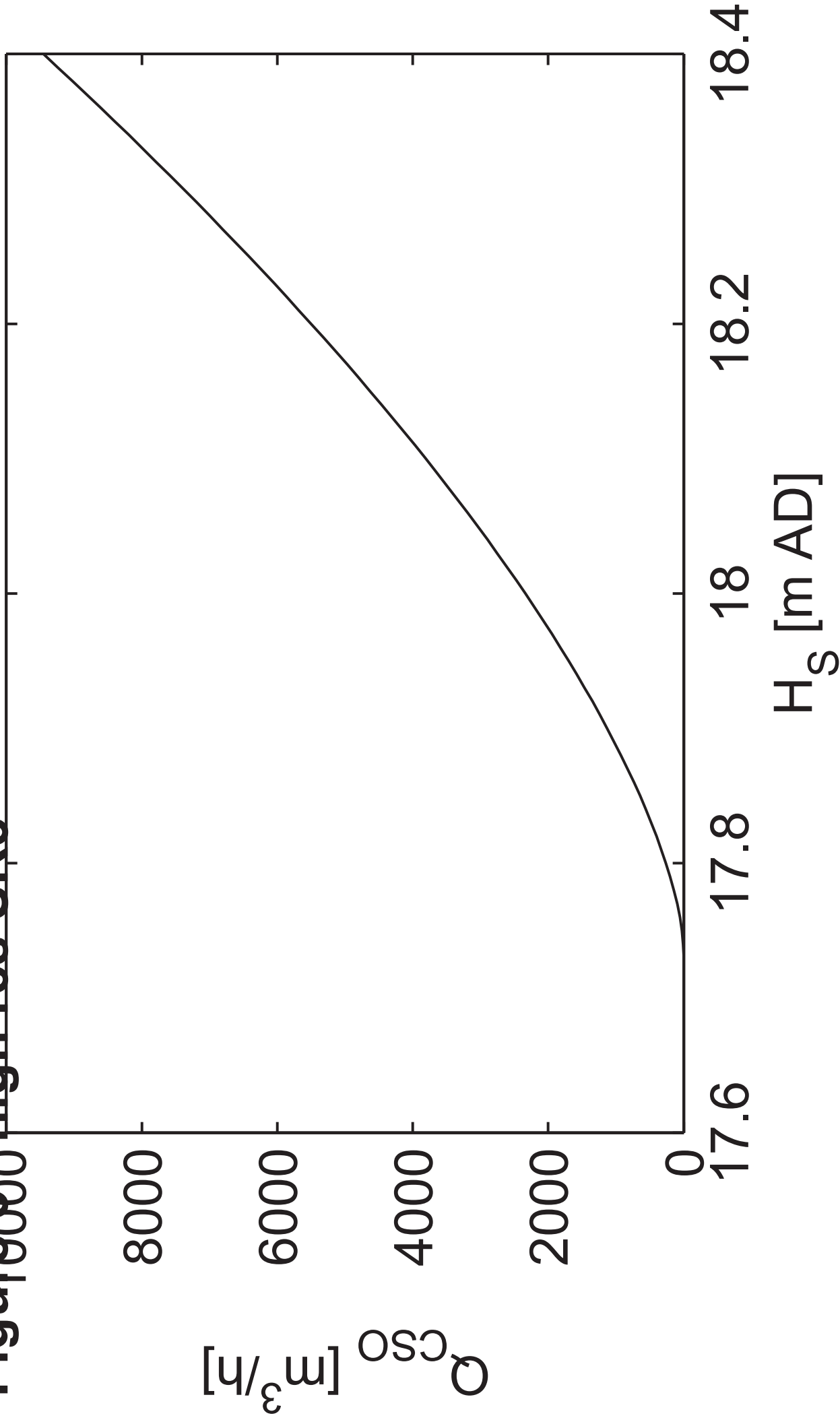


Figure 6 - total SR model Waalre with graphs SR4-SR10

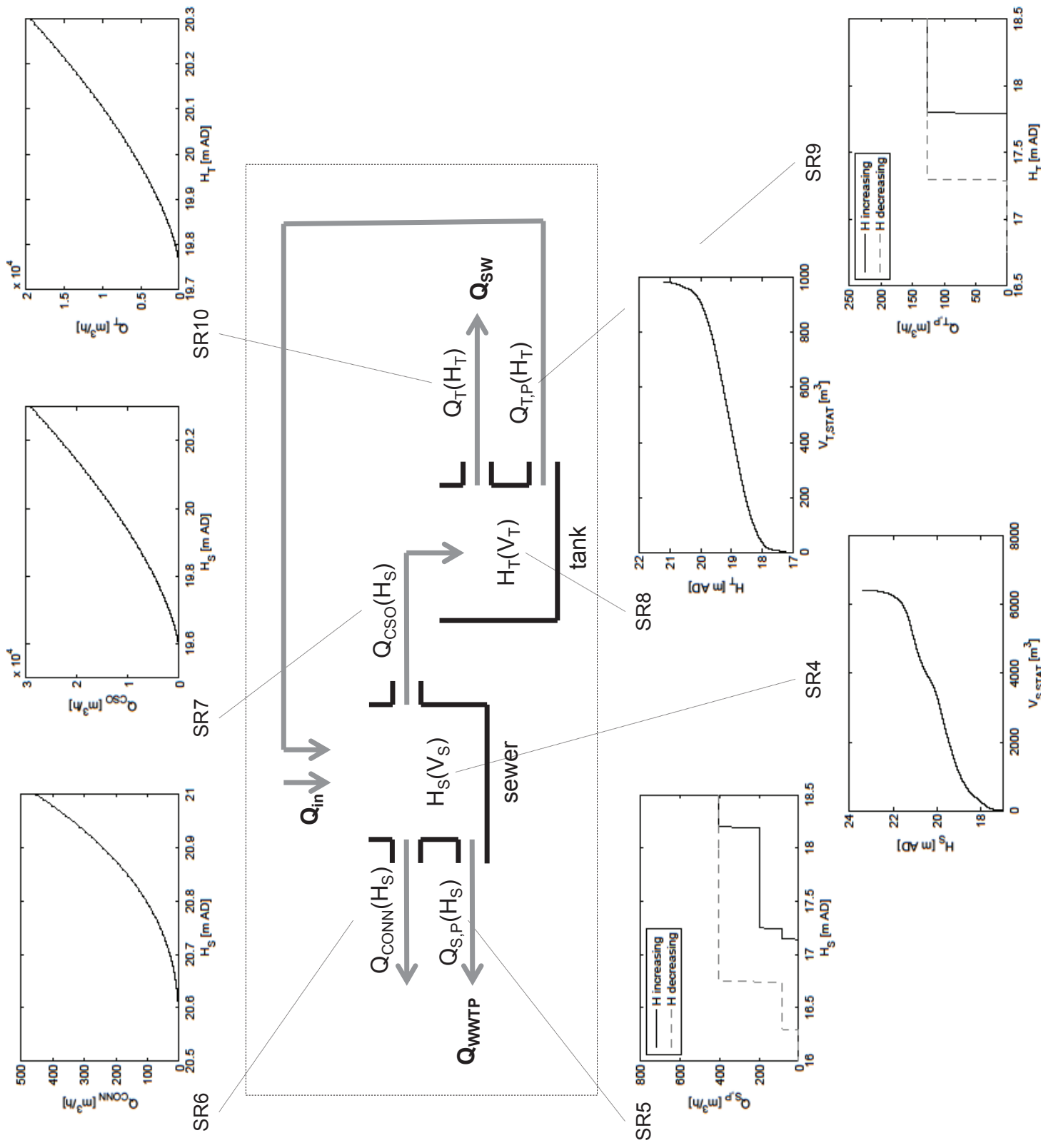


Figure 6 - high res SR4

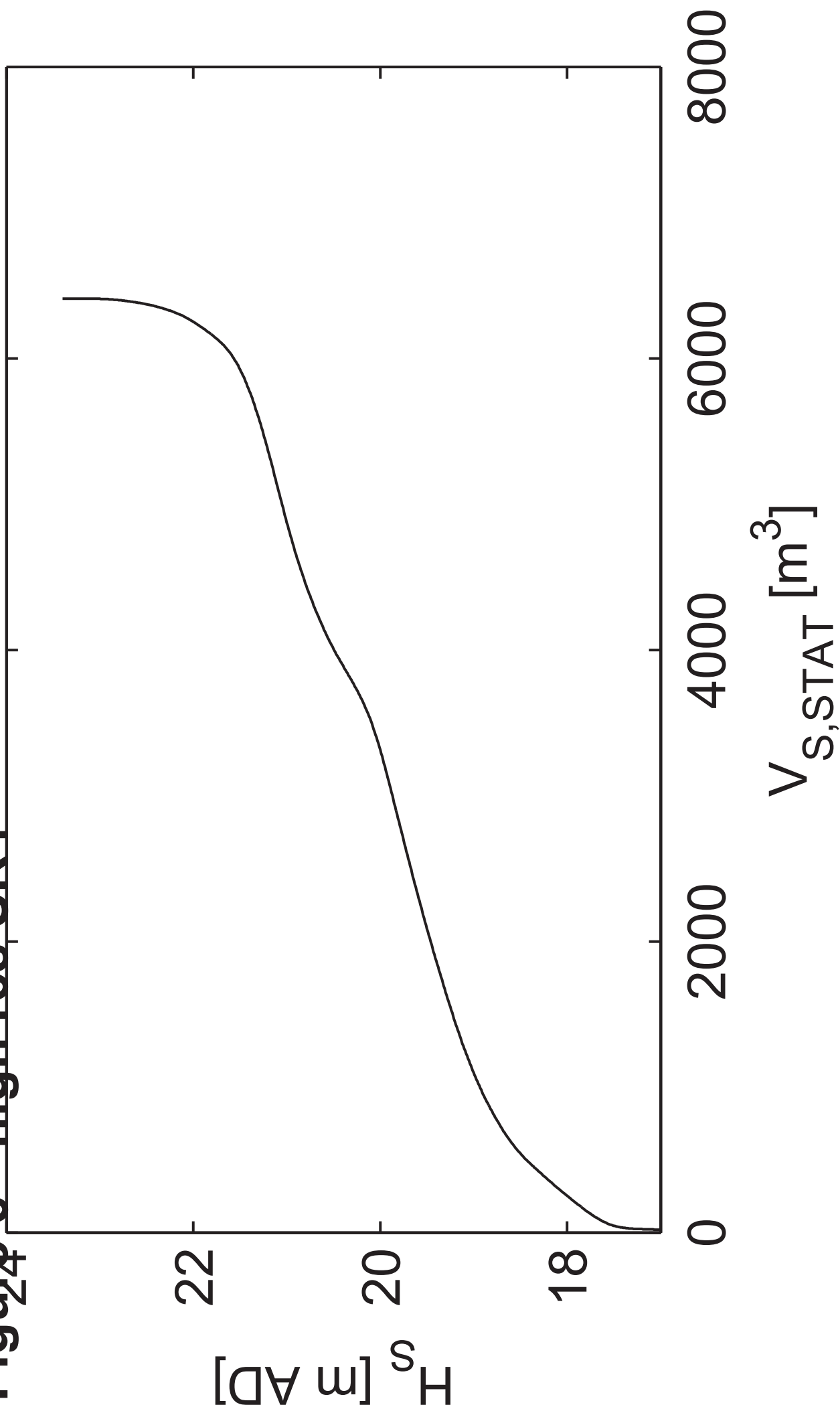


Figure 6 - high res SR5

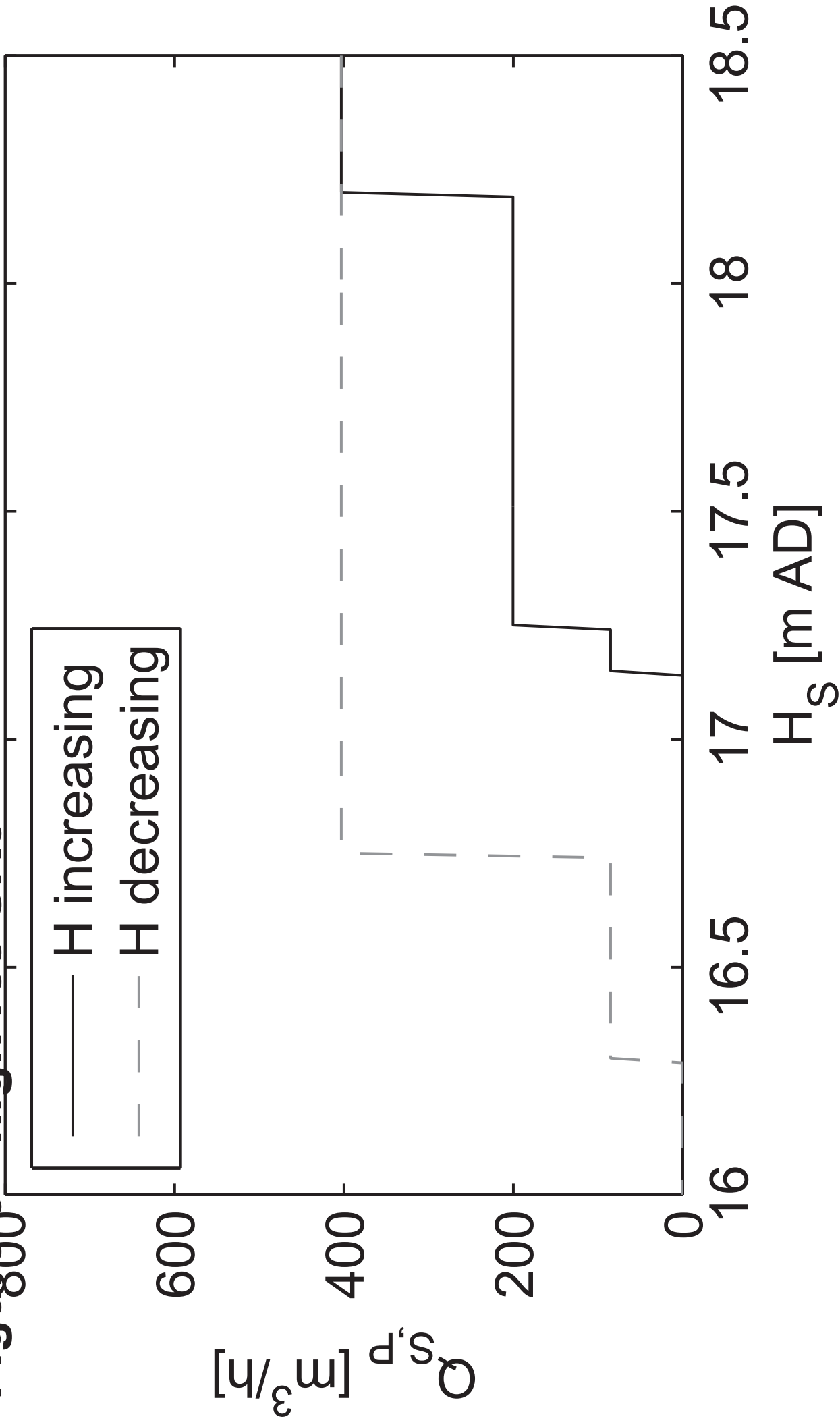


Figure 6 - high res SR6

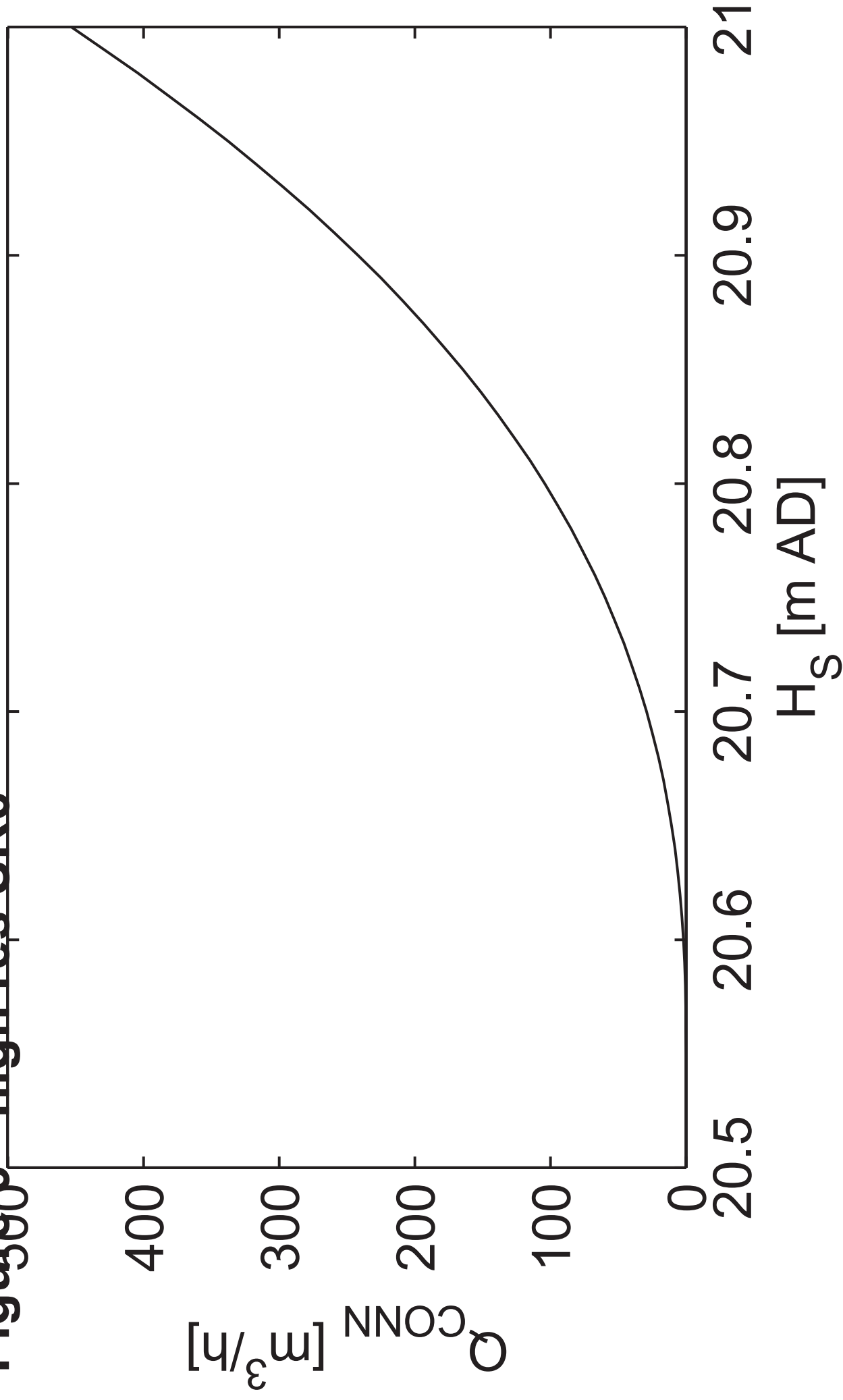


Figure 6-10⁴ high res SR7

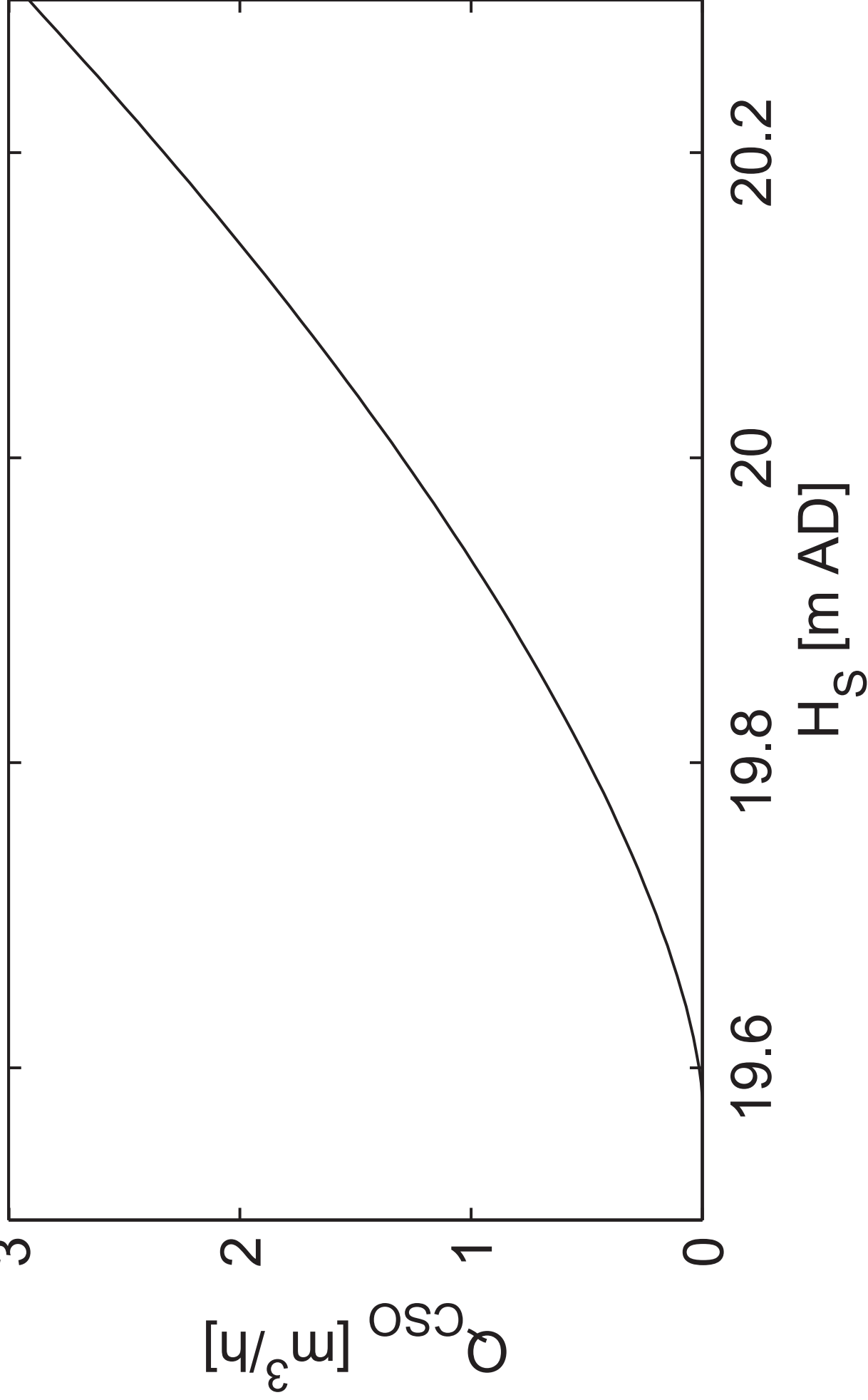


Figure 6 - high res SR8

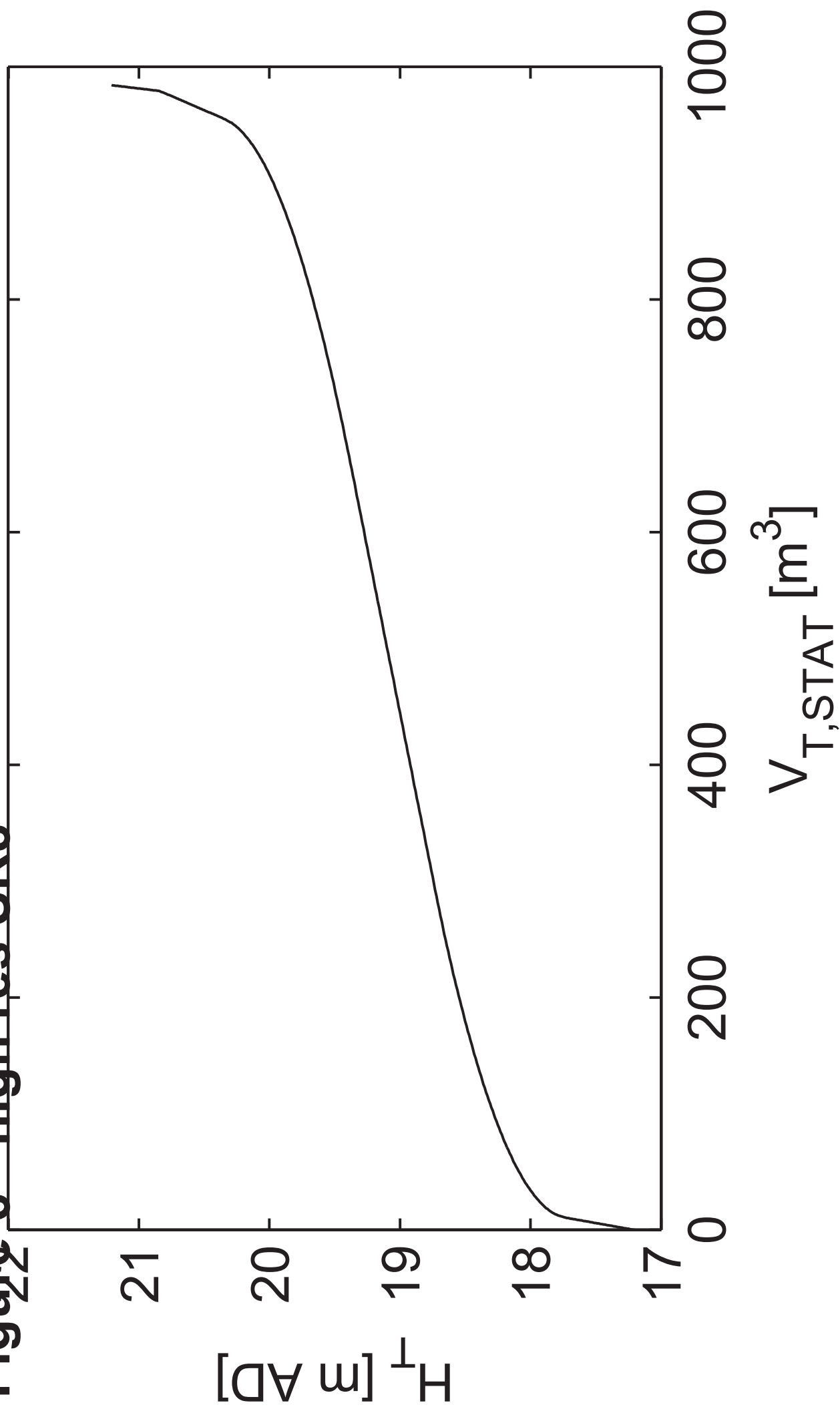


Figure 506 - high res SR9

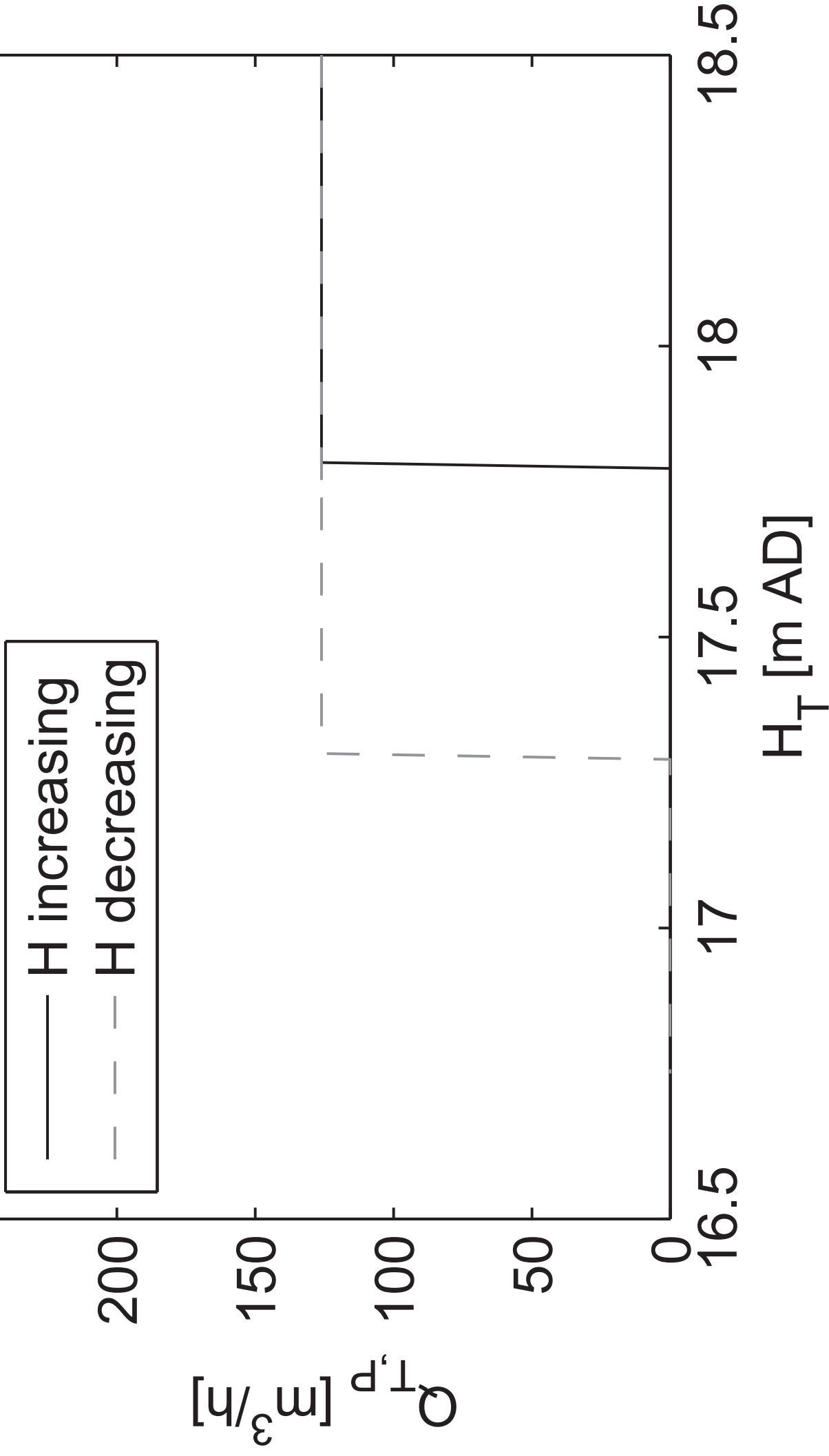


Figure 6-10⁴ High res SR10

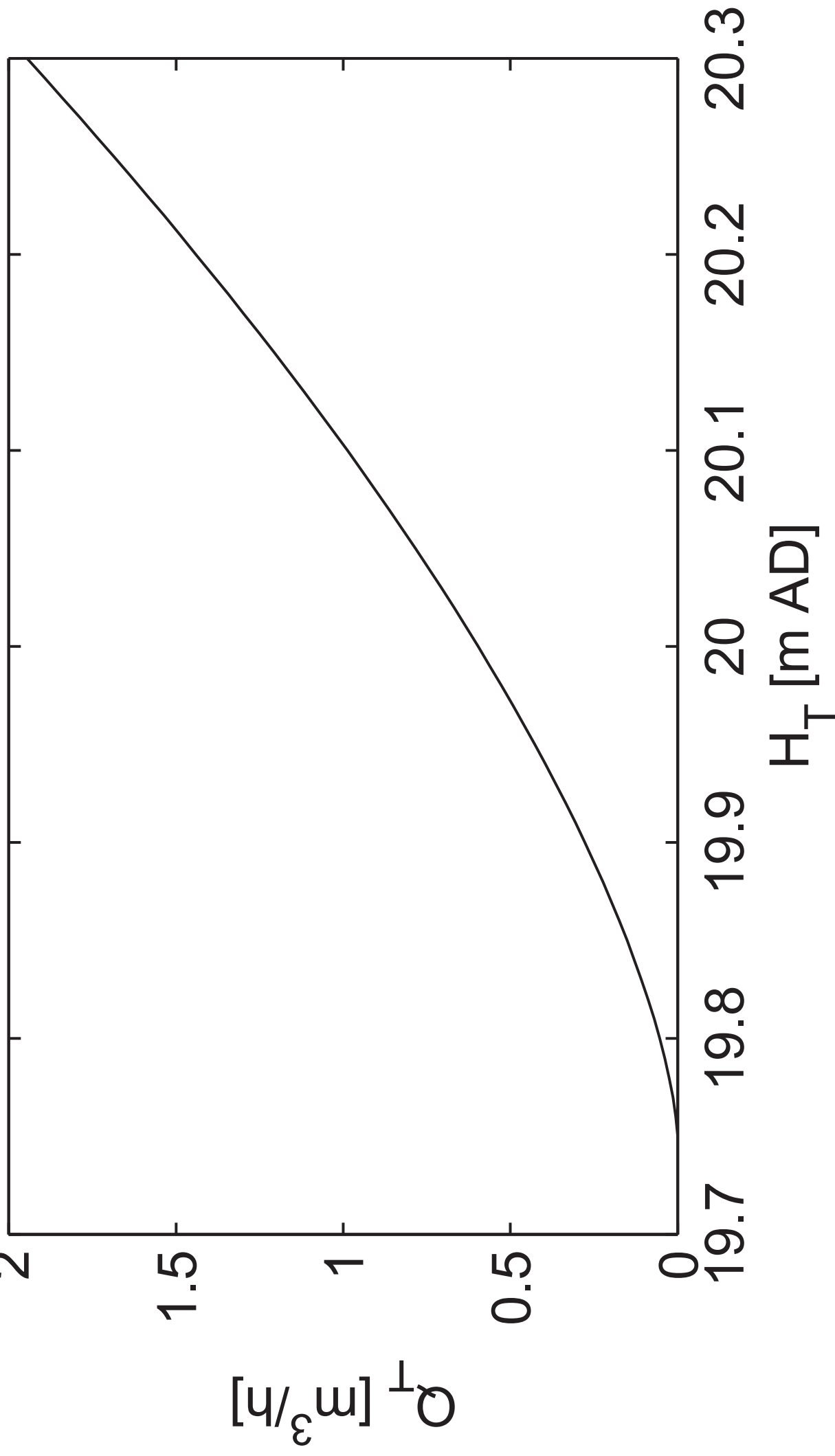


Figure 7 - total DR model Loenen with graphs DR1-DR4

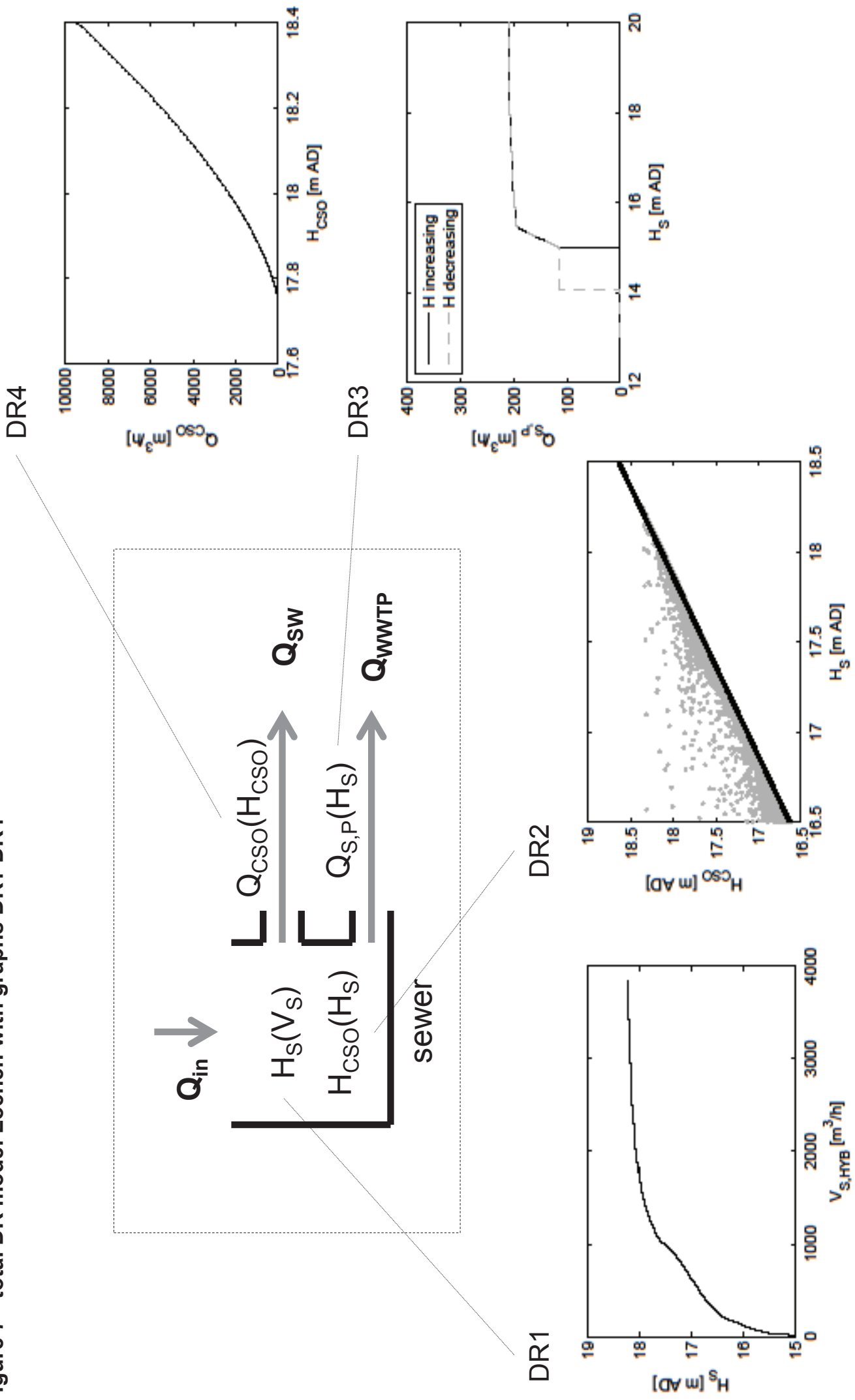


Figure 7 - high res DR1

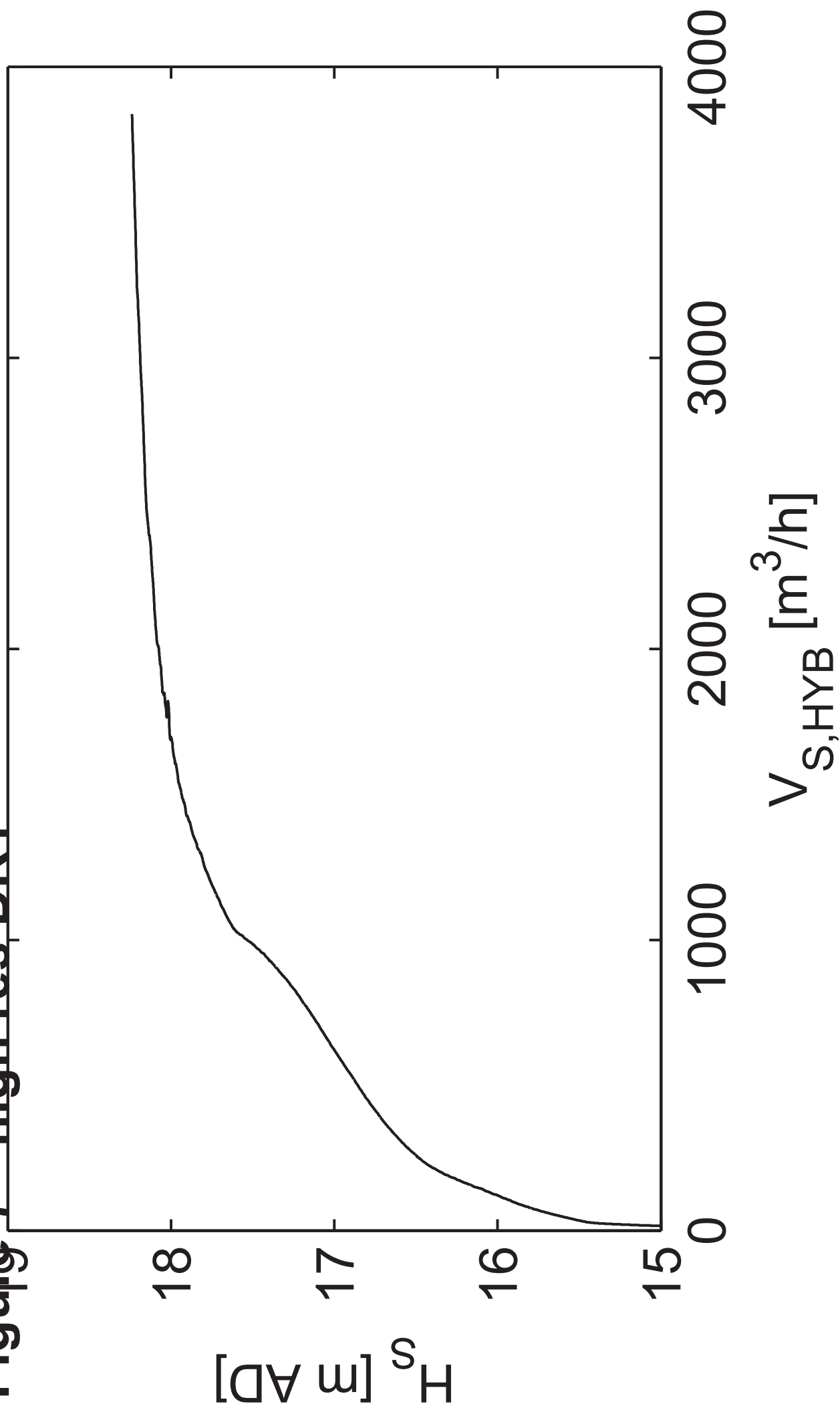


Figure 7 - high res DR2

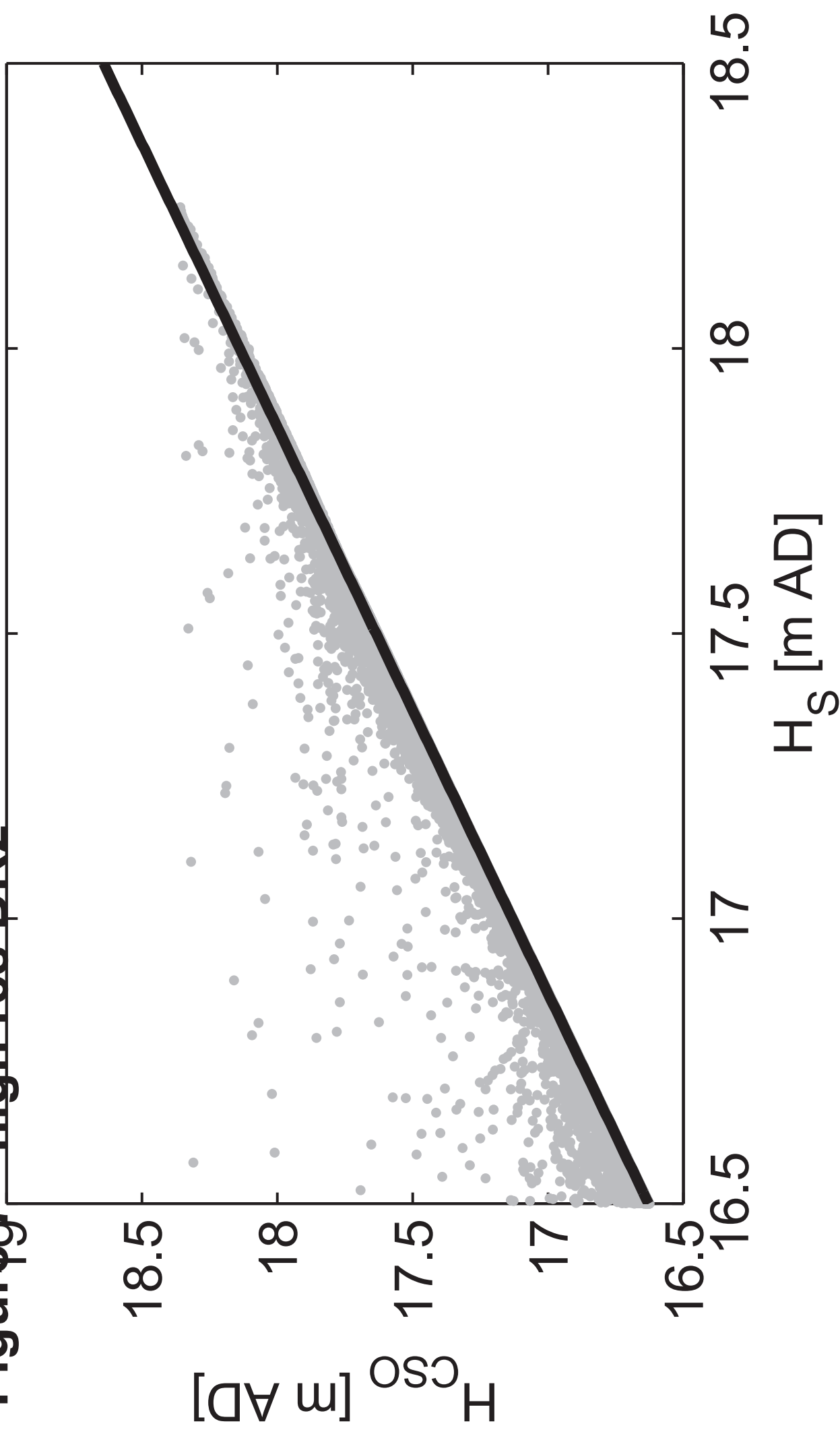


Figure 7 - high res DR3

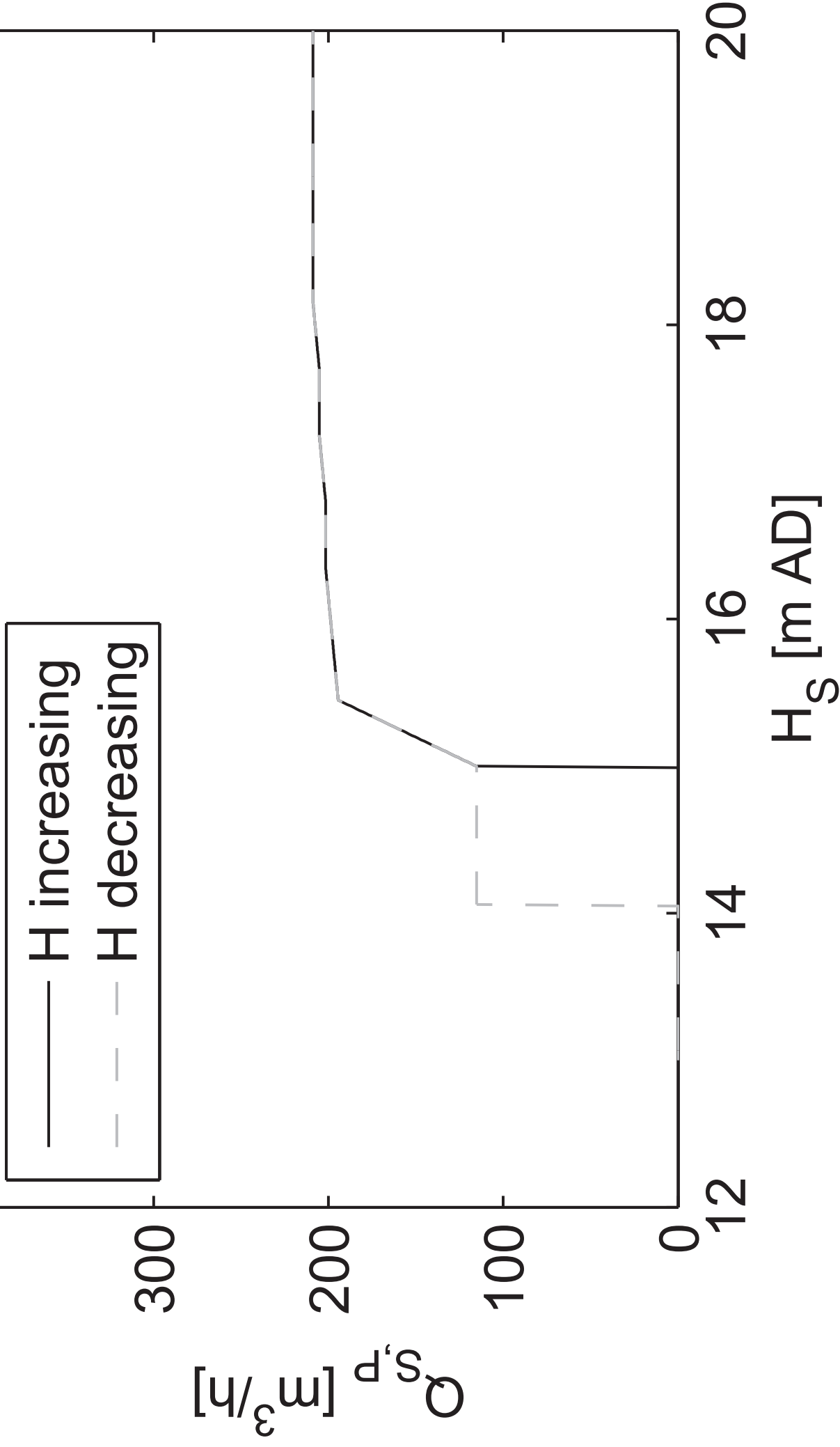


Figure 700 high res DR4

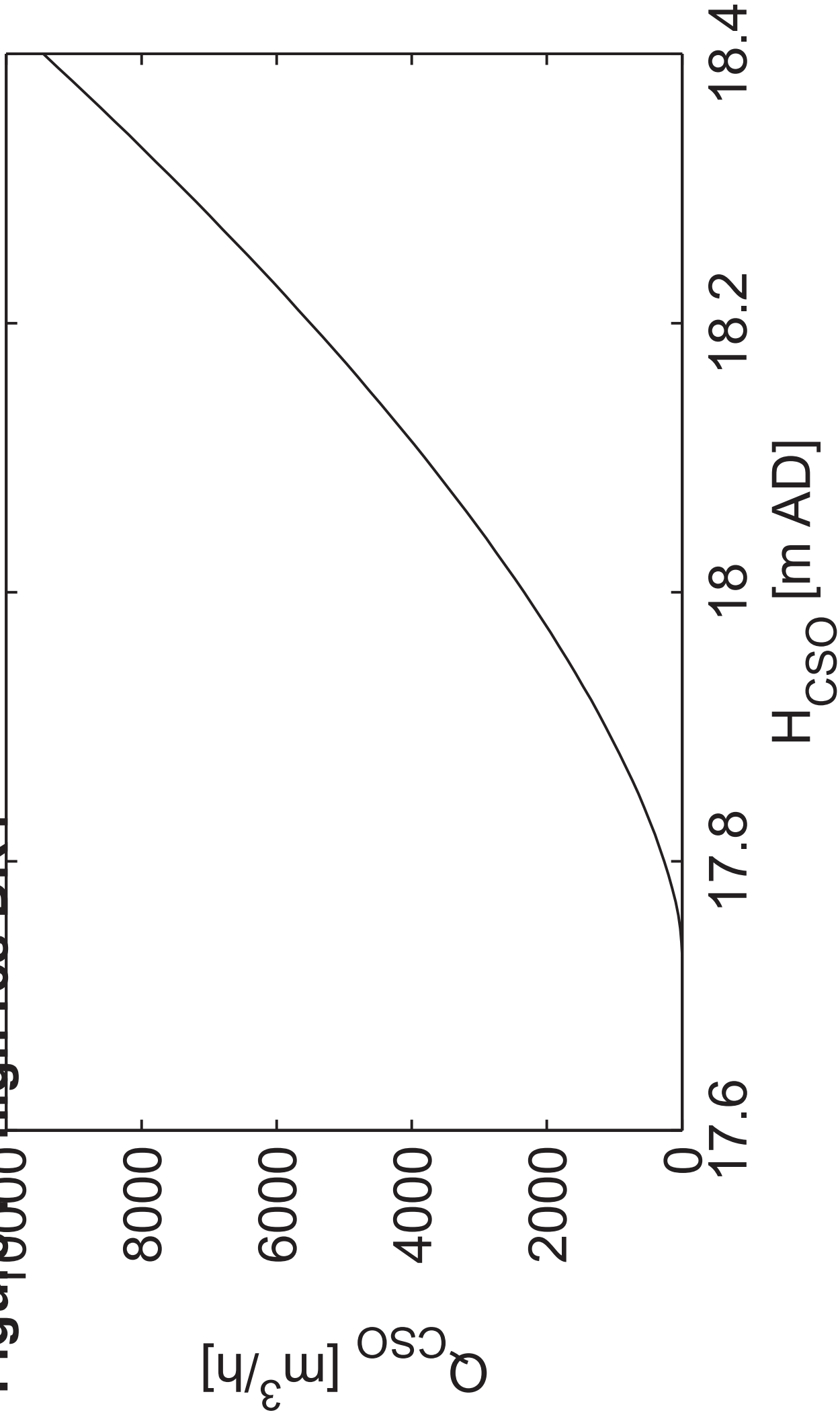


Figure 8 - left

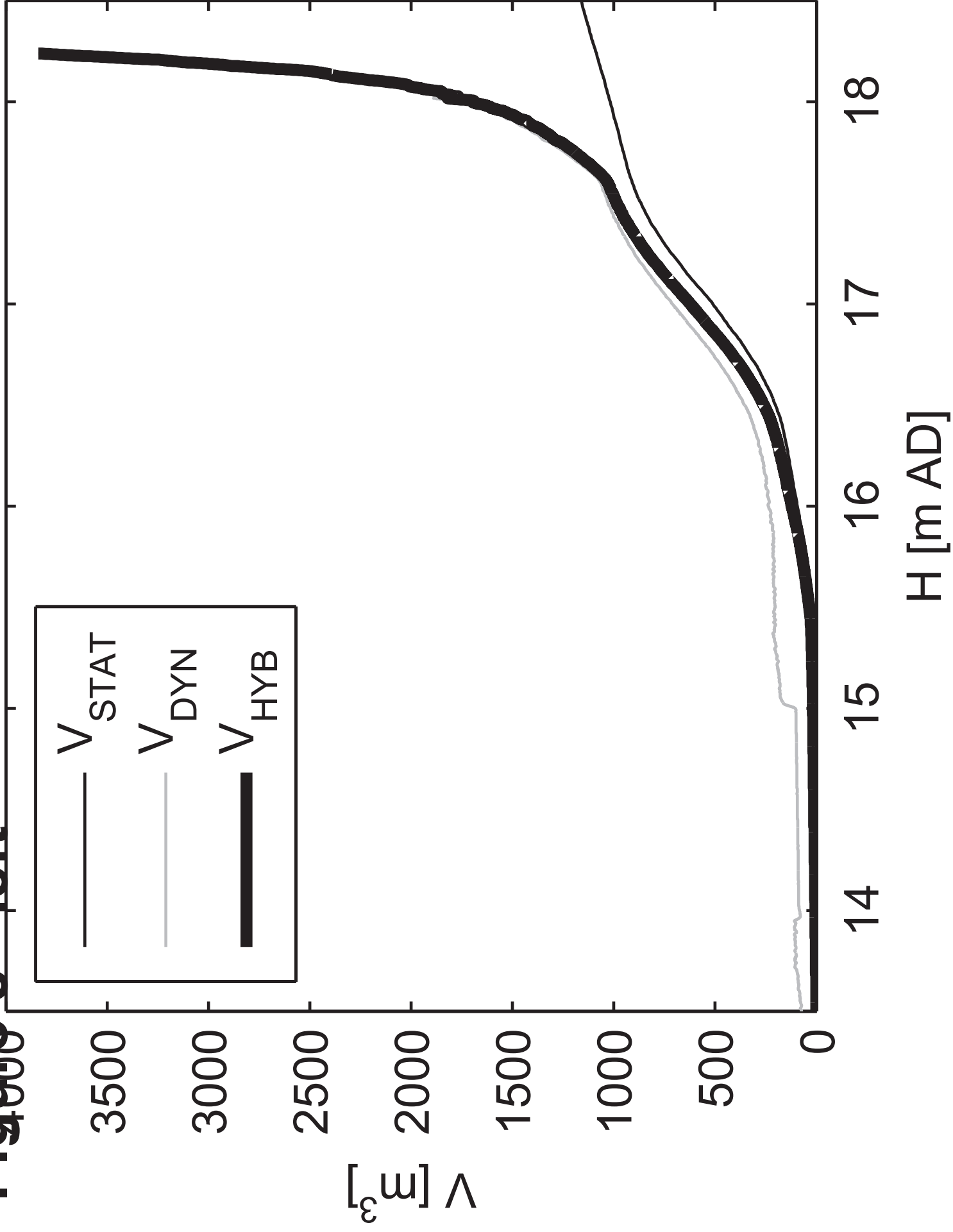


Figure 8 - right

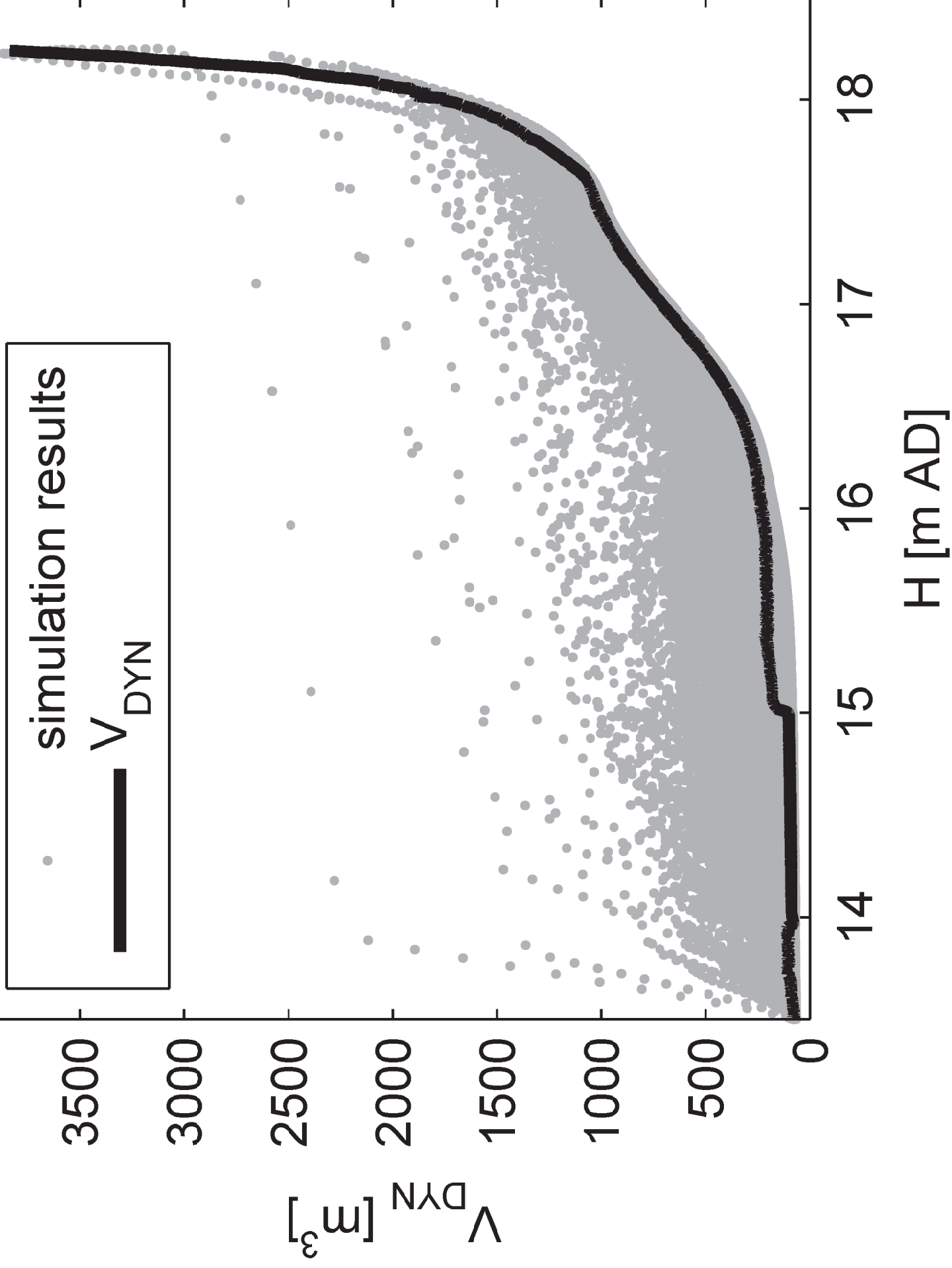


Figure 9 - total DR model Waalre with graphs DR5-DR13

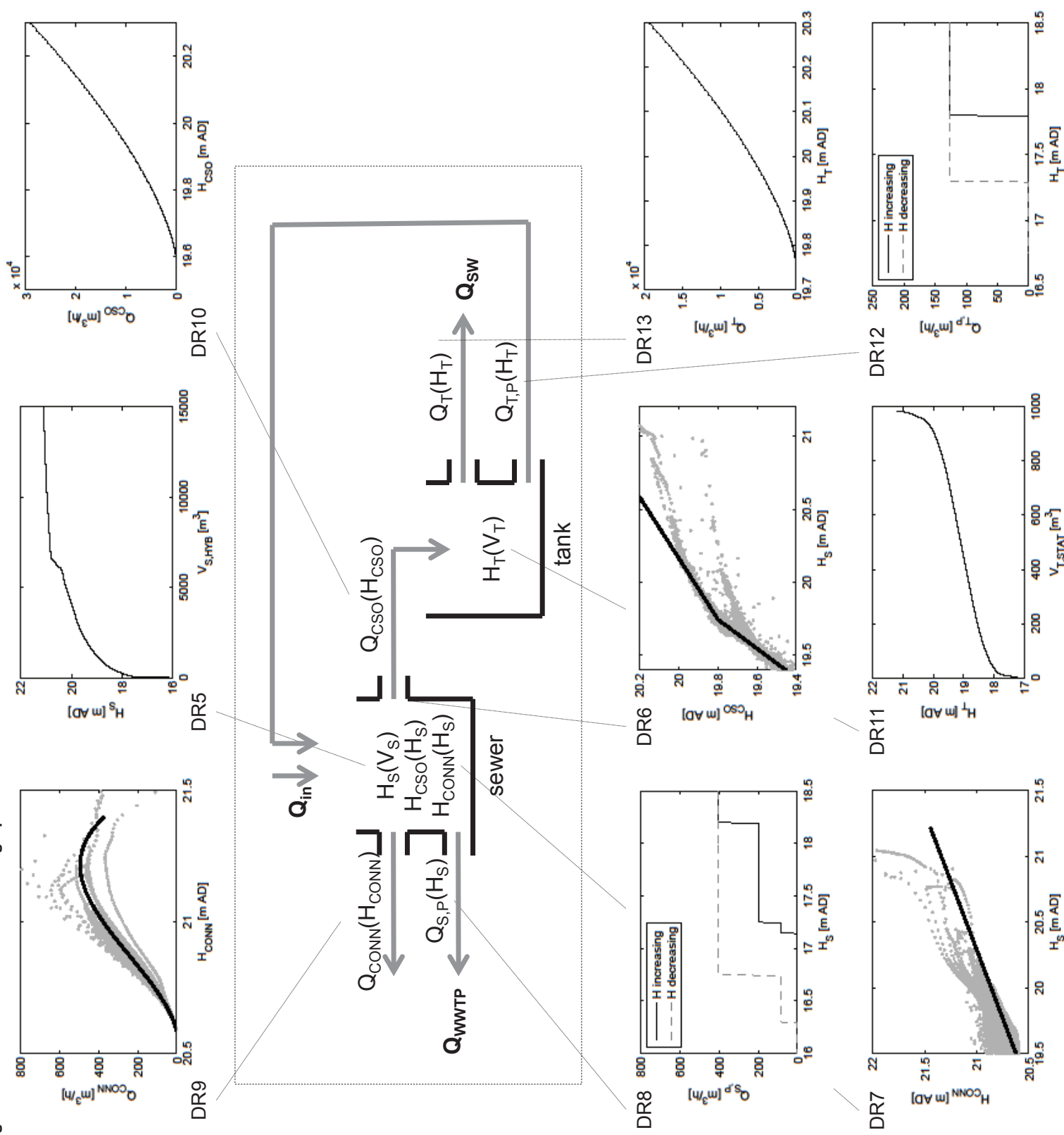


Figure 9 - high res DR5

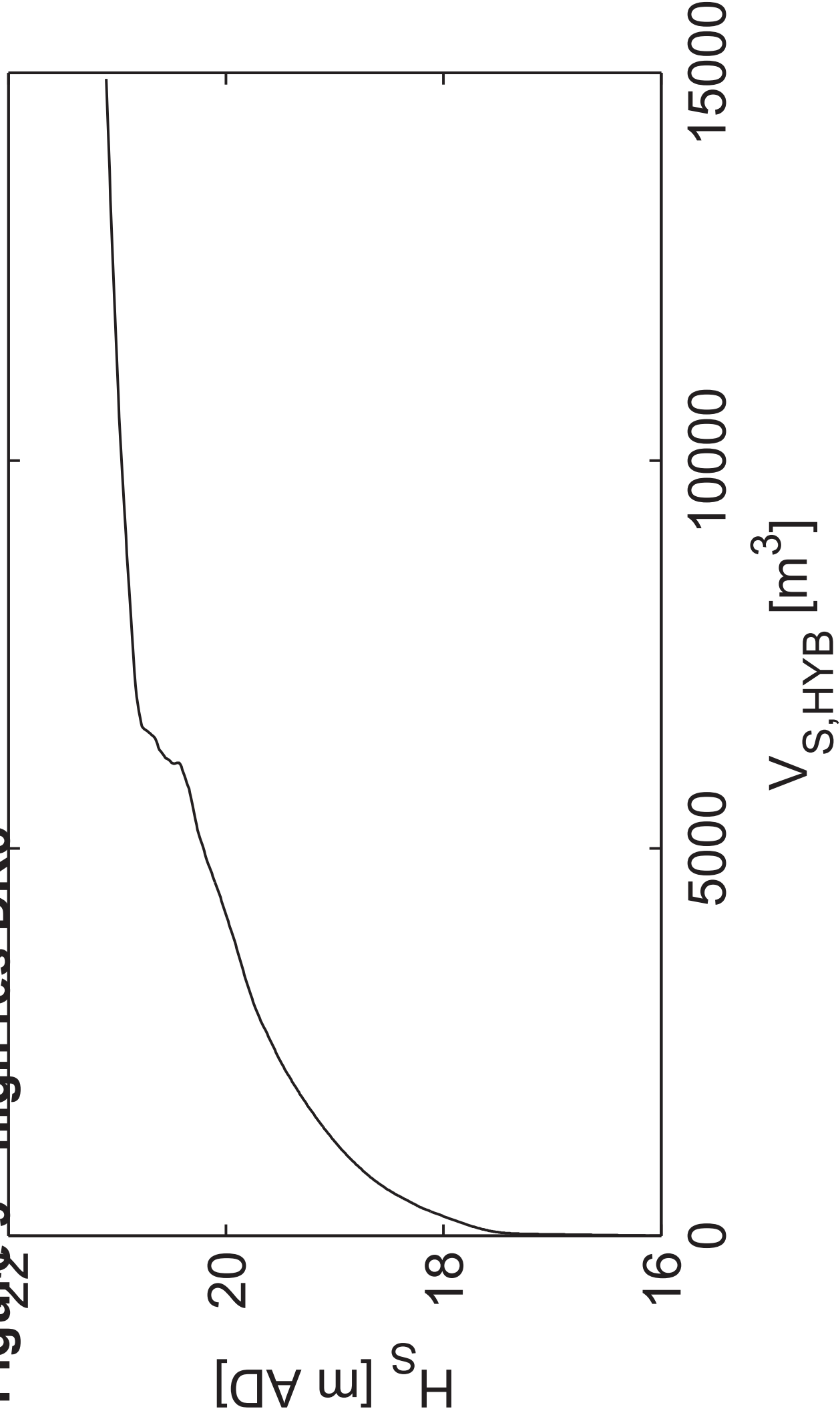


Figure 9 - high res DR6

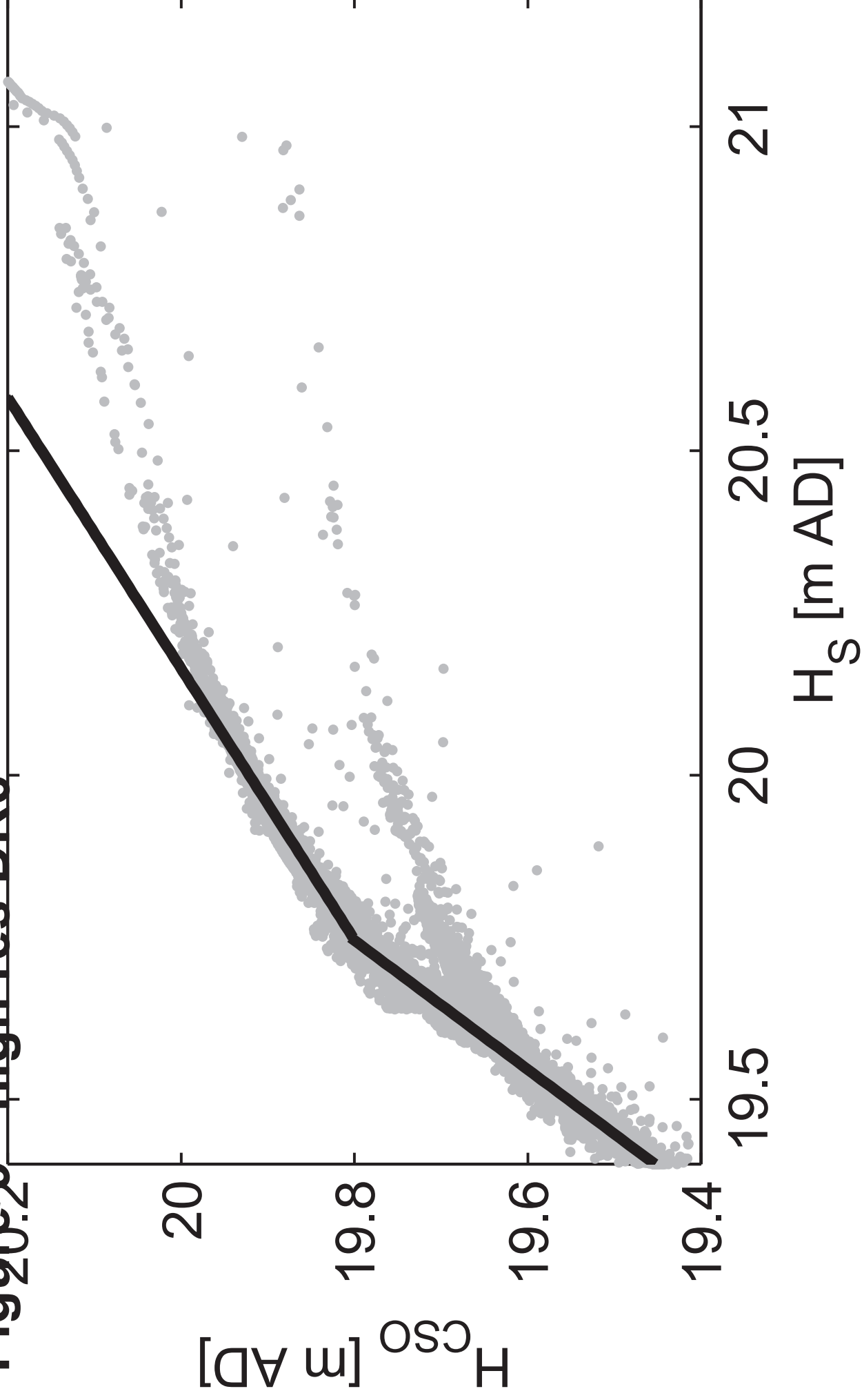


Figure 9 - high res DR7

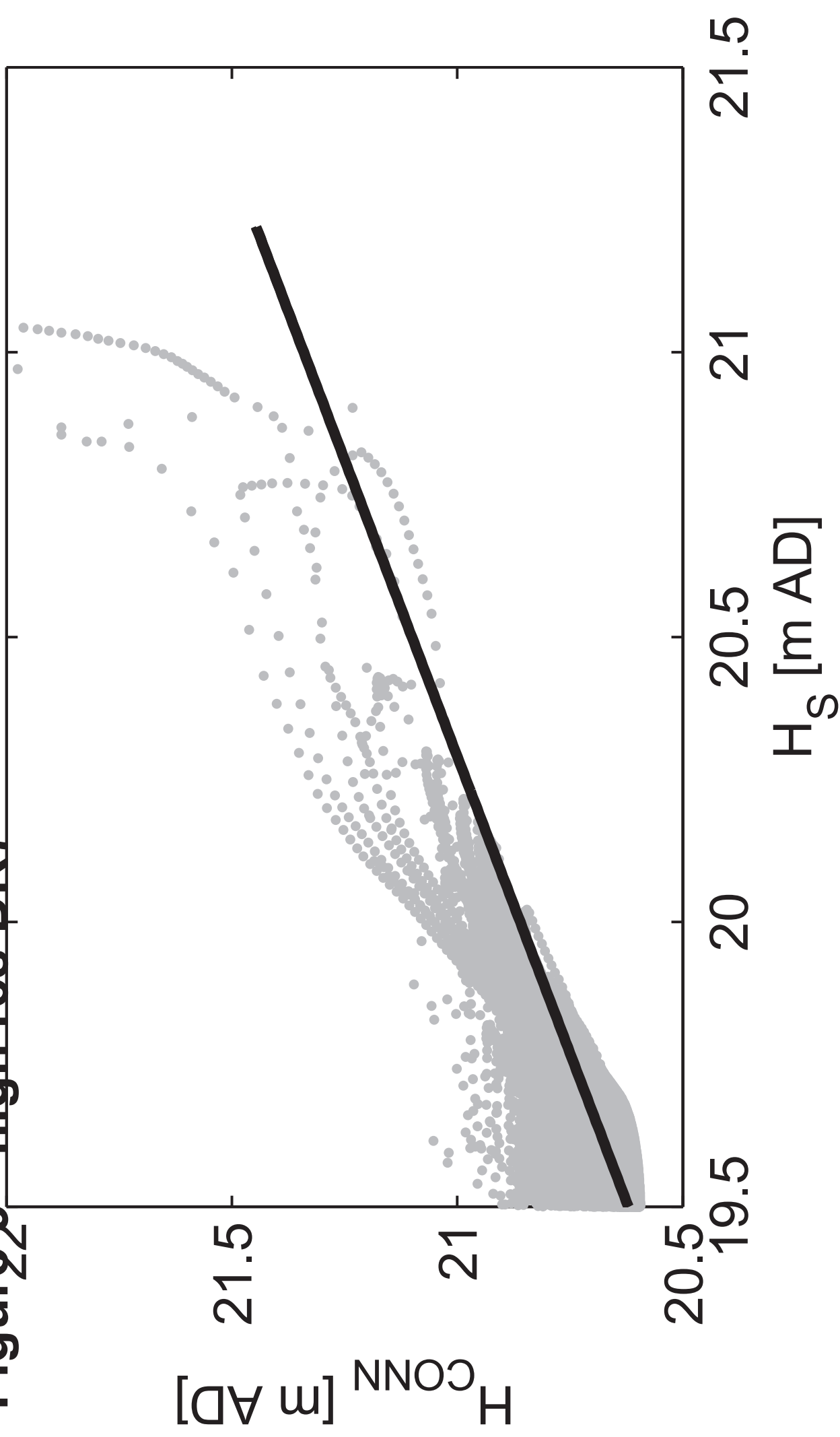


Figure 9 - high res DR8

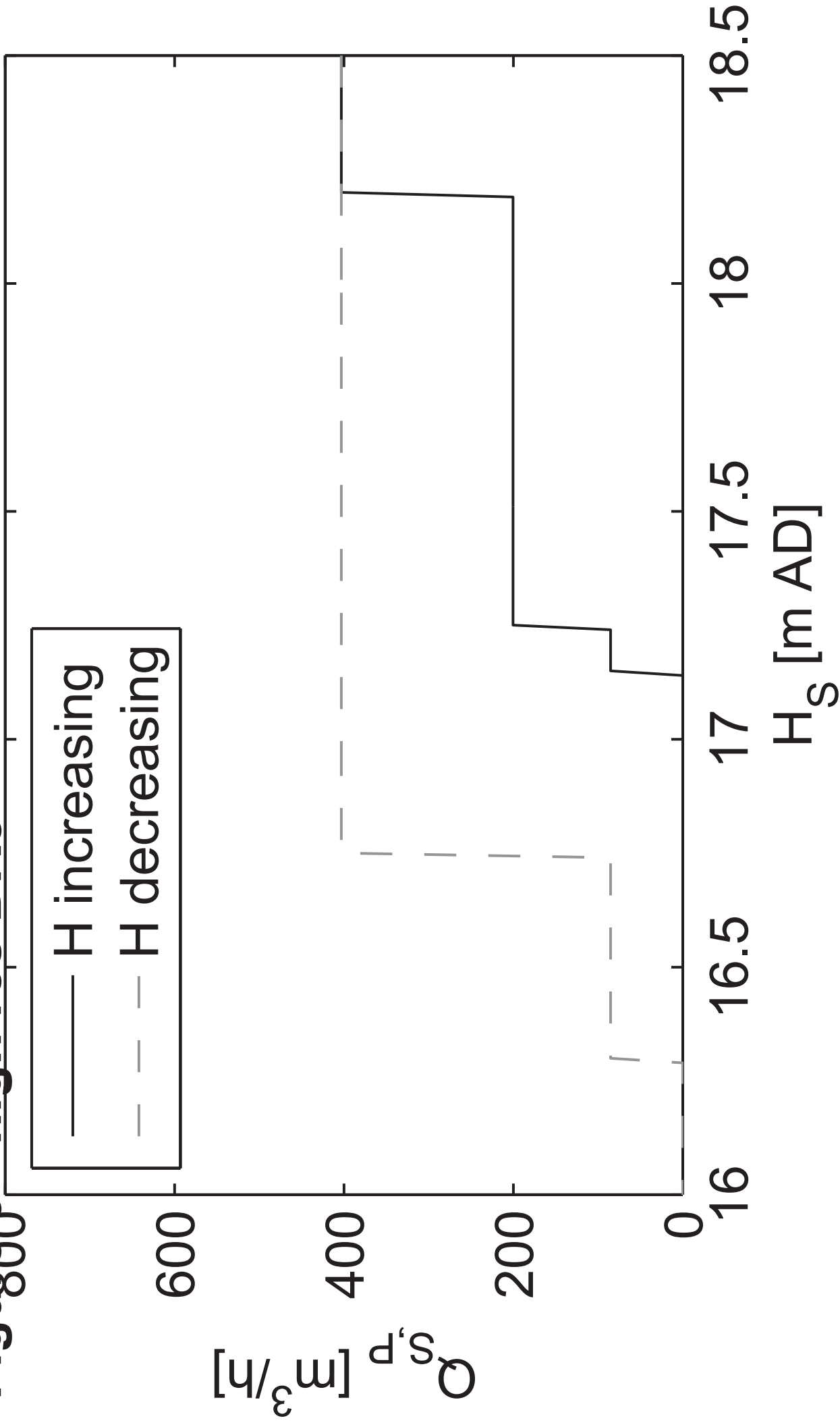


Figure 9-10⁴ high res DR10

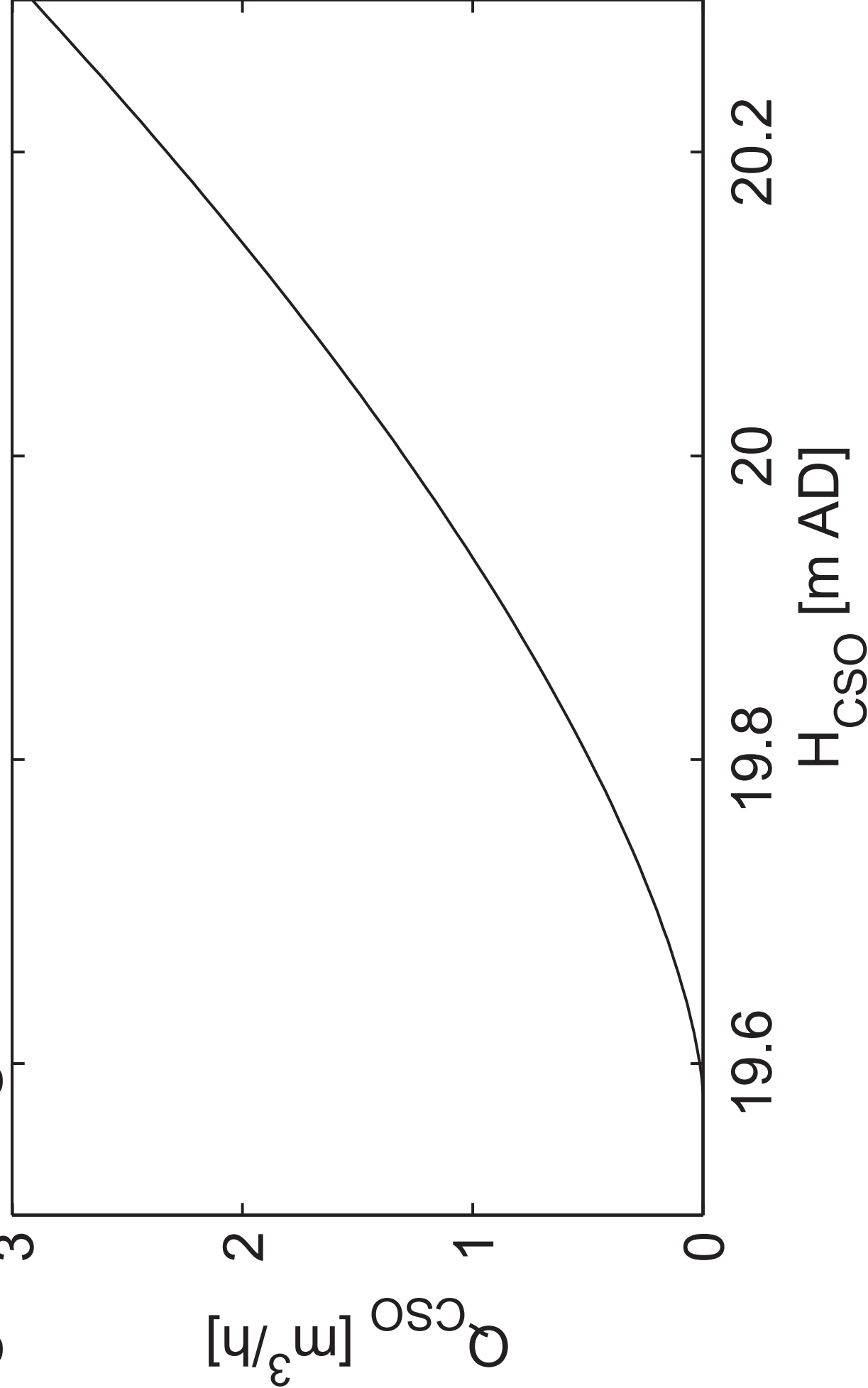


Figure 9 - high res DR9

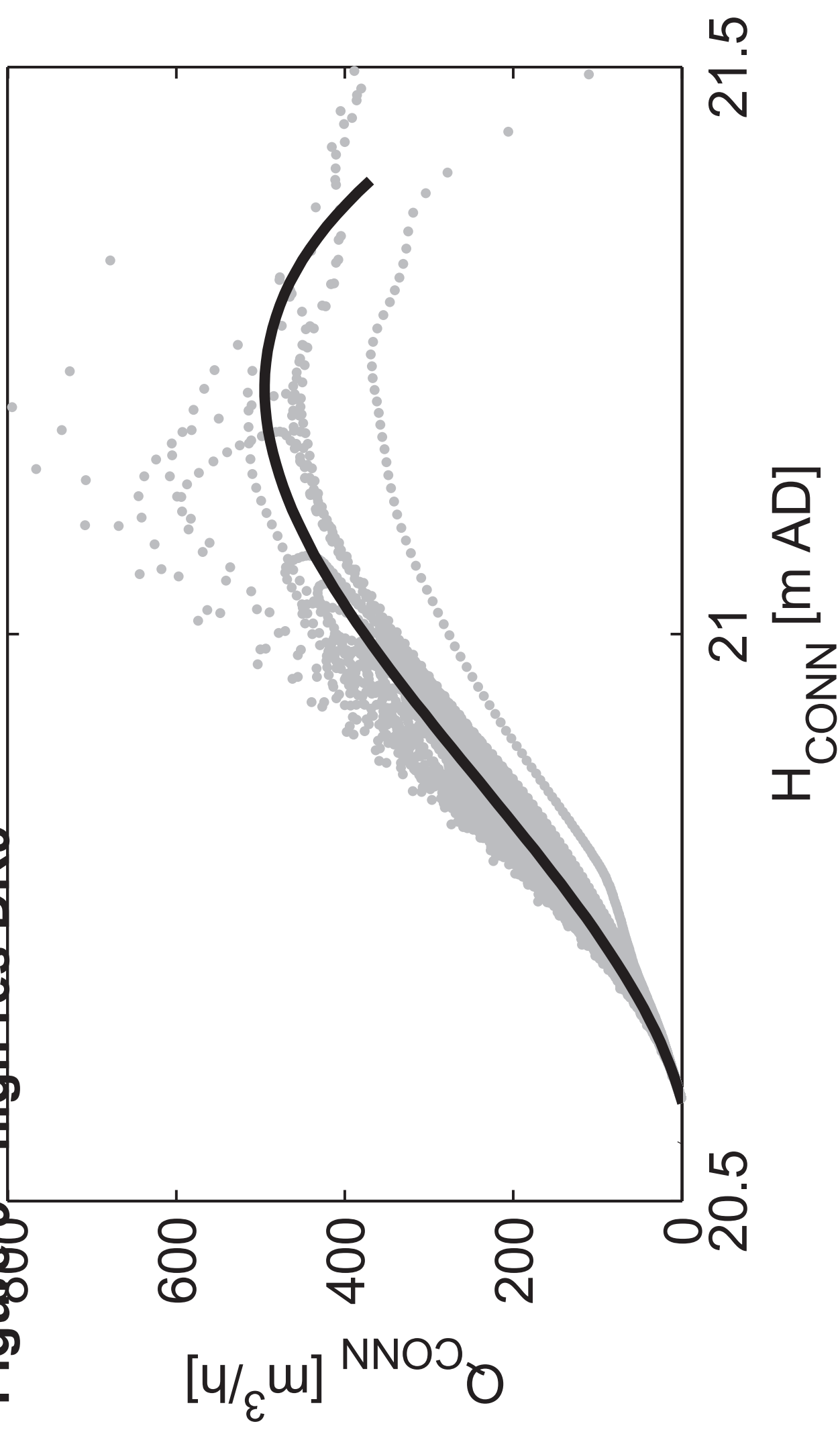


Figure 9 - high res DR11

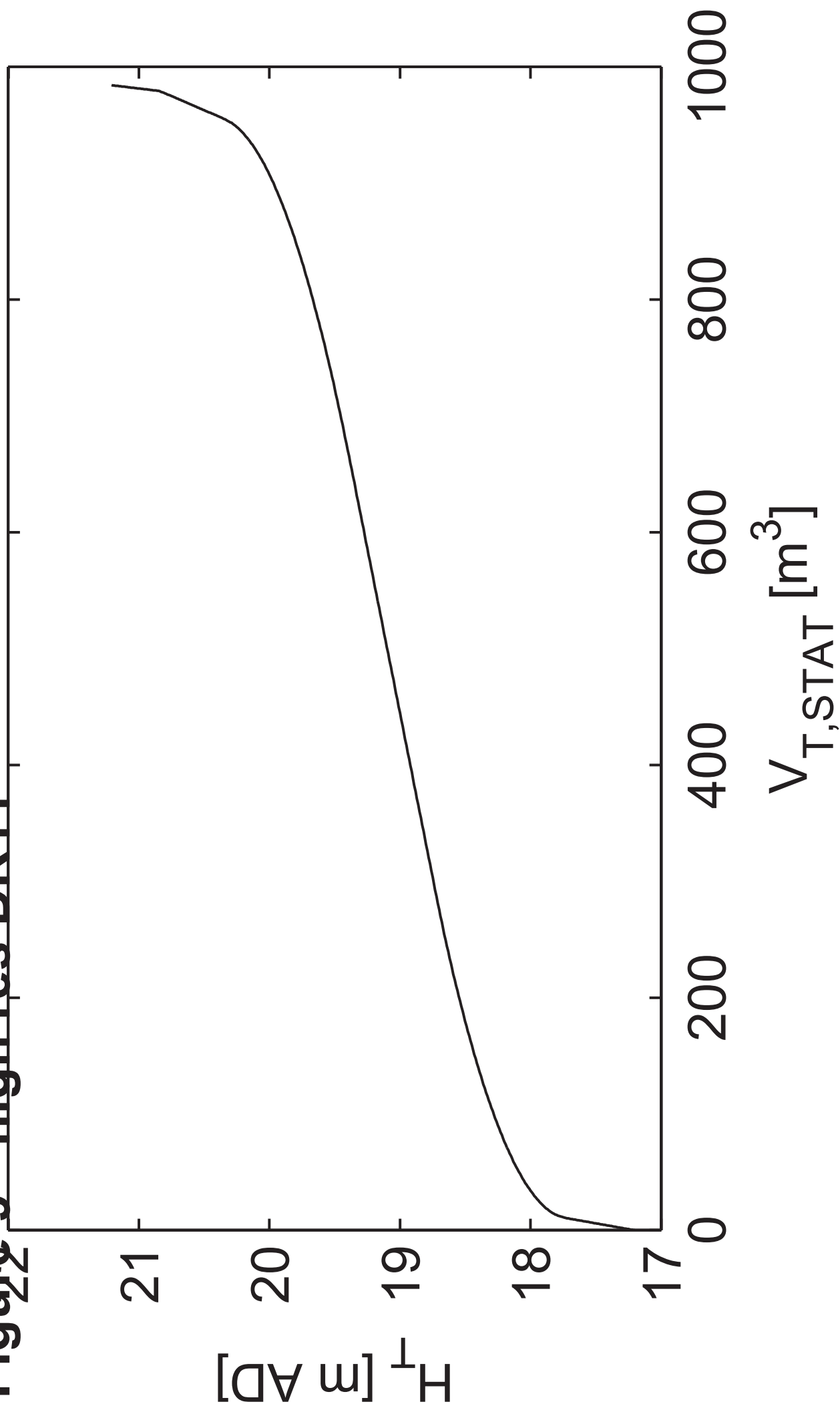


Figure 9 - high res DR12

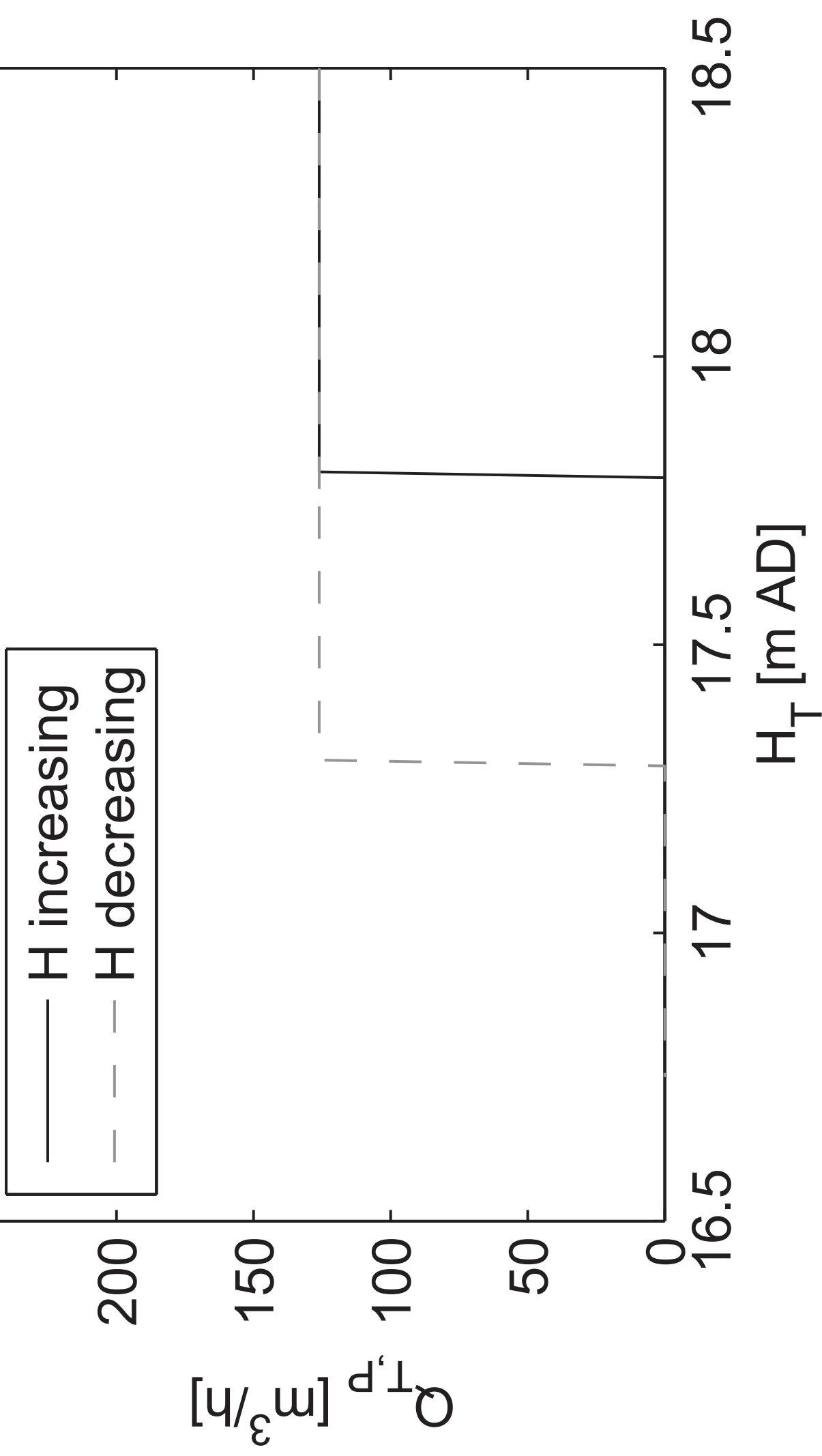


Figure 9-10⁴ High res DR13

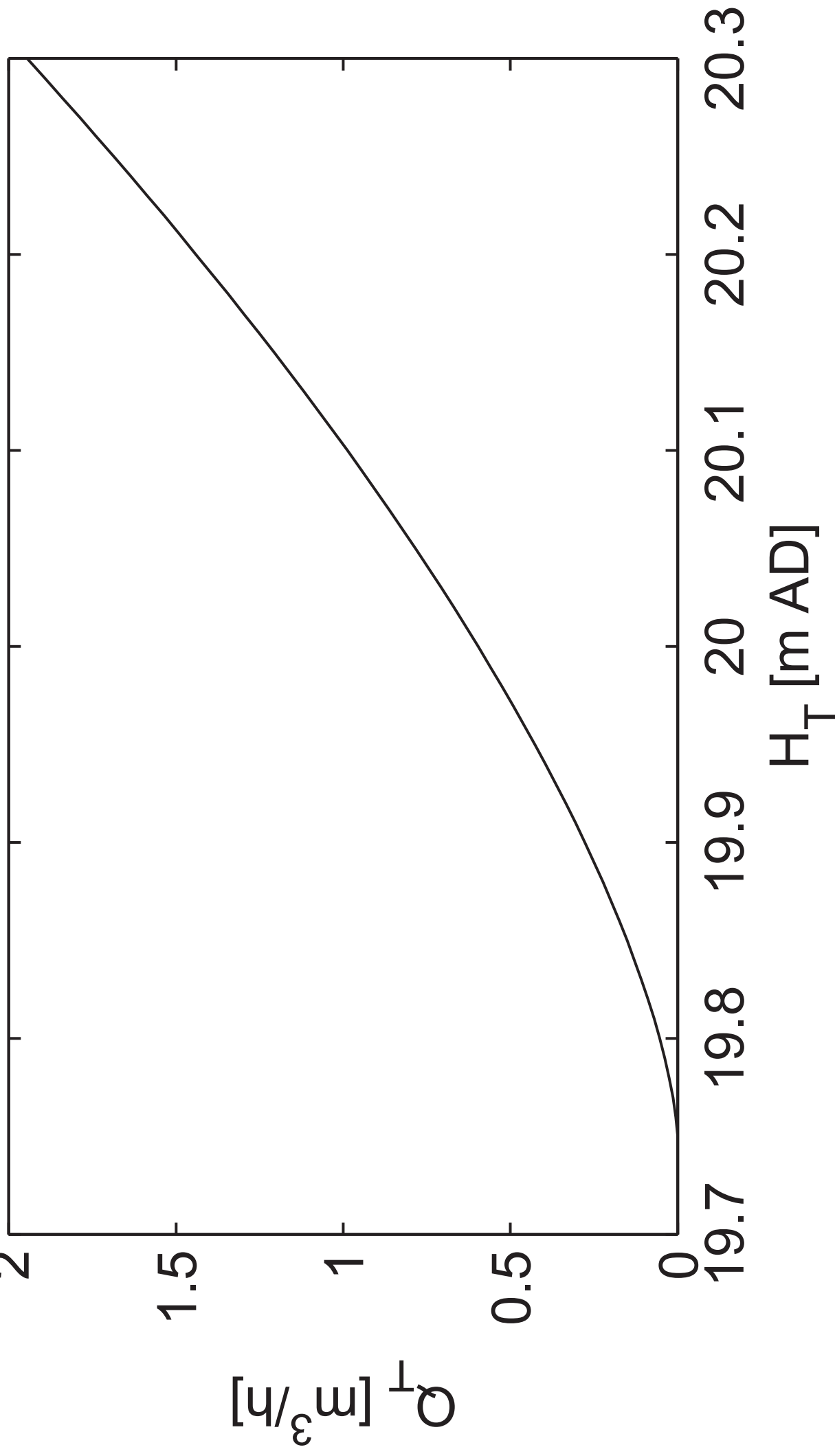


Figure 10 - left

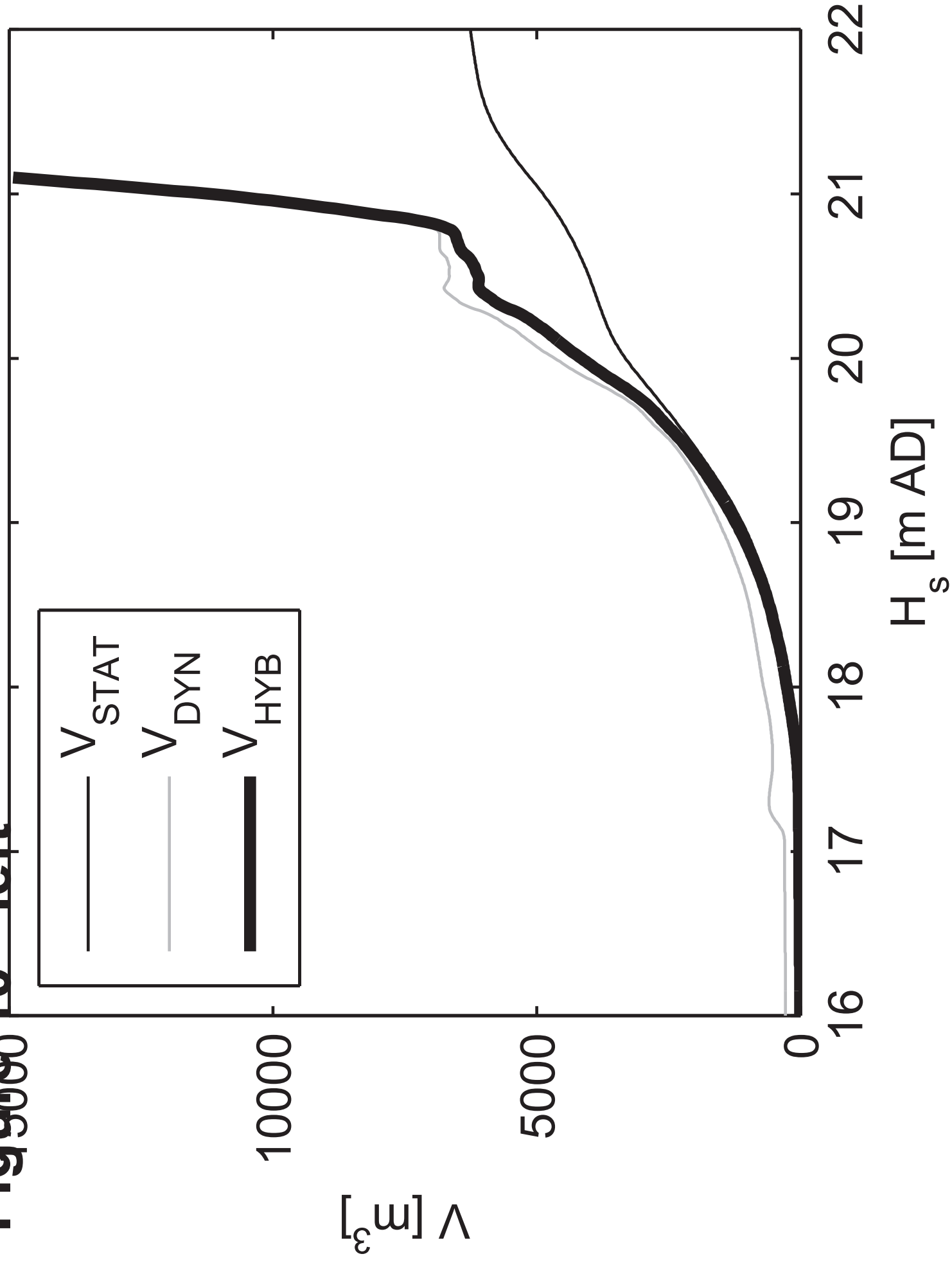


Figure 10 - right

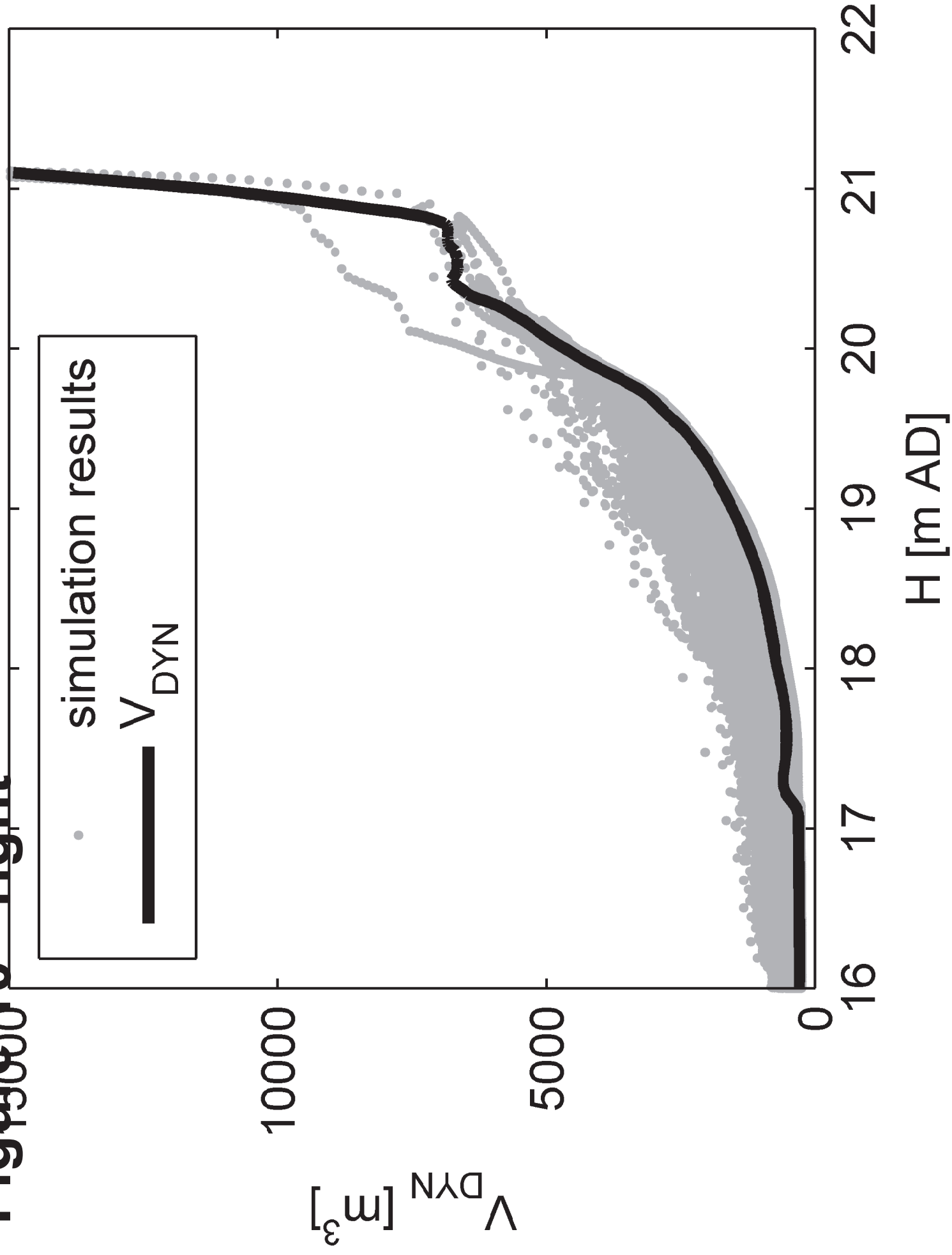


Figure 11

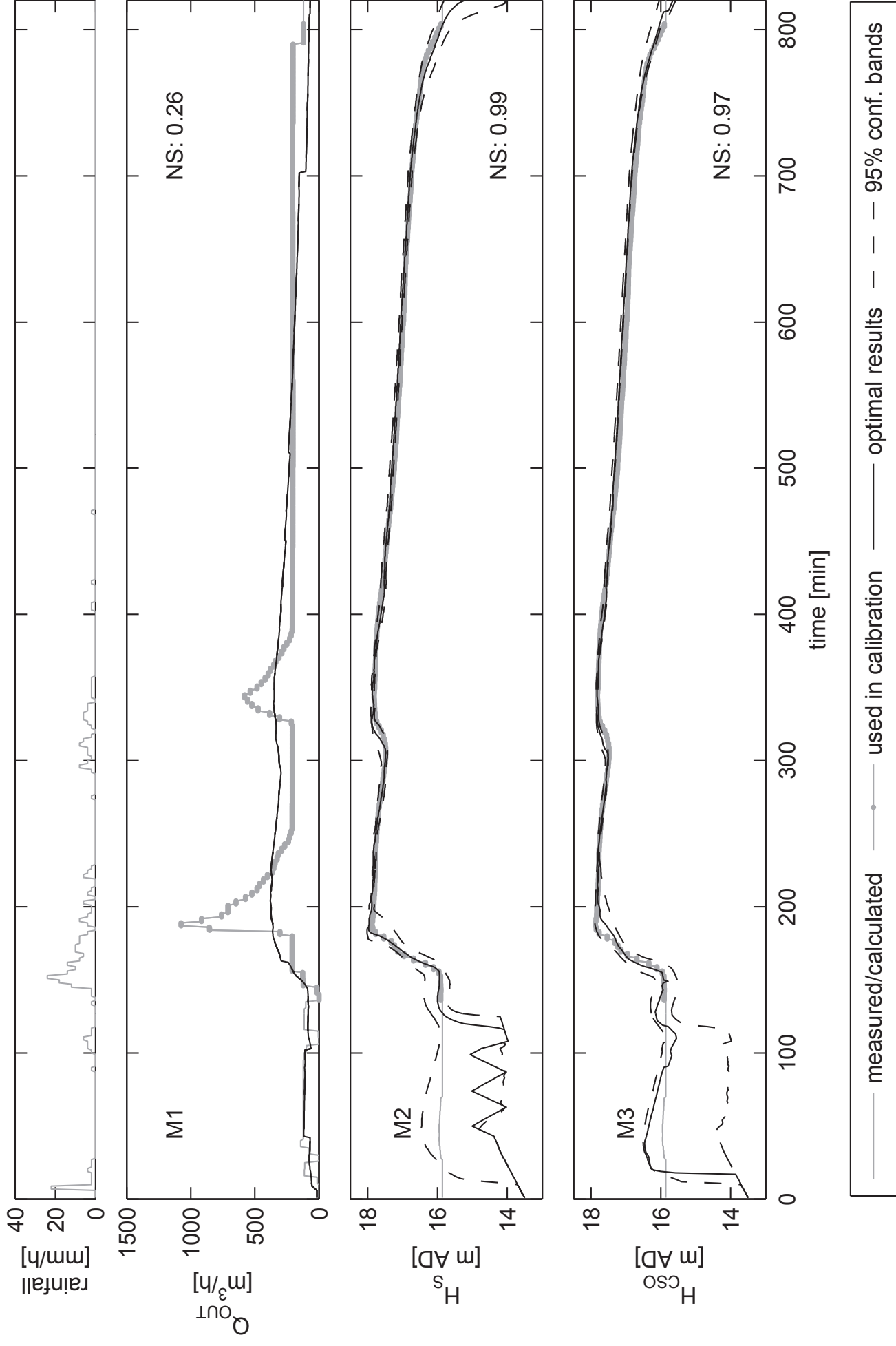


Figure 12

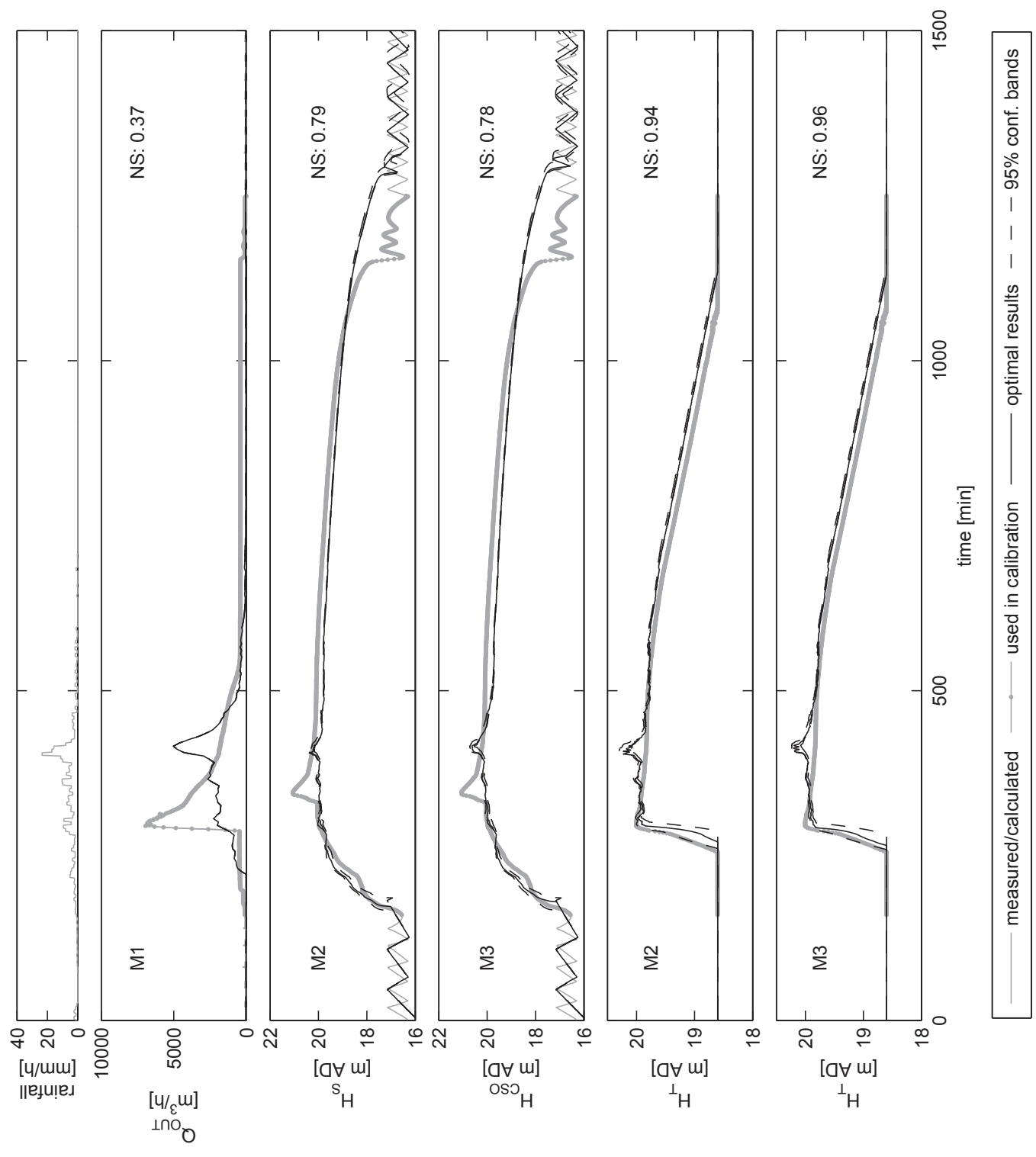


Figure 13

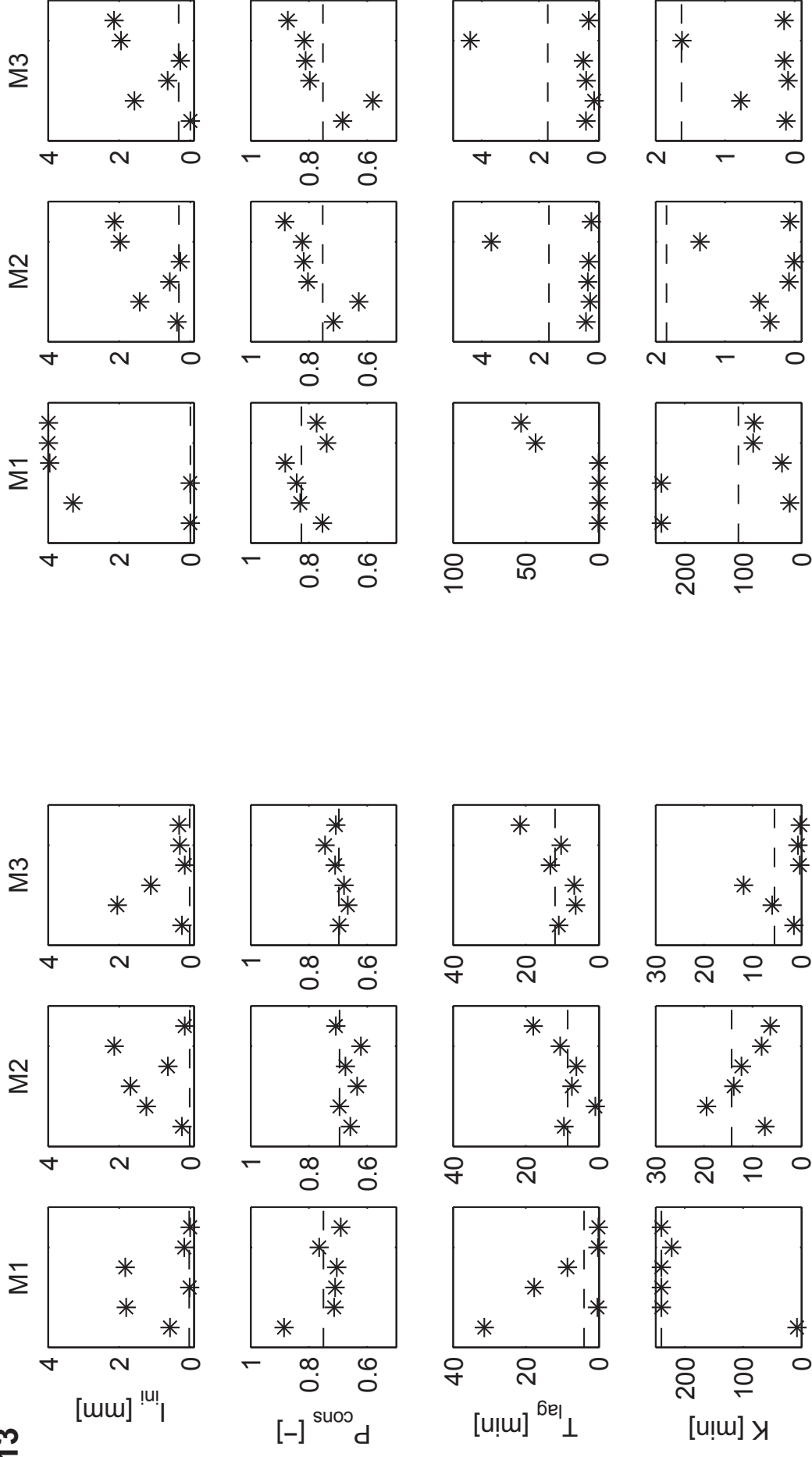


Figure 14

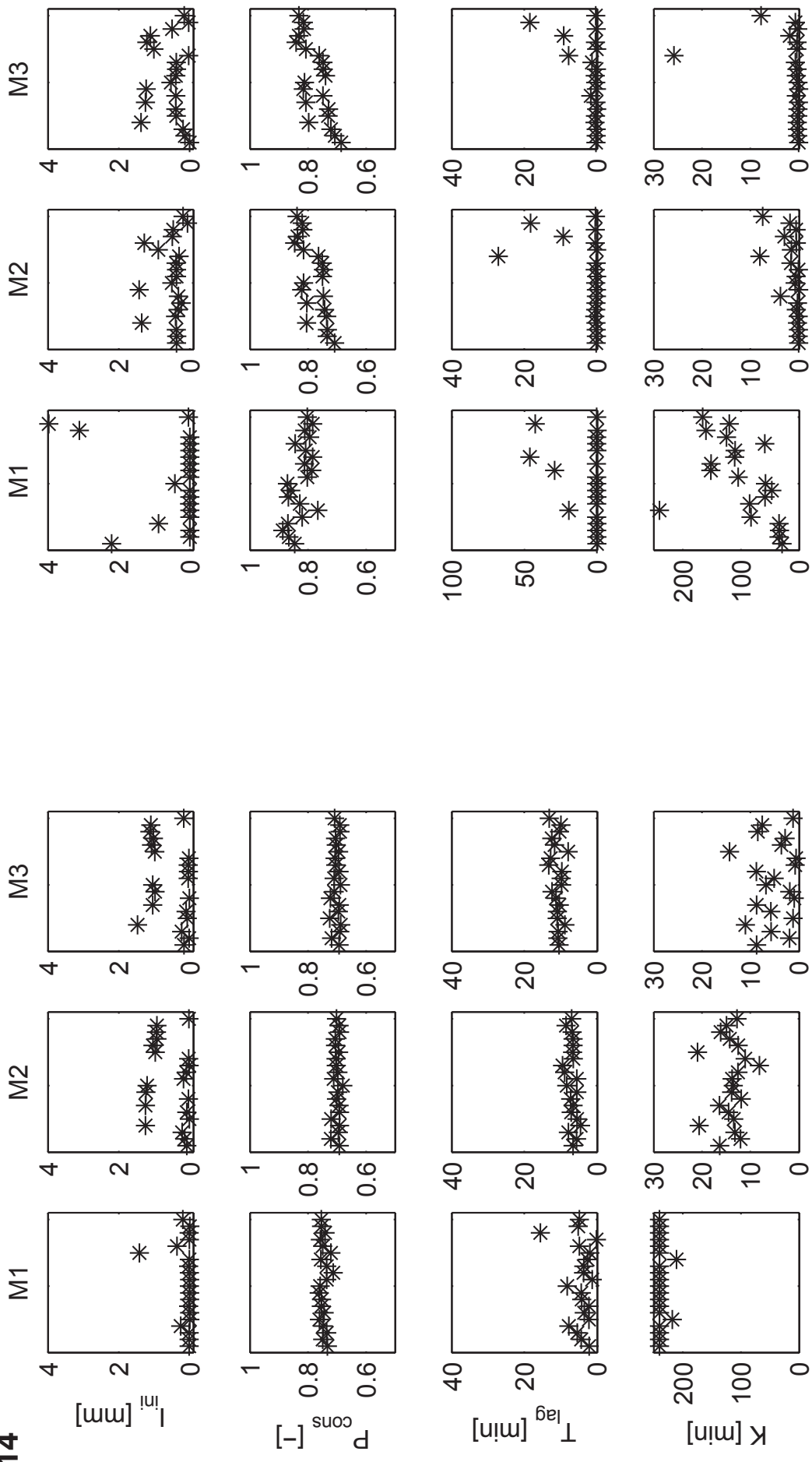


Figure 15

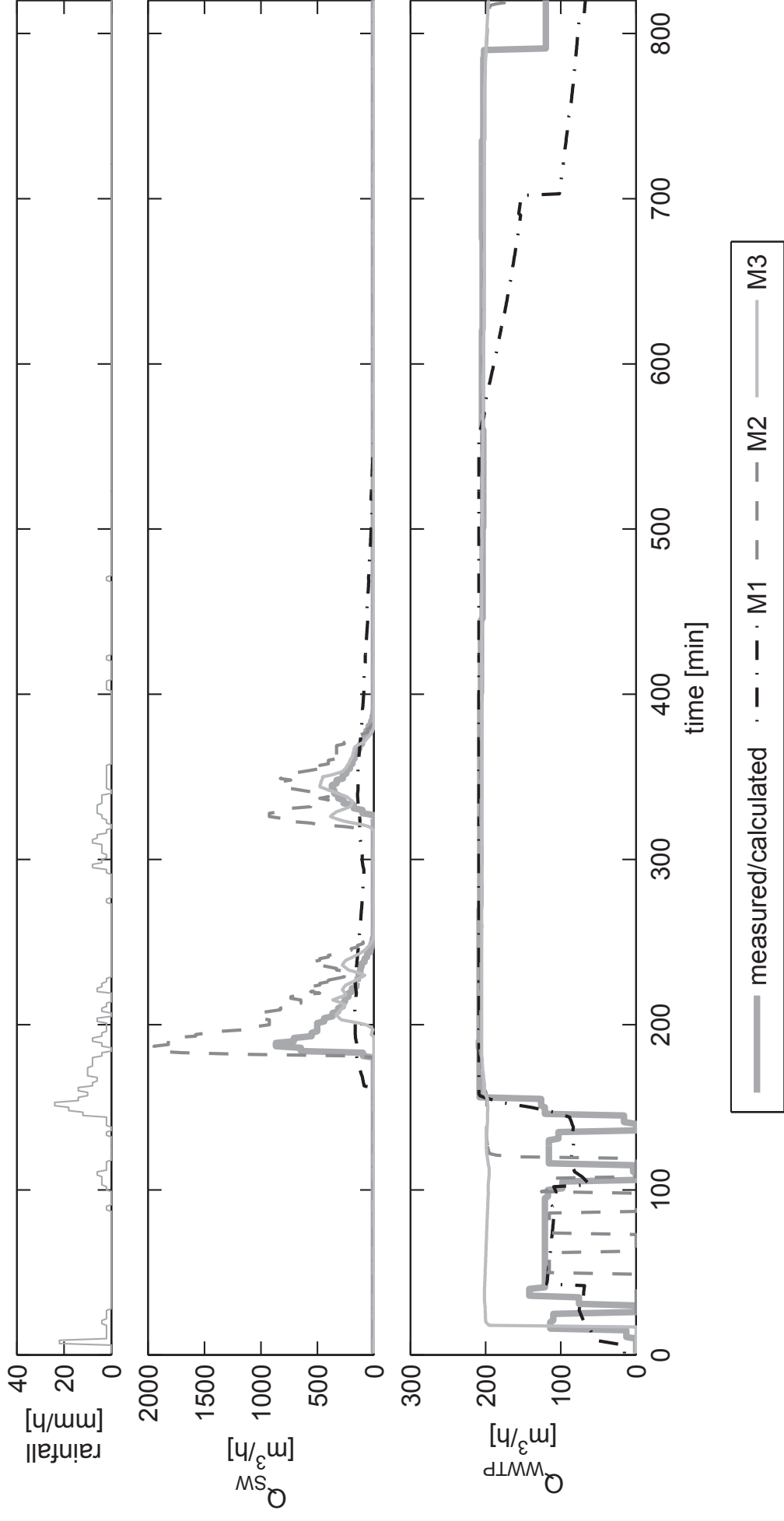
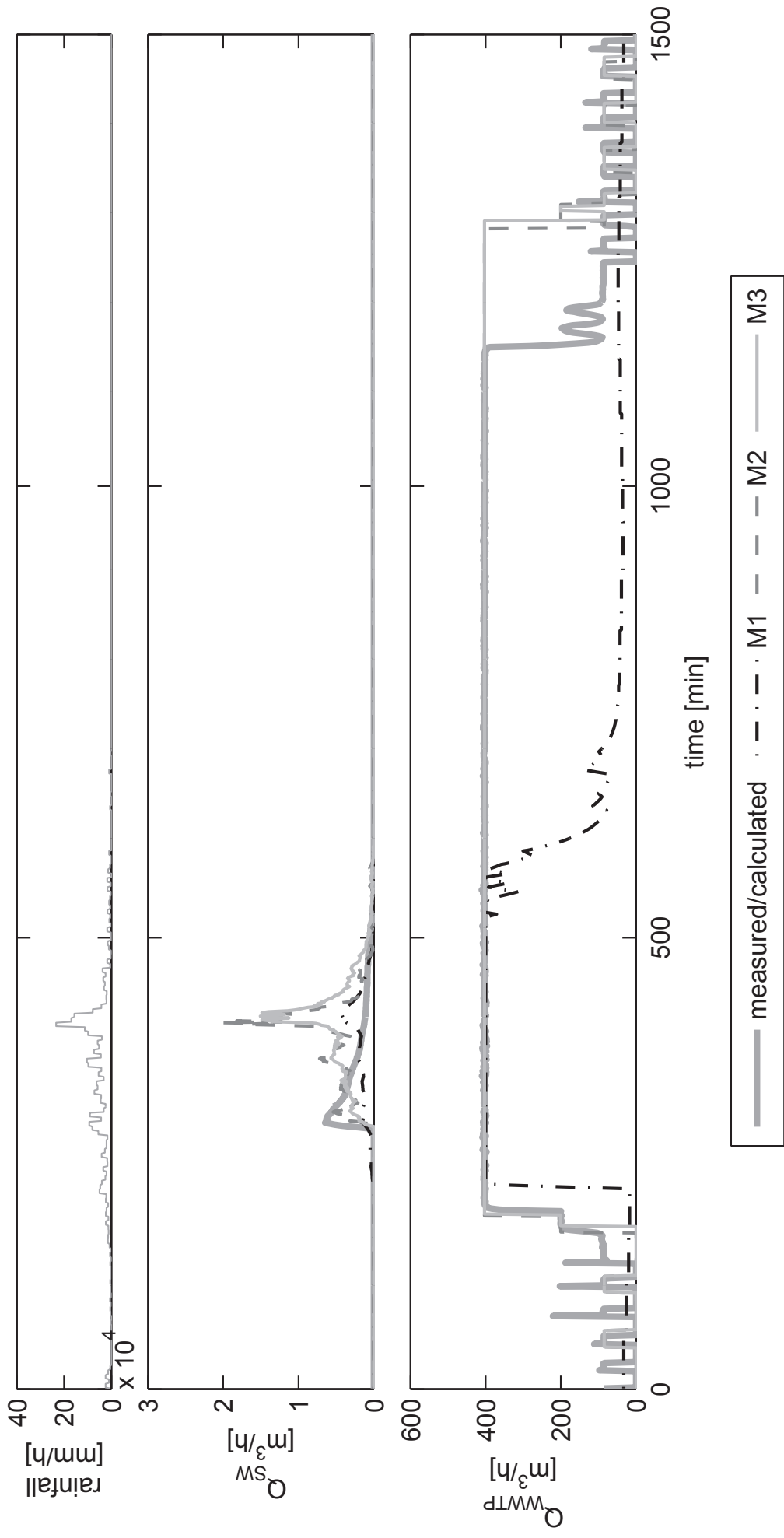


Figure 16



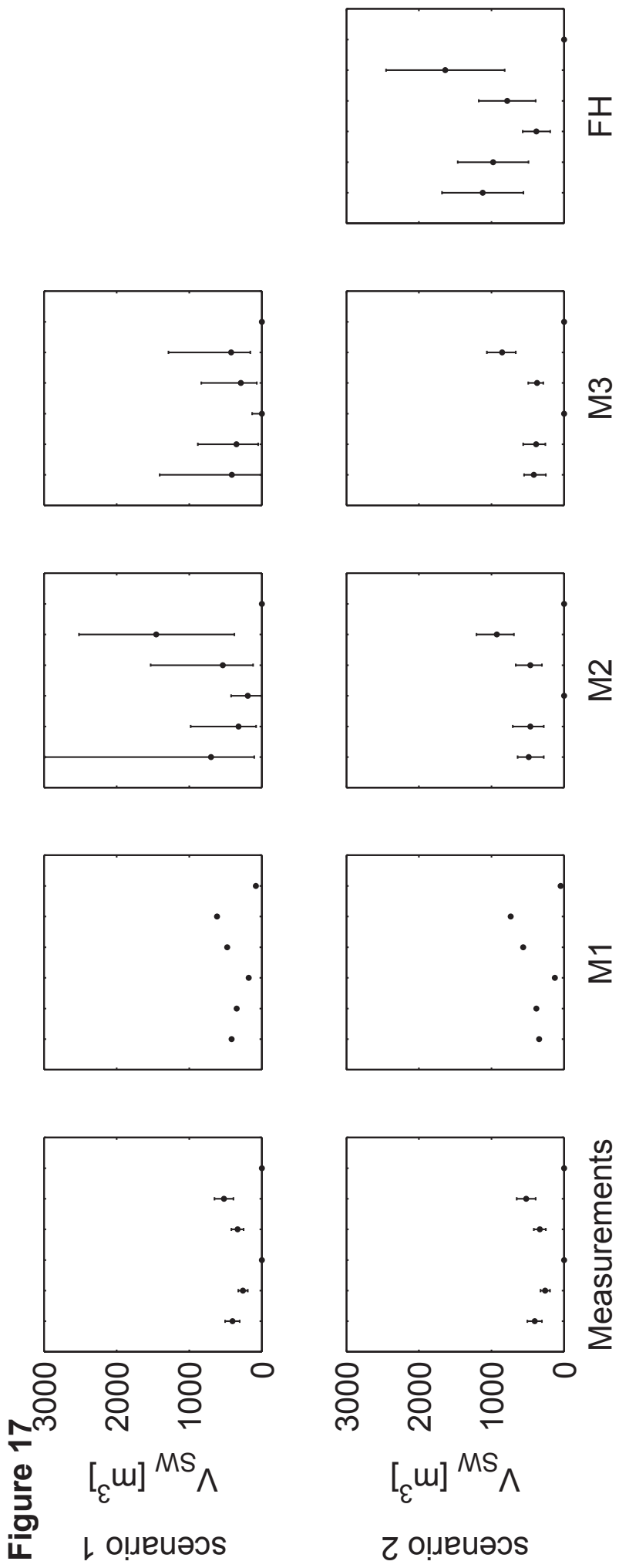
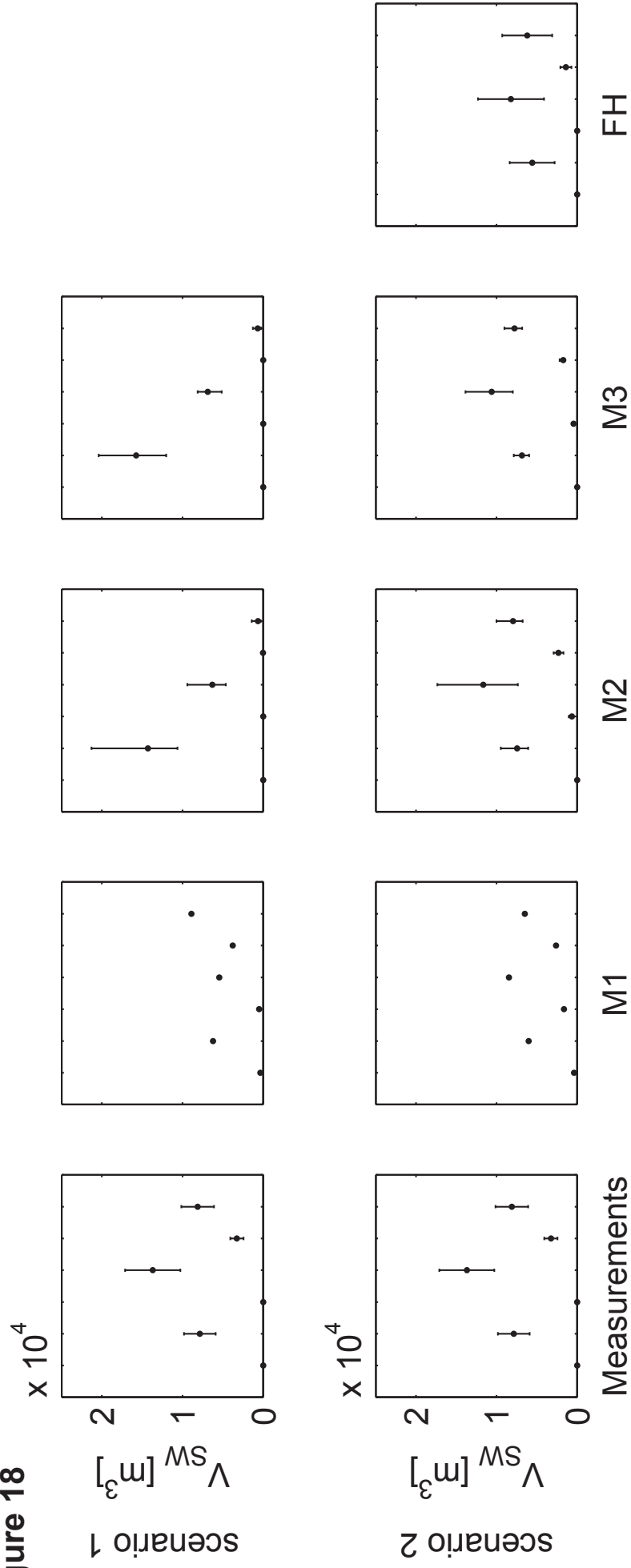


Figure 18



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

3
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16
17
18 **Abstract**

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

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

33

34

35 **Keywords**

36 calibration, conceptual models, full hydrodynamic models, integrated modelling, monitoring,

37 urban drainage systems

38

39 **1. Introduction**

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

55

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

63 model. Attempts to find appropriate calibration algorithms are described in e.g. (Krebs et al.,
64 2014; Mair et al., 2012; Vrugt et al., 2009; Wolfs et al., 2013).

65

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

78

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

87

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

105

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

112

113 **2. Materials and method**

114 **2.1. Catchment areas**

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

123

124 Waalre is located in the south of the Netherlands. The sewer system is looped with one
125 pumping station, a primary CSO equipped with a settling tank and a secondary CSO that rarely
126 discharges. Additionally Waalre is connected to a neighbouring catchment in the east.

127 Although water can flow both ways, it serves as a discharge for Waalre. Characteristics of the
128 sewer systems are listed in table 1, while figure 1 (right) displays the sewer system layout.

129 **2.2. Monitoring data**

130 For Loenen monitoring data is available at a one minute interval from June 2001 to January
131 2002, collected as part of a dedicated research project. Flow measurements are available at
132 the pumping station and an inflow into the pumping station from a neighbouring catchment.
133 Level measurements are available in the pumping chamber and at the CSO locations, as
134 displayed in figure 1 (left). Additionally, two rain gauges were installed in the catchment. Due
135 to various reasons no continuous data set is available for the measuring period.

136

137 For Waalre monitoring data at the sewer system edges is available at a one minute interval.
138 Flow is measured at the pumping station. Level measurements are available in the pumping
139 chamber, inside the settling tank and at the secondary CSO location. The measuring locations
140 are indicated in figure 1 (right). Rain radar data with pixel sizes of one square kilometre are
141 available. The radar data is calibrated against rain gauge measurements located approximately
142 10 km away using a procedure based on conditional merging as described in (De Niet et al.,
143 2013). The calibrated rain radar data is available only during wet weather days and when the
144 rain gauges functioned in the period April 2011 to January 2012. All other measurements are
145 registered permanently. Data validation was performed applying the algorithms described in
146 (Van Bijnen and Korving, 2008).

147

148 **Dry Weather Flow (DWF)**

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

158 **2.3. Full hydrodynamic (FH) models**

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

172

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

182

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

189 **2.4. Model structures**

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

195 **2.4.1. Rainfall runoff outflow (RRO) model**

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

202

$$203 \quad Q_{out}(t) = \exp\left(-\frac{\Delta t}{K}\right) Q_{out}(t - \Delta t) + \left[1 - \exp\left(-\frac{\Delta t}{K}\right)\right] I_{net}(t - T_{lag})A, \quad (1)$$

204

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

207

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

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

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

224

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

227 SR1. Static storage-level curve

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

232 SR2. Discharge through pump

233 The discharge through the pump ($Q_{s,p}$) is calculated through H_s and the pump
234 characteristic. The pump characteristic is taken from the FH model.

235 SR3. Discharge through CSO

236 The discharge through the CSO (Q_{CSO}) is taken to be only caused by the primary CSO.

237 The discharge is calculated through H_s and the standard weir equations for frontal
238 weirs:

239

$$240 \quad Q_{free} = c_1 h^{c_2} \quad (2)$$

241

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

244

$$245 \quad Q_{sub} = c_3 h_{DS} \sqrt{2g(h_{US} - h_{DS})} \quad (3)$$

246

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

252

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

259

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

262 SR4. Static storage-level curve sewer

263 See SR1, and excluding the settling tank.

264 SR5. Discharge sewer through pump

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

269 SR6. Discharge sewer through connection

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

274

$$275 \quad Q = c_1 \tan(\theta/2) h^{5/2}, \quad (4)$$

276

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).

301

302 The characteristics or relationships applied in the DR model are numbered DR1-DR4 in figure 7.

303 Their representation and derivation are explained bellow:

304 DR1. Hybrid storage-level curve

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

311 Figure 8 (left) displays the static, dynamic, and hybrid storage curves for Loenen.

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

320 DR2. Level at CSO

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

325 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

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

387 **2.5.2. Parameter optimisation**

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

391

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

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

405

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

414

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

421 **2.5.3. Events**

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

427

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

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

437 **2.6. Performance evaluation**

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

446

447 Common sense dictates that the impact of CSO events depends foremost on the occurrence of
448 such events, with the absolute discharged flows of secondary consequence. This is supported
449 by literature stating that impact based RTC can influence the systems performance for small
450 and moderate events, contrary to large events on which it has no influence (Langeveld et al.,
451 2013), and that up to a certain point overflow frequency is a good indicator of receiving water
452 impact (Lau et al., 2002). Therefore the first evaluation criterion for the simplified sewer
453 models is the correct determination of CSO event occurrences. The second evaluation criterion
454 is the correct determination of the total discharged volume.

455

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

462

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

470

471 For comparison purposes the selected rain events have also been simulated using the FH
472 models. The comparison between simplified models with calibrated inflow parameters and FH
473 models with uncalibrated inflow parameters is relevant since the FH models simulate the
474 sewer systems behaviour in greatest detail and hence are deemed to be most accurate (Ferreri
475 et al., 2010; Meirlaen et al., 2001; Rubinato et al., 2013). This might hold true for calibrated FH
476 models but not for the much more commonly applied uncalibrated models, as proper
477 calibration of FH models is very time consuming and requires a very large monitoring data set.
478
479 Finally, the simulation time needed by different simplified model structures and the FH model
480 will be compared.
481

482 3. Results and discussion

483 3.1. Calibration

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

490

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

498

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

505 sewer storage. The response to rainfall is therefore more smoothed, which is best
506 demonstrated in figure 11. NS values < 0.4 are found.
507
508 For both catchments and all model structures the 95% confidence bands are mostly $< 1\%$.
509 Logically, the influence of the (inflow) calibration parameters on water levels in sewer systems
510 is most apparent at the onset of a rain event or during temporal changes, resulting in
511 confidence bands up to 10% for M2 and M3, while they stay $< 1\%$ for M1.
512
513 For all scenarios for Loenen NS values for M2 and M3 > 0.90 . For M1, values differ strongly
514 from -8.52 to 0.44. For Waalre for M2 and M3 in scenario 1, NS values range between 0.61 and
515 0.96, with one event around zero. In scenario 2 the values drop to 0.5 to 0.6. The NS values for
516 M1 again differ strongly between events and scenarios from -9.42 to 0.82.
517
518 Figure 13 shows the optimal parameter values for Loenen (left) and Waalre (right) for all
519 model structures. In asterisks the results for scenario 1 (calibration on single rain events) are
520 given, the line indicates the parameter values for scenario 2 (all events together). Results for
521 all twenty possible combinations of three calibration events in scenario 3 can be found in
522 figure 14. The optimal parameter values reflect the results for the water levels and NS values:
523 the parameters for M2 and M3 show much resemblance within a catchment, while M1
524 deviates. Especially the difference in K stands out, as the RRO model in M1 has to account for
525 the surface and in-sewer storage, while in M2 and M3 only for the surface storage. The
526 optimal parameter values between scenarios 2 (line in figure 13) and 3 (figure 14) are
527 consistent, indicating that the exact split in a calibration and verification set does not have a
528 major impact on the outcome.

529 **3.2. Performance evaluation**

530 **3.2.1. Model discharge**

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

534

535 Optimal Q_{SW} and Q_{WWTP} for all model structures for the calibration of the single events of 2001-
536 08-27 (Loenen) and 2011-08-14 (Waalre) are displayed in figures 15 and 16 as well as the
537 discharges determined from the measurements. The difference between M1 and M2/M3
538 observed in the calibration results are also clear from these figures, as Q_{SW} for M1 tends to be
539 more smoothed because of the higher value for K.

540 **3.2.2. Determination of CSO events**

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

545

546 Based on the FPs and FNs in table 4, M1 can be immediately discarded for these catchments.
547 For each scenario and catchment two FPs were recorded, the exact number of rain events that
548 did not lead to a CSO event. This is easily explained since a rain event leading to a significant
549 rise in water level in a pumped sewer system will likely contain rain intensities higher than the
550 pumping capacity of the sewer system reserved for WWF (design guideline in the Netherlands:
551 0.7 mm/h). In M1 all rainfall in excess of this capacity has to be discharged to the surface
552 water, leading to a CSO event. The calibration algorithm unsuccessfully tries to overcome this

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

563 **3.2.3. Determination of discharged volumes**

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

577

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

582

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

593

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

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

604

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

614

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

619

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

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

630 **3.2.4. Uncalibrated FH models**

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

635

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

639

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

646

647 The simulation time for the FH models takes 1,000-5,000 times longer than for M2/M3 or
648 250,000-475,000 times longer than for M1.

649

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

654 **4. Conclusions and future research**

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

661

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

668

669 From this research the following conclusions can be drawn:

- 670 – Model M1 simulates > 100,000 times faster than the FH model; models M2/M3
671 are > 1,000 times faster than the FH model.
- 672 – M1 is unsuitable to correctly predict CSO occurrences for pumped catchments.
673 The model structure is unable to retain rain intensities higher than the pumping
674 capacity reserved for WWF, resulting in too many CSO discharges.
- 675 – M2 and M3 are able to describe the behaviour of pumped sewer systems.
- 676 – Performance indicators for the selection of the most appropriate model structure
677 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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708

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

802

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

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

806

807

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.

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

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.

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

5

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

7

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

11

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

14

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

17

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

20

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

23

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

26

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

29

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

32

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

35

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

38

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

42

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

46

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

48

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

50

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.