# Dendrobium Mine

## Longwalls 20 and 21 Groundwater Assessment

FOR

Illawarra Coal Pty Ltd

PREPARED BY

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# 1 INTRODUCTION

The Dendrobium Mine is located approximately 12 kilometres (km) west of Wollongong (NSW) in the Southern Coalfield and within the Metropolitan Special Catchment Area managed by WaterNSW. The mine is operated by Illawarra Coal (IC), a subsidiary of South32. **Figure 1** shows that the designated areas of extraction at Dendrobium are:

- Area 1, the easternmost and lying adjacent to the Cordeaux Reservoir and close to the Illawarra Escarpment;
- Area 2, immediately to the west and south of Cordeaux Reservoir;
- Area 3A, to the west of Cordeaux Reservoir and adjacent to Wongawilli Creek;
- Area 3B, further west, between Wongawilli Creek and Avon Reservoir; and
- Area 3C, to the north of Areas 3A and 3B, between Donalds Castle Creek and Lake Cordeaux.

Coal is extracted from the Wongawilli Seam by longwall mining. Previous workings in the Wongawilli Seam are located to the south at Elouera and Nebo (also referred to as 'Wongawilli'), and to the east at Kemira. The overlying Bulli Seam has been mined at Mt Kembla, partially coincident and to the east of Area 1.

HydroSimulations (HS) was engaged by IC to prepare an assessment of potential impacts of the extraction of the proposed Longwalls, 20 and 21 within Area 3C. Prior to approval being given to mine this area, IC is required to prepare a Subsidence Management Plan (SMP) outlining the potential impacts that may occur to identified features of significance within and near to this area (see **Section 1.3**). This assessment provides information about predicted groundwater behaviour in response to mining and subsidence for consideration by NSW Department of Planning and Environment (DPE) in the assessment of the SMP. Some of the information provided is in response to the comments and recommendations of the Independent Expert Panel for Mining in the Catchment (IEPMC)

## 1.1 HISTORICAL AND APPROVED MINING AT DENDROBIUM

Longwall mining has been occurring at Dendrobium Mine since early 2005 (**Table 1-1**). Area 1 (Longwalls 1 and 2) was completed in 2007, then Area 2 (Longwalls 3, 4, and 5) in 2009, and Area 3A (Longwalls 6, 7 and 8) in 2012. Mining of Area 3B has been undertaken since February 2013. Four of the ten proposed longwalls remained to be mined in Area 3B following the completion of mining at Longwall 14 in April 2019. **Figure 2** shows the location of the mining areas and longwalls at Dendrobium and the relative location of nearby reservoirs and watercourses.

**Table 1-1 Historical and Proposed Longwall Dates and Dimensions**

| MINE AREA | LONG-WALL | DATE START | DATE END | DAYS | LW WIDTH | VOID WIDTH | LW LENGTH | CUTTING HEIGHT | | DEPTH OF COVER [m] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Historical Panels** | | | | | | | | **Mean** | **Max** | **Min** | **Mean** | **Max** |
| 1 | 1 | 30/03/05 | 15/12/05 | 261 | 237 | 247 | 1750 | 3.2 | 3.70 | 170 | 262 | 316 |
| 1 | 2 | 09/02/06 | 22/01/07 | 348 | 237 | 247 | 2000 | 3.3 | 3.66 | 162 | 264 | 320 |
| 2 | 3 | 30/03/07 | 22/11/07 | 238 | 235 | 245 | 1590 | 3.6 | 3.75 | 138 | 211 | 282 |
| 2 | 4 | 17/12/07 | 30/09/08 | 289 | 235 | 245 | 1940 | 3.6 | 3.80 | 159 | 249 | 310 |
| 2 | 5 | 04/12/08 | 18/12/09 | 380 | 235 | 245 | 2300 | 3.7 | 3.90 | 213 | 252 | 293 |
| 3A | 6 | 9/02/10 | 28/03/11 | 413 | 238.5 | 248.5 | 2617 | 3.5 | 3.60 | 287 | 345 | 389 |
| 3A | 7 | 04/05/11 | 23/01/12 | 265 | 238.5 | 248.5 | 2217 | 3.4 | 3.50 | 288 | 338 | 379 |
| 3A | 8 | 24/02/12 | 29/12/12 | 310 | 295 | 305 | 2538 | 3.5 | 3.70 | 261 | 321 | 373 |
| 3B | 9 | 09/02/13 | 02/06/14 | 479 | 295 | 305 | 2155 | 3.9 | 4.50 | 314 | 381 | 409 |
| 3B | 10 | 20/01/14 | 20/01/15 | 366 | 295 | 305 | 2210 | 3.9 | 3.95 | 325 | 383 | 406 |
| 3B | 11 | 18/02/15 | 05/01/16 | 322 | 295 | 305 | 2304 | 3.9 | 3.95 | 327 | 381 | 404 |
| 3B | 12 | 22/01/16 | 31/01/17 | 377 | 295 | 305 | 2591 | 3.9 | 3.95 | 329 | 376 | 404 |
| 3B | 13 | 04/03/17 | 19/04/18 | 411 | 295 | 305 | 2222 | 3.2 | 3.70 | 299 | 375 | 400 |
| 3B | 14 | 22/05/18 | 26/02/19 | 223 | 295 | 305 | 1980 | 3.89 | 3.90 | 325 | 378 | 395 |
| **Proposed Panels** | | | | | | | | | | **Min** | **Mean** | **Max** |
| 3B | 15 | Apr-2019 | Sep-2019 | 245 | 295 | 305 | 1963 | | 3.90 | 324 | 370 | 390 |
| 3B | 16 | Oct-2019 | Jun-2020 | 245 | 295 | 305 | 1874 | | 3.90 | 280 | 350 | 390 |
| 3B | 17 | Jul-2020 | Mar-2021 | 245 | 295 | 305 | 2013 | | 3.90 | 279 | 345 | 385 |
| 3B | 18 | Apr-2021 | Nov-2021 | 215 | 295 | 305 | 1928 | | 3.90 | 248 | 332 | 375 |
| 3A | 19 | Jan-2022 | Jun-2022 | 150 | 295 | 305 | 1600 | | 3.60 | 287 | 331 | 369 |
| **3C** | **20** | Apr-2023 | Aug-2023 | 150 | 245 | 256 | 872 | | 3.90 | 320 | 365 | 410 |
| **3C** | **21** | Aug-2022 | Mar-2023 | 240 | 245 | 256 | 1154 | | 3.90 | 290 | 335 | 390 |

Width and length all in metres (m).

Longwall widths and cutting heights increased from Area 1 to Area 3B (**Table 1-1**). Maximum cutting heights were approximately 3.7 m in Area 1, and 3.5-3.9 m in Areas 2 and 3A. Earlier Area 3B longwalls had maximum cutting heights between 3.95 and 4.5 m. Recent SMP approvals stipulate that Longwalls 14 to 16 must have a maximum cutting height of no more than 3.9 m. A maximum cutting height of 3.9 m is proposed for Longwalls 20 and 21.

## 1.2 PROPOSED MINING

This study incorporates IC's proposal for Dendrobium Longwalls 20 and 21. The planned timing and dimensions of the proposed longwalls are presented in **Table 1-1**, along with planned longwalls in Area 3B (Longwalls 15-18) and Area 3A (Longwall 19).

### 1.2.1 LONGWALLS 15-19

These longwalls are proposed to be at least 300 m from the Lake Avon Full Storage Level (FSL), as in *Condition 3* of the SMP approval. Some of these longwalls have also been shortened at their eastern end to avoid mining under tributaries of Wongawilli Creek (i.e. WC15 – as per *Condition 3*).

As shown on **Figure 2**, Longwalls 15 to 18 extend into the DSC Avon Notification Area.

Longwall 19 in Area 3A is proposed for extraction after Area 3B and would be located immediately south of the previously mined Longwall 8 (Area 3A).

### 1.2.2 AREA 3C LONGWALLS 20 AND 21

Longwalls 20 and 21 are both to be 256 m wide (**Table 1-1**). Cutting heights are similar to recent, with a maximum of 3.9 m as imposed by the most recent Area 3B SMP approval.

**Figure 2** shows that these longwalls are distant from WaterNSW's reservoirs, being at least 1.5 km from Lake Cordeaux and 2.9 km from Lake Avon and are therefore outside of DSC Notification Areas. Longwall 20 is 120 m west of Wongawilli Creek, and 570 m east of Donalds Castle Creek at their closest points. Longwall 21 is 240 m east of Wongawilli Creek at its closest point.

There are no overlying historical workings associated with or near Longwalls 20 and 21.

## 1.3 SCOPE OF WORK

Numerical modelling has formed part of previous groundwater assessments carried out by Coffey (2012b) and HS (2014, 2016a, 2018). A detailed regional groundwater model has been developed for previous assessments, most recently updated for the Longwall 16 SMP approval (HS, 2018).

**Table 1-2** outlines the conditions within Schedule 3 of the *Consolidated Dendrobium Consent* DA 60-03-2001 that are relevant to groundwater and the sections of this report that address them.

This assessment focuses on predicting the potential impacts of Longwalls 20 and 21, on groundwater, watercourses and reservoirs, with reference to the subsidence assessment of MSEC (2019a). For this assessment, historical mining and mining at proposed Longwalls 16-19 has been simulated to provide an understanding of the potential cumulative impacts that may be experienced with the addition of Longwalls 20 and 21.

**Table 1-2 Groundwater-related SMP Requirements and Conditions**

| CONDITION | | DETAIL | WHERE DEALT WITH |
|---|---|---|---|
| **2** | **Watercourse Impact Management** | | |
| | The Applicant shall ensure that underground mining operations do not cause subsidence impacts at Sandy Creek and Wongawilli Creek other than "minor impacts" to the satisfaction of the Secretary. | "Minor Impacts" refer to minor fracturing, gas release, iron staining and minor impacts on water flows, water levels and water quality. | Predictions of loss of surface water provided in Section 5.6. |
| **3** | The Applicant shall ensure the development does not result in reduction (other than negligible reduction) in the quality or quantity of surface water or groundwater inflows to Lake Cordeaux or Lake Avon or surface water inflow to the Cordeaux River at its confluence with Wongawilli Creek, to the satisfaction of the Secretary. | | Predictions of loss of surface water provided in Sections 5.4, 5.5 and 5.6. |
| **13** | **Groundwater Monitoring Program** | | |
| | The SMPs prepared under Condition 7 must include a Groundwater Monitoring Program, which must include: | (a) proposals to develop a detailed regional and local groundwater model, with special reference to flows to and from nearby water storages; | This report in general. Specific reference to Sections 5.4 and 5.5. |
| | | (b) detailed baseline data to benchmark the natural variation in groundwater levels, yield and quality; | Provided separately. |
| | | (c) groundwater impact assessment criteria; | Provided separately. |
| | | (d) a program to monitor the impact of the development on:<br>▫ groundwater levels, yield and quality (particularly any potential loss of flow to, or flow from,<br>▫ SCA (WaterNSW) water storages);<br>▫ coal seam aquifers and overlying aquifers;<br>▫ groundwater springs and seeps; and | Provided separately. |
| | | (e) consideration of the requirements of the latest version (or subsequent replacement) of SCA's The Design of a Hydrological and Hydrogeological Monitoring Program to Access the Impacts of Longwall Mining in SCA (WaterNSW) Catchment. | Provided separately, although NRAR has advised that this is "no longer a key reference" and that this condition be removed. |

HS has also considered the additional Conditions that were imposed on the mining of Area 3B in 30 May 2018, as listed in **Table 1-3**. These are not directly relevant, but the content has been incorporated into the modelling and reporting here.

**Table 1-3 Additional A3B SMP Requirements re: the Groundwater Model (30/05/18)**

| CONDITION | | DETAIL | WHERE DEALT WITH |
|---|---|---|---|
| **13** | **Groundwater Model** | (a) provide adequate water table contour plots, drawdown plots and pore pressure vertical section plots for predicted and observed conditions; | Section 4.6.3 (Calibration) and Sections 5.7.1, 5.7.2 and 5.7.3 (Predictions). |
| | Prior to the extraction of Longwall 15, unless otherwise agreed by the Secretary, the Applicant must review and update the Area 3B | (b) take into consideration the findings of any independent report on groundwater commissioned by DPE, or advice from the IEPMC, and the report required under condition 18(c) [*sic* 14(c)] of this approval; | Table 1-4, Sections 2.9 and 2.9 and HS (2017) are relevant. |

| CONDITION | | DETAIL | WHERE DEALT WITH |
|---|---|---|---|
| | Groundwater Model to the satisfaction of the Secretary.<br>The updated model must: | (c) be peer reviewed by a suitably qualified, experienced and independent expert, who is approved by the Secretary. | Review by Kalf and Associates (KA) carried out for HS (2018) [LW16 model update]. Comments made by KA are incorporated into this report. |
| **14** | **<u>Groundwater Monitoring and Height of Cracking</u>** | | |
| | The Applicant must undertake a comprehensive program of groundwater monitoring and assessment… to the satisfaction of the Secretary, including: | (a) undertaking detailed geotechnical and hydrological investigations of the height of connective cracking in Longwalls 6 to 12, prior to the extraction of Longwall 14; | Details provided separately. |
| | | (b) installing a combination of extensometers and multi-level piezometers directly above Longwalls 14, 15 and 16, in consultation with Water NSW and OEH, prior to the extraction of Longwall 15; | Details provided separately. |
| | | (c) engaging a suitably qualified, experienced and independent expert, who is approved by the Secretary, to prepare and submit a report to the Department prior to the extraction of Longwall 15, unless otherwise agreed by the Secretary, which includes:<br>▫ a model describing the measured height of connective cracking across Longwalls 6 to 12;<br>▫ detailed predictions of the height of cracking for Longwalls 14 to 18, and associated impacts on sensitive surface features, including watercourses, swamps and Avon Reservoir;<br>▫ an analysis of the extent of surface cracking and potential connections with horizontal partings; and<br>▫ consideration of the findings and recommendations of any independent report on groundwater commissioned by DPE; | Provided separately. |
| | | (d) an assessment of the height of connective fracturing and the extent of surface cracking before and after the extraction of Longwalls 14 and 15 and 16. | Provided separately. |

Recommendations from the DPE-commissioned study into the Height of Connected Fracturing (PSM, 2017) are described in **Section 2.9**, and many were incorporated into this groundwater model as reported in a previously report (HS, 2018).

In 2018, IEPMC was formed to provide informed expert advice to the DPE on the impact of mining activities in the Greater Sydney Water Catchment Special Areas, with a particular focus on risks to the quantity of water in the Catchment. The IEPMC released an initial report in late 2018, and the relevant recommendations are summarised in **Table 1-4**.

**Table 1-4 Recommendations of IEPMC (2018)**

| RECOMMENDATION | | | DETAIL / RESPONSE | WHERE DEALT WITH |
|---|---|---|---|---|
| **p.35** | **2.3.4** | There is a need to consider the ability of geological structures to transmit effects over distance beyond the angle of draw, e.g. as noted at Springvale Mine | This effect not yet seen at Dendrobium – impacts on shallow piezometers at Dendrobium have all been within 120 m. Recommend that the position of structures be considered in EOP reporting re: swamp piezometers when analysing hydrographs. | |
| **p.47** | **Para 3.** | the Panel foresees that faulting, basal shear planes, lineaments and the potential to unclamp and reactivate fault planes will need to be very carefully considered | Investigations are currently underway at major geological structures in Area 3B, however these are not relevant to Longwalls 20 and 21. | Minor geological structures around Longwalls 20 and 21 are discussed in Section 2.1. |

| RECOMMENDATION | | | DETAIL / RESPONSE | WHERE DEALT WITH |
|---|---|---|---|---|
| | | | Basal shears are modelled around the deeper valleys near Longwalls 20 and 21, e.g. along Wongawilli Creek. | Modelling of off-goaf effects in Section 4.5.3. |
| GROUNDWATER IMPACTS AT DENDROBIUM MINE | | | | |
| **p.91** | **6** | Notwithstanding that uncertainty is associated with both the Tammetta and the Ditton height of complete drainage equations, it is recommended to err on the side of caution and defer to the Tammetta equation until field investigations quantify the height of complete drainage AND/OR geomechanical modelling of rock fracturing and fluid flow is utilised | The method used here is as conservative as that recommended by IEPMC in that the Tammetta method is used as a starting point, and then seam-to-surface connection is simulated for 300 m wide panels. | See discussion of model representation of the height of fracturing in Section 2.8 and 4.5.1. |
| | **8** | Groundwater models should:<br>i. continue to be updated<br>ii. be migrated from MODFLOW-SURFACT to MODFLOW-USG only if significant benefits can be demonstrated<br>iii. be underpinned by unified material properties (for common stratigraphic layers) unless differences can be demonstrated to exist through measurements | i) the model has been updated numerous times, with additional layering, parameters and methods for deformation. A more advanced modelling platform is being developed as part of a long-term project.<br>ii) HS do not agree that specific software should be specified. Both SURFACT and USG have advantages and disadvantages.<br>iii) Differences in material properties may exist between the two sites identified by IEPMC, however HS agree that more analysis should be done on Southern Coalfield material properties. The parameters of this model rely heavily on the extensive Dendrobium packer test dataset. | Model development and evolution is described through Coffey (2012), HS (2014, 2016, 2018, 2019).<br>Details can be provided separately if required.<br>Recommend a future study to document this (Section 7.2), covering as many datasets as available. |
| SURFACE WATER IMPACTS AT DENDROBIUM MINE | | | | |
| **p.119** | **17** | ii. installation of weirs and/or flumes at selected sites agreed by WaterNSW and the Dendrobium Mine. ... sites should… include catchments …potentially affected by LW 16 to LW 18 | New surface water sites have been installed. | Section 2.3.1. |
| | **17** | iv. additional basal shear monitoring, implemented as a priority between the Avon Dam and LW 14 to 18 before mining commences. The sites should be designed to complement the … strategy (geotechnical and groundwater) at S2313 and S2314. | Aside from S2313 and S2314, new monitoring holes installed between Area 3B and Lake Avon, including S2376, S2377, S2378, S2379, S2435, S2436. | See network of "Avon monitoring" sites on **Figure 7**. |

## 1.4 WATER MANAGEMENT

Water use in NSW is managed by Dept. of Industry - Water (DoI Water) through Water Sharing Plans (WSP). The Dendrobium Mine lies within the Nepean Sandstone Groundwater Source of the *Greater Metropolitan Region Groundwater Sources* WSP[1], which is the instrument through which groundwater is managed by the NSW Government. Specifically, the

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[1] https://www.industry.nsw.gov.au/__data/assets/pdf_file/0007/168505/metro-groundwater-background.pdf

Dendrobium mining area is in Management Zone 2 of that Groundwater Source. This Groundwater Source has been classified as 'Highly Productive'.

Surface Water in this area is managed under the *Greater Metropolitan Region Unregulated River Water Sources W*SP[2].

## 1.5 STRUCTURE OF THIS REPORT

Review and assessment of rainfall, evaporation, topography, geology, or a full description of the conceptual or numerical models is available in the following previous reports:

- Coffey, 2012a and 2012b;
- HS, 2014;
- HS, 2016a;
- HS, 2016b;
- HS, 2018;
- HS, 2019;
- End of Panel reports:
  - Groundwater: e.g. HS 2012-2016 and HGEO, 2017; and
  - Surface Water and Shallow Groundwater, e.g. Ecoengineers 2013-14, HS, 2016c and HGEO, 2017 and 2018.

New information, analysis and interpretation, as well as changes to the groundwater modelling are described in this report. The structure is as follows:

| SECTION | TITLE | CONTENTS |
|---|---|---|
| **1** | Introduction | Description of Dendrobium Mine operations and scope of work. |
| **2** | Hydrogeology | A summary and discussion of key facets of the groundwater system, including discussion of relevant points from PSM (2017) and IEPMC (2018). |
| **3** | Conceptual model | Summarises the data analysis and the conceptual model developed, which then leads to the design and operation of the numerical model in the following sections. |
| **4** | Model construction and calibration | Describes changes to the groundwater model to meet relevant conditions as well as other modifications. |
| **5** | Predictive modelling | Presents output from the updated model, including predicted groundwater inflow, groundwater level and pressure hydrographs/maps/profiles, and incidental take from surface water features. |
| **6** | Conclusions | Includes assessment of Longwall 20 and 21 and Dendrobium Mine against the *Aquifer Interference Policy* (2012). |

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[2] https://www.water.nsw.gov.au/water-management/water-sharing/plans_commenced/water-source/gmr-unreg

# 2 HYDROGEOLOGY

The hydrogeology of the Dendrobium area is described in previous reporting, such as HS, 2016a,b. This section includes a summary of an updated conceptual model of hydrogeology around the Dendrobium Mine based on interpretation of new data collected since these reports, including additional investigative bore holes over and adjacent the mining area as well as the IEPMC (2018) report and DPE's independent 'Height of Fracturing Study' (Pells Sullivan Meynink [PSM], 2017). An integration of the data and analysis is then provided as a conceptual model of geotechnical/groundwater effects in **Section 3**.

## 2.1 GEOLOGICAL STRUCTURE

The dip of the sedimentary strata in this area is predominantly to the north, with some westerly dip toward a regional south-to-north syncline which is located near Donalds Castle Creek.

The general effects of structures on groundwater were discussed in Section 3.7 of HS, 2016a. More targeted work, focussing on the role of structures, such as the Elouera Fault, has been commissioned by IC.

**Figure 2** shows the geological structures that have been mapped around the proposed footprint of Longwalls 20 and 21. The key features are listed below, along with some information obtained from IC geologists:

- East-west trending dykes and faults (detected in the Wongawilli Seam), mainly lying to the south or within the southern end of Longwall 20 or to the immediate north of Longwall 21:
    - Dyke "DD9": is a long feature running from near Area 2, 170 m north of Longwall 21 and through the southern quarter of Longwall 20. It is a thick and persistent dyke zone.
    - Dyke "DD25": starts about 90 m north of the north-western corner of Longwall 21 and then runs about 75 m south of Longwall 20.
    - DD9 and DD25 merge into one another. There is no obvious vertical displacement, and hard and soft phases are present within this zone.
    - Faults "DF32" and "DF33": pass 120 m north of Longwall 21, across Wongawilli Creek and through the southern end of Longwall 20. These are low confidence faults that are part of the DD9 dyke zone. IC has several UIS holes through both of them with no significant displacement noted at either.
- A number of lineaments have been detected in this area:
    - "DSD1" is interpreted as being an indication that the dykes mapped at seam level in the DD9-DD25 dyke zone extend to surface.
    - "DL_1" and "DL_2" are lineaments interpreted from aeromagnetic survey. These broadly align with the wider dyke zone and support the general structural trend in this area.

As noted in IEPMC (2018 and raised again in a letter of 2019) lineaments may exacerbate the distance or ability of far-field effects of mining to have an impact on water features, such as swamps and waterfalls. IEPMC (2018) gave the example of water related impacts to swamps near Springvale Mine being affected by longwall extraction at a distance of 700-1200 m. Based on a review by Watershed HydroGeo (2019), at Dendrobium such effects on swamps have not been observed, with shallow piezometers being affected to a maximum of 125 m from panels, and an association of these effects to mapped lineaments have not been concluded.

Overall, interpretation of transmissivity of these structures is difficult, but the lack of displacement suggests that these structures do not enhance hydraulic conductivity or storage properties. This is consistent with the review of structures in the Southern Coalfield, including at Dendrobium, by Tonkin and Timms (2015).

## 2.2 CLIMATE

The climate of Dendrobium has been discussed in previous reporting. Average annual rainfall is approximately 1200 mm/yr and average potential evaporation is 1430 mm/yr (from Bureau of Meteorology [BoM] records).

Since previous reporting, conditions in the mining area has been very dry, with rainfall being below average for an extended period. BoM's Drought Statement indicates that the period April 2017 to October 2018 is the driest, or as dry, as any 18-month period on record for the area.

## 2.3 SURFACE WATER AND SWAMPS

As noted above, neither of these panels would underlie Wongawilli Creek, being about 130 m (Longwall 20) and 230 m (Longwall 21) from that watercourse.

Longwalls 20 and 21 would underlie several small watercourses (**Figure 2**). Longwall 20 directly underlies the small tributaries WC23 and WC25.

The footprint of Longwall 21 would intersect approximately 400 m of WC20 (a tributary of Wongawilli Creek) and is close to the headwaters of WC24. This panel would also underlie a small fraction of the catchment to LC5, although it is about 290 m from the watercourse itself.

The following sections outline monitoring, natural groundwater-surface water interaction and the effects on streamflow from historical mining at Dendrobium.

See HGEO (2018) and IC (2017) for more detail on swamps.

### 2.3.1 MONITORING

See HS (2016a) and HGEO (2017) for more detail on surface water monitoring. In recent months, IC has installed gauging stations on the following watercourses, shown on **Figure 7**:

- LA2 – installed 01/02/2019.
- LA3 – installed 31/01/2019.
- WC12 – installed 14/02/2019.
- NDT1 – installed 28/02/2019.
- LC5 – installed 13/02/2019.

The first four of these are distant from Longwalls 20 and 21, but the last (LC5S1) is approximately 1.5 km north-east the footprint of Longwall 21.

This addresses *Condition 11* of the latest SMP conditions regarding the need for further monitoring of these streams around the southern part of Area 3B.

Monitoring data will be available in the near-future, although the baseline period will be very short for LA3 and WC12.

### 2.3.2 BASEFLOW ESTIMATES

IC has been monitoring stream level and flow around Areas 3A and 3B since late 2007. The Dendrobium area baseflow indices (BFI) have been estimated and converted to baseflow yield (mm/yr) and % long-term average rainfall and are summarised in **Table 2-1**. The BFI in the table are consistent with the regional average of about 10% concluded in Advisian (2016).

**Table 2-1 Summary of calculated BFI and Baseflow Yield**

| Watercourse | BFI | Baseflow yield [mm/yr] | %LTA rainfall |
|---|---|---|---|
| **Wongawilli Creek** | 10-16 % | 31 to 50 | 2.5 to 4.2% |
| **Donalds Castle Creek** | 1-6 % | 1.5 to 10 | 0.1 to 1% |
| **Sandy Creek** | 8-20 % | 22 to 55 | 1.8 to 4.6% |

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This analysis suggests that baseflows in the Dendrobium area are equivalent to approximately 2-60 mm/yr (with a mean of about 20-50 mm/yr), or approximately 1-4% of long-term average (LTA) rainfall.

The higher porosity of swamp deposits means that these features are considered to supply reliable baseflow to watercourses for an extended period after rainfall. Analysis of two similarly sized gauged catchments at Dendrobium, SCU and WC15 suggests that WC15 has more consistent recession flows than does SCU, which may be a result of the swamp deposits (Swamp 14) covering about 5% of the area of the WC15 catchment, while SCU has no mapped swamp deposits in its catchment.

However, subsequent analysis of water levels from Swamp 14 is not definitive. A calculation of swamp area and water level decline indicates that this swamp could contribute as much as about 20% of the daily flow in WC15 during a recession period, but when evapotranspiration is considered as a cause of water level decline in the swamp, this could be significantly lower, with the potential contribution by the swamp to flows in WC15 being anywhere from 0-20%.

It seems likely that swamps do contribute some baseflow to downstream watercourses; however, the significance of that baseflow would be dependent on swamp-specific factors (sediment type, position in the catchment), catchment-specific factors (topography, slope, geology, rainfall). The relatively shallow swamp deposits also limits the volume of water that can be stored in them, despite their higher porosity.

### 2.3.3 BASEFLOW DEPLETION

Mining-induced subsidence and depressurization can result in reductions in low-flows and increases in the duration of cease-to-flow conditions.

Reports such as HS (2016a,b) and McMahon (2015) discuss the loss of surface flow in undermined headwater streams such as WC21, DC13S1, DCS2 (HS, 2016c; HGEO, 2017). However, changes in surface water flow are not as easily discernible at the major downstream gauges (e.g. Donalds Castle Upper [DCU], Wongawilli Creek Lower [WWL]).

This is likely a result of gauging accuracy and the relatively small magnitude of loss compared to total flow at the downstream gauging stations. That understanding is in line with earlier assessments which made similar statements about the observed loss of surface flow and possibility of re-emergent flow:

"*Effects* (baseflow losses) *are not clearly observed in the downstream catchments to Donalds Castle Upper (DCU) and Wongawilli Creek Lower (WWL); this suggests that some or all flow lost in the headwater catchments is returned downgradient, but is not conclusive, as evapotranspiration (ET) might account for some fraction of that.*" (HS, 2016c).

This is in agreement with both the findings on longwall-induced alteration of habitat by the NSW Scientific Committee and with work on Waratah Rivulet (e.g. Mclean *et al*., 2010), as discussed in Section 3.6 of HS (2016d). The NSW Scientific Committee states:

> *"If the coal seam is deeper than approximately 150 m, the water loss may be temporary unless the area is affected by severe geological disturbances such as strong faulting. In the majority of cases, surface waters lost to the sub-surface re-emerge downstream"* (OEH, 2011).

For context, the coal seam at Dendrobium Area 3A is typically 330 m deep, in Area 3B is typically >350 m deep (**Table 1-1**). In the area around Longwalls 20 and 21, the Wongawilli Seam is typically 340 to 400 m above the panels. Beneath the incised valley of Wongawilli Creek, the depth of the seam is approximately 240 m.

This understanding is routinely re-assessed during the End-of-Panel process. The most recent End-of-Panel report (HGEO, 2018) indicates no discernible effect at WWL, despite the reach of Wongawilli Creek adjacent to Longwalls 6-11 experiencing 'discontinuous flow', i.e. a sequence of very low flows and cease to flow conditions and dry pools, that is very likely due to groundwater depressurisation resulting in baseflow capture. Watershed HydroGeo (2018) indicated the magnitude of loss along this reach is approximately 0.2 ML/d (allowing for gauging error at the upstream gauging station Wongawilli Creek Upper [WWU]) in this specific reach. Further there is likely to be a mining-related effect on flows at DCU – an effect that is clearly discerned from the comparison of modelled (via AWBM [Boughton, 2004]) and recent observed data, yet too small to result in the triggering of the defined Trigger Action Response Plan. This recent effect at DCU is in addition to the previously identified, but variable impacts on the gauged headwater catchments around Area 3B (WC21, DC13, DCS2, LA4).

## 2.4 GROUNDWATER USERS (REGISTERED BORES)

The Dendrobium mining area lies entirely within the WaterNSW Metropolitan Special Area and so there are few registered 'groundwater works' (typically bores) in the vicinity of the Dendrobium Mine (**Figure 6**). The nearest are listed in **Table 2-2** (data from the 'Pinneena' database).

**Table 2-2 Bores (GW works) nearest Dendrobium Mine**

| GW work # | Distance from Dendrobium Mine | Distance from Longwalls 20 or 21 | Comment |
|---|---|---|---|
| GW112386 | 1.9 km N of Area 2 | 1.8 km NE | Monitoring bore installed by WaterNSW on western edge of L. Cordeaux. |
| GW040945 | 7.2 km WNW of Area 3B | 8.7 km N | WaterNSW test bore drilled to investigate groundwater supply near L. Avon dam. |
| GW068119 and a number of others | 4.5 km S of Areas 1-2 | 9.1 km SE | GW068119 and nearby private bores are located on the coastal plain, and in the lower Permian units (e.g. Shoalhaven Group). |
| GW102528 | 10.5 km N of Areas 3B | 9.0 km N | Domestic/stock bore completed in the Hawkesbury Sandstone, just south of Wilton. |

All other Groundwater Works are further from Longwall 20 and 21, and most of them along the coastal plain. In line with the requirements of the *Aquifer Interference Policy* (2012), an assessment of drawdown at these GW works, based on the modelling, is presented in Section 5.7.4.

## 2.5 GROUNDWATER MONITORING

Dendrobium operate one of the largest groundwater monitoring networks in NSW. As outlined in the Groundwater Monitoring and Modelling Plan (HS, 2015a) this includes monitoring of:

- Groundwater pressures or levels via some stand-pipe bores but primarily via multi-level vibrating wire piezometers (VWPs). Most of these bores are drilled and completed down to the Wongawilli Seam, i.e. 300-500 m deep. There are currently over 600 piezometer instruments installed in different strata around Dendrobium.
- Groundwater quality sampling from bores fitted with groundwater pumps, usually monitoring water quality in the Hawkesbury Sandstone and Bulgo Sandstone (Section 2.12).
- Shallow piezometers, typically 1-3 m deep, installed in swamp deposits and other surficial deposits (i.e. regolith). Approximately 98 of these piezometers have been installed around Areas 2, 3A, 3B, 3C, and proposed Areas 5 and 6.
- Mine water management sumps and pumps, which have flow meters attached and which allow measurement of water pumping underground and an estimation of area-by-area groundwater inflows via a detailed water balance (Section 2.7).
- Mine water chemistry sampling points, sampling from the underground strata via roof-drippers in roadways and from goaves (Section 2.12).

Of primary interest to this report and the modelling are the groundwater levels in the hard-rock strata. The monitoring points (VWP bores) relevant to Area 3B Longwall 17 are shown on **Figure 7**. The groundwater monitoring network has expanded in spatial extent and scope over time. More of the types of sites listed above are being installed (e.g. more longwall centre-line bores, Lake Avon shore-line bores) in response to recommendations by technical specialists and Government agencies.

## 2.6 HYDRAULIC PROPERTIES

The set of pre-mining hydraulic conductivity data is presented in **Appendix B**. **Figure B1** shows the packer test data, which measures in-situ horizontal hydraulic conductivity (Kh), and **Figure B2** shows the vertical hydraulic conductivity (Kv) data as determined by (laboratory) core testing. These Kh and Kv data are classified according to the stratigraphic unit tested. **Figure B3** shows the variation in Kh by mine area and by depth. In general, the different stratigraphic units are slightly deeper in Area 3C than in Areas 3A and 3B, which are deeper than Area 2. This leads to *generally* lower Kh in Area 3C than in other recent mining areas.

These datasets have been used to inform and constrain the permeability parameters used in the groundwater model (**Section 4.7**).

## 2.7 MINE INFLOW

Groundwater inflow to the mine workings is inferred from the detailed site water balance that is maintained by the IC Water Balance Officer at Dendrobium. **Figure 3** presents the mine inflow for each of the four historical areas in relation to the total inflow, rainfall trends (residual mass) and longwall timing. Modelled recharge has been added to the charts in response to IEPMC's (2018) statement that there was a "*need to consider the runoff-infiltration component in a cumulative way*". The modelled recharge shows the infiltration component is estimated as a function of accumulated rainfall and antecedent soil moisture, as described in Section 4.4.4.

Each area has a somewhat different character of inflow. These are discussed by various authors (e.g. HS, 2016a,b; Mackie, 2017, IEPMC, 2018), with a summary in **Table 2-3**.

**Table 2-3 Summary of trends in mine inflow**

| AREA | COMMENTS ON APPARENT TRENDS IN INFLOW |
|---|---|
| **Area 1** | After two significant peaks correlating to rainfall events in 2007-2008, inflow has been relatively consistent, typically fluctuating between ~200 and ~800 m$^3$/d. Since those early peaks there has been a weak correlation with residual rainfall trends (also identified by Ziegler and Middleton, 2011), with broad inflow peaks delayed by several months. This mild correlation appears to continue into 2016, other than an unexplained peak (up to 1900 m$^3$/d) in September 2016.<br>** as of September 2016, the flow meter in Area 1 failed, and is no longer operable. Due to the low rate of inflow in this old area, an average inflow (330 m$^3$/d) is reported by IC.* |
| **Area 2** | Highly variable inflow, with a baseline inflow of between ~200 and 1000 m$^3$/d and peaks of between 4000 and 9000 m$^3$/day that are strongly correlated with very large rainfall events. The largest inflow peaks in recent times were 6400 m$^3$/d (2014), 4600 m$^3$/d (2015) and 4500 m$^3$/d (2017). Outside these short peaks the inflow tends to be in the range 500-1000 m$^3$/d but has declined in the past year. Peak inflow is delayed by 8 to 10 days after the rainfall event. |
| **Area 3A** | Inflow increased linearly with area mined during active mining (2010 to 2012). This hydrograph appeared to be more correlated to rainfall, including to individual events, during mining, i.e. Longwalls 6-8 and the first 'half' of Longwall 9.<br>From mid-2012 inflows have fluctuated between ~1000 and ~4000 m$^3$/d, with average inflows correlated with residual rainfall trends. Since 2013 (when mining moved to Area 3B) average inflow has reduced from about 3000 to 1050 m$^3$/d, possibly correlated with recent dry conditions. A recent spike in inflow (mid-2018) is not well correlated with rainfall.<br>It is possible that the weakened correlation of inflow to rainfall trend in this area from about August 2013 is associated more with the onset of mining in Area 3B, rather than the cessation of mining in Area 3A. |
| **Area 3B** | Area 3B is the lowest point in the mine (by elevation), lying across the axis of a large syncline, and water naturally drains toward the Area 3B sump at TG9 (Longwall 9). IEPMC (2018) report that the correlation to rainfall is 'moderate' and we generally agree with this, at least from Longwall 12.<br>HGEO (2018c) noted: *Groundwater ingress to Area 3B has increased steadily since the start of mining (2013), and correlates approximately with the total area mined. However, the overall rate of increase appears to have slowed during the mining of Longwalls 12 and 13, representing a possible departure from the area-inflow relationship, as was seen at Area 3A after Longwall 7.*<br>*As of Longwall 12 there is an apparent correlation between periods of high inflow to Area 3B and periods of high rainfall with a lag time of between two and three months. Peak inflow rates to Area 3B following high rainfall events is one to two ML/day higher than during low rainfall periods. The inflow peak that followed the high rainfall event of early 2017 accounts for approximately 20% of the total inflow for the 2017 year. The peak component in 2016 was approximately 12%.* |

Correlation to rainfall trends in Area 3B are possible due to review of hydrograph behaviour. But these are not considered completely definitive when considering the use of chemical methods to assess the relationship to rainfall (**Section 2.12.2 and 2.12.3**).

**Table 2-4** summarises the average inflow by mine area during the extraction of Longwall 14.

Table 2-4 Summary of Dendrobium Mine Inflow during Longwall 14

| STATISTIC | AREA 1* | AREA 2 | AREA 3A | AREA 3B | TOTAL |
|---|---|---|---|---|---|
| Mean | 0.33 | 0.27 | 1.03 | 4.28 | 5.87 |
| Minimum | -- | 0.01 | 0.06 | 0.27 | 2.06 |
| Maximum | -- | 3.90 | 6.27 | 7.15 | 8.90 |

Units in ML/d. * Area 1 flow meter failed in early 2017, so this is an average of the historical record.

The total inflow during the past 12-months was approximately 2235 ML. This is less than the groundwater entitlement (4,037 ML/yr) currently held for the Dendrobium Mine.

## 2.8 HEIGHT OF CONNECTED FRACTURING ABOVE THE SEAM

There are a number of published methods for estimating the height of connected fracturing above longwall panels. The vertical height to which connected fracturing occurs and the models for estimating this were the subject of the IEPMC (2018) as well as PSM (2017) and the associated peer reviews (Mackie, 2017; Galvin, 2017a).

A brief assessment of these models is presented below.

These models rely on one or more longwall geometry parameters to estimate the height of connected fracturing:

- W = panel (void) width [m];
- T = mining or cutting height [m]; and
- D = depth of cover [m].

Three of the recent models are Mills (2011), the Ditton 'Geology' Model (Ditton and Merrick, 2014) and the 'Collapsed Zone' (*H*) of Tammetta (2012). The Mills (2011) method relies on panel width, while the other two most recent models (Ditton and Tammetta) use more of the geometric parameters. These two models have been the subject of review and assessment in recent times. In some instances, based on longwall geometry, the Ditton and Tammetta models produce very similar results and both models provide a good match to observation/inference (e.g. above Tahmoor Longwall 10A; SCT, 2014). However, at Dendrobium the models diverge, e.g. at bore S2220 above Longwall 9 (in Area 3B) the Tammetta H would be 20 m below the surface, while the Ditton A-zone would be 115 m below and the Ditton B-zone would be 80 m below.

While PSM (2017) indicated that neither of these empirical models were robust, no alternative method was suggested. The result is that while they are not universally accepted, these methods may still provide useful estimates (Galvin, 2018b, IEPMC, 2018). HS had used both the Ditton 'Geology Model' (Ditton and Merrick, 2014) and the 'Height of Complete Groundwater Drainage' (Tammetta, 2012) in previous assessments. **Section 2.13** outlines some analysis of panel geometry and these empirical methods in relation to mine water chemistry (**Section 2.12**).

PSM made the conclusion that there was connective fracturing between the seam and surface above Longwall 9, therefore this condition has been represented in the modelling presented here. As a result, the adopted conceptual model (and the numerical model) assumes that the profile of connected fracturing shown in **Appendix D**, which shows the simulated height of this zone intersecting the surface cracking zone, if not ground surface, for most of the area within the longwall footprint at Dendrobium, specifically for longwalls with a void width of >300 m. For longwalls that are narrower, the conceptual and numerical models rely on the use of the Tammetta (2012) method to estimate the height of connected fracturing, which is consistent with the finding of IEPMC (2018) that the more conservative Tammetta method be adopted in cases where other data is not available.

These assumptions mean that the modelling-based assessment is conservative – more detail is presented in **Section 4.5**.

## 2.9 DPE 'HEIGHT OF FRACTURING STUDY' (PSM, 2017)

In 2016 DPE commissioned an independent 'Height of Fracturing Study' to assess the height of fracturing and related behaviour above longwalls at the Dendrobium Mine. This study was carried out by PSM, with peer review by Emeritus Professor Jim Galvin and Dr Col Mackie.

HS reviewed the PSM study and associated reviews, providing comment to IC and DPE (HS, 2017). A summary of the implications for groundwater modelling is presented in **Table 2-5**.

**Table 2-5 Summary of Implications for Groundwater Modelling**

| #. | ISSUE | ACTION / RECOMMENDATION |
|---|---|---|
| 1 | Accounting for structures, specifically Elouera Fault | South32 maps structures in the mining area and has commissioned studies to investigate the role of structures within and around Area 3B longwalls. Additional studies on the Elouera Fault are underway and initial data will be available in late 2018, and will not be available for the current round of groundwater modelling. |

| #. | ISSUE | ACTION / RECOMMENDATION |
|---|---|---|
| 2 | Valley-bulging (valley-closure) around lakes | Suggestions for incorporation into modelling are that this be dealt with by increasing the hydraulic conductivity of the strata along valley walls and beneath valley floors, using 'Connected Linear Networks (CLNs) to simulate discrete features, or increasing the 'conductance' of the relevant model boundary condition(s).<br>The modelled increase in hydraulic conductivity used to represent this mechanism is described in **Sections 2.11 and 4.5.3**. |
| 3 | Accounting for basal shears | Increased permeability resulting from basal shears around ends of Area 3B longwalls and the potential to connect to Lake Avon has been incorporated into the model. Based on advice from SCT, and the PSM study, these occur around the claystones (BHCS and SPCS).<br>PSM stated that "based on its general experience in sedimentary rock geological terrains, this shearing is likely to be continuous throughout the Dendrobium Mine region." Basal shears are modelled via an increase in hydraulic conductivity. |
| 4 | Off-goaf fracturing | The groundwater model needs to simulate off-goaf Kh enhancement, although this may be accounted for via the 'valley-bulging' mechanism described earlier (#2). Enhancement has been represented as:<br>• occurring up to 500 m from longwalls;<br>• being an increase of 2-3 times as a minimum, but up to 15 times based on recent testing at S2314A *(more discussion of this in HGEO, 2018b and Section 2.11*). PSM's claim of up to 3 orders of magnitude was not supported by data or literature; and<br>• being applied as declining with distance, based on S2313 and S2314A data. |
| 5 | Representation of fracturing through to surface in Area 3B | Neither the Tammetta (2013) or Ditton (Ditton and Merrick, 2014; DGS, 2016) models are supported by the PSM study or reviews.<br>There is clearly some form of fracturing at the surface above Area 3B, although the specific mode of fracturing is subject to some dispute. PSM assert there is vertical connection from seam to surface above Area 3B (e.g. based on the Longwall 9 investigations), however HS does not consider that all of the water budgets, groundwater levels and inflow chemistry consistently support this conceptual model (see **Sections 2.12, 2.13**).<br>However, to carry out a conservative assessment of impacts, the baseline model now incorporates seam-to-surface connection, while maintaining calibration (where possible) to inflow and groundwater levels. |
| 6 | Geotechnical modelling | Geotechnical modelling could be done prior to groundwater modelling (e.g. FLAC) or coupled (e.g. COSFLOW).<br>If geotechnical modelling is used, as it is for other parts of Dendrobium Mine, then we recommend that it be calibrated or verified to observed conditions, especially to mine inflow. Secondly, methods will need to be developed to use the outputs of such modelling in groundwater modelling, chiefly around up-scaling from the fine detail of local-scale geotechnical models to regional groundwater models. HS have found that FLAC modelling produces estimates of strata permeability that are significantly greater than would be used in a calibrated groundwater flow model (possibly because they focus on fracture, not bulk, permeability). |

## 2.10 SURFACE CRACKING

Packer testing in the Longwall 9 boreholes (PB, 2015; PSM, 2017) shows fracturing through the vertical profile, with no separation between fracturing from the panel and from the surface (i.e. no obvious 'Constrained Zone'). Therefore, it is difficult to assess the depth of the surface influenced (unconfined) cracking zone (a complication also noted by Advisian, 2016).

Surface cracking specifically related to the unconfined nature of the surface strata has been measured down to 15-20 m above the Bulli Seam Operations (Appin) Mine, and Advisian (2016) state that it could extend to 10-15 m (Table 4.2 of that report). Given the different longwall geometry and depths of cover at Dendrobium Mine, especially in Area 3B, the discrete surface cracking zone due to the unconfined nature of the surface strata can overlap with the fracturing from the seam to the surface.

While it is likely that longwall width, topographic relief (slope) and geological conditions, instead of cutting height alone, will govern this depth, we have assumed that the depth of the surface cracking zone is approximately 10 x cutting height (t). Above Longwalls 20 and 21, this would mean depths of around 40 m, as also estimated for longwalls in Areas 1, 2 and 3A (as shown in **Appendix D**). For Longwalls 10-12, in Area 3B, however, the depth of surface cracking zone is expected to exceed 40 m due to the greater cutting heights in those longwalls (**Table 1-1**).

The cross-sectional charts in **Appendix D** suggest that the surface cracking zone (extending downward from surface) will likely intersect the zone of connected fracturing (extending up from the goaf) with resultant condition of seam-to-surface connection, even despite the narrower panels proposed for Longwalls 20 and 21.

## 2.11 OFF-GOAF DEFORMATION AND VALLEY CLOSURE

Ground movement can occur at some distance away from the longwall panels themselves. This can take the form of valley closure or valley-bulging. It is our understanding that these two geotechnical phrases refer to the same or similar processes, with PSM (2017) favouring ‘valley-bulging’ while others prefer the term ‘valley closure’.

### 2.11.1 VALLEY CLOSURE OR VALLEY BULGING

Recent testing at a number of boreholes between Area 3B longwalls and Lake Avon has indicated the following in terms of changes to horizontal permeability (as determined from downhole packer testing).

**Table 2-6 Recent packer test locations**

| Bore(s) | Location | Change | Comment |
|---|---|---|---|
| S2313-S2331 | near L. Avon, 80 m from Longwall 12. | x 2 or 3 | SCT, 2016. |
| S2314-S2314A | near L. Avon, ~200 m from Longwall 13. | x 14 | HGEO, 2017b |
| S2376 aka AD6 | Near L. Avon, Longwall 13. | *Results available in late 2017.* | |
| General | Not specified | “larger” | PSM, 2017. No data cited. |
| General | Hawkesbury Sandstone within ¬200 m | → 5E-2 m/d | HGEO, 2018b |

The later testing and analysis has led to HGEO recommending that despite some pre- and post-mining boreholes showing little to no change in Kh, due to the limited dataset, the modelling should use an absolute Kh (5E-2 m/d), rather than a multiplier in order to make a conservative estimate of impacts on surrounding waterbodies (e.g. Lake Avon). Based on this, the conceptual model for enhancement of horizontal permeability is:

- For conservatism, we will ignore the apparent reduction in permeability (Kh) that has been inferred or measured in some boreholes.
- Occurring up to a maximum of 600 m from longwalls.
- Being applied as declining with distance, based on S2331 vs 2313 and S2314 vs S2314A data.
- Specifically, enhancement to approximately 5E-2 (when averaged over significant thickness, like those of the groundwater model layers) within 200 m.

- Beyond 200 m, being an increase of up to 15 times based on recent testing at S2314A but based on other bores is likely to be an increase of 2-3 times.

PSM's claim of Kh increases of '1-3 orders of magnitude', specifically the upper part of that range, was not supported by data from Dendrobium Mine or literature. The model could be modified in future if further data is supplied to support a change of 3 orders of magnitude, however so far, additional data has suggested that Kh can change (e.g. to about 5E-2 m/d) but also may only increase mildly or even show no systematic increase (HGEO, 2018b).

### 2.11.2 BASAL SHEAR PLANES

The presence of basal shear planes, discussed by various geotechnical engineers (Walsh *et al.*, SCT, PSM) has a potential role in connecting features to the goaf. The mobilisation of such features and enhanced permeability that may result from them might be taken into account by the more general 'off-goaf deformation' or valley closure described above, however given the conjecture about specific or discrete features connecting reservoirs (namely, Lake Avon) to the zone of connected fracturing above the goaf, this has warranted additional consideration.

SCT (2015) provides discussion on the presence and behaviour of such features. They are conceptualised as being 'horizontal planar features, located around the claystone, e.g. Bald Hill and Stanwell Park Claystones and the floors or valleys adjacent to longwall mining. **Figure 4** shows the general conceptual model developed by SCT.

Packer testing (SCT, 2017) suggested that a horizontal hydraulic conductivity of about 2E-6 m/s (0.17 m/d) across a 6 m test interval was a plausible permeability for such a feature.

Basal shears and the likely distance over which these may act as conduits to groundwater flow need to be considered in the context of the distances between the proposed longwalls and various hydrological features (Section 1.2.2). Basal shears are unlikely to cause or increase connection between these longwalls and either of the Cordeaux or Avon Reservoirs. The shorter distance from these longwalls to nearby watercourses, including Wongawilli Creek, means that shear planes may increase connection to these features.

## 2.12 WATER QUALITY

More than 2,740 water samples have been collected and analysed at Dendrobium Mine since 2004, providing an extensive database with which to assess mine water chemistry against baseline surface and groundwater chemistry. IC provides regular reports on water quality data and analysis (e.g. HGEO, 2017d), and the following discussion is based on that.

### 2.12.1 GROUNDWATER QUALITY

Groundwater quality is highly variable depending on the geological unit and sampling depth. A summary of electrical conductivity (EC) data is presented in **Table 2-7**.

**Table 2-7 Summary of Electrical Conductivity (EC) variation at Dendrobium**

| Type | Site Name | Electrical Conductivity (µS/cm) | | | | |
|---|---|---|---|---|---|---|
| | | 5%-ile | median | 95%- | mean | n |
| Rain | Rain | 72 | 85 | 103 | 86 | 28 |
| Surface Water | Wongawilli Ck | 67 | 94 | 130 | 96 | 596 |
| | Donalds Castle | 73 | 108 | 149 | 110 | 715 |
| | Sandy Ck | 66 | 87 | 112 | 90 | 124 |
| | Lake Cordeaux | 72 | 94 | 113 | 93 | 249 |

| Type | Site Name | Electrical Conductivity (µS/cm) | | | | |
|---|---|---|---|---|---|---|
| | | 5%-ile | median | 95%- | mean | n |
| | Lake Avon | 56 | 70 | 78 | 69 | 67 |
| Groundwater | Hawkesbury Sst | 70 | 123 | 357 | 157 | 275 |
| | Bald Hill | 153 | 200 | 247 | 200 | 2 |
| | Bulgo Sst | 137 | 400 | 2058 | 557 | 67 |
| | Scarborough Sst | 468 | 550 | 763 | 555 | 109 |
| Pre-longwall seeps | Area 1 seep | 2981 | 3340 | 7907 | 4543 | 7 |
| | Area 2 seep | 876 | 1355 | 1886 | 1310 | 231 |
| | Area 3A seep | 1029 | 2240 | 2791 | 1956 | 58 |
| | Area 3B seep | 829 | 2040 | 3699 | 2130 | 55 |
| Post-Longwall goafs | Area 1 goaf | 1700 | 2350 | 2579 | 2246 | 182 |
| | Area 2 goaf | 1015 | 1560 | 1882 | 1510 | 628 |
| | Area 3A goaf | 738 | 857 | 1223 | 919 | 162 |
| | Area 3B goaf | 1786 | 1930 | 2235 | 1942 | 51 |

As shown in **Table 2-7**, in general, the salinity of groundwater increases with stratigraphic age, reflecting the longer groundwater residence times in the deeper units. The Hawkesbury Sandstone hosts water that is generally fresh (EC < 1000 µS/cm), with a mixed major ion composition. The relatively fresh nature of groundwater in Hawkesbury Sandstone is indicative of relatively recent rainfall recharge via fracture networks in the weathered zone. Groundwater in progressively deeper stratigraphic units (Bulgo Sandstone, Scarborough Sandstone), become both more saline and dominated by $Na^+$ and $HCO_3^-$ ions. There is a corresponding increase in the concentration of minor and trace ions.

Deep groundwater samples are collected from development roadway roof seepages and mining faces which have not been impacted by the formation of the goaf during mining. Roof seepage samples are considered representative of the Wongawilli seam and adjacent shales. Deep groundwater in the Wongawilli seam is geochemically dominated by $Na^+$ and $HCO_3^-$ ions, across the three existing mine areas, and spatial variation in salinity (EC) can primarily be related to changes in the concentrations of these two major ions. Spatial variations are evident; the highest salinities are in Area 1 and the western end of Area 3B. Based on data from Area 3B mine workings, the salinity of roof drippers increases from east to west, i.e. fresher near Longwall 21 (EC = 2,000-3,000 µS/cm), and slightly more saline near Longwall 20 (EC = 3,000-4,000 µS/cm).

### 2.12.2 WATER SOURCE DISCRIMINATION

Background and operational water quality monitoring carried out at Dendrobium to date has shown a number of dissolved constituents that are useful in discriminating (“fingerprinting”) waters derived from different sources (HGEO, 2017d). The most useful indicators are:

- **Tritium** (indicating the average time elapsed since the water fell as rain).
- **Electrical Conductivity** (EC, an indicator of salinity or total dissolved salts).
- **Na/Cl ratio** (an indicator of sodium enrichment as a function of aquifer processes).
- **Si** (dissolved silica derived from weathering of silicate minerals).
- **Li, Ba, Sr** (minor or trace ions liberated during weathering or dissolution).

Of these, tritium, EC and Na/Cl are identified as the most useful indicators for routine monitoring and reporting. In addition, the Li/Cl ratios allow discrimination of some deep groundwater sources. Tritium typically identifies waters derived from rain within the last ~50 to 70 years (or mixing with a young source). IC is currently investigating other isotopic tracers such as 14C, 36Cl, 7Li/6Li and 87Sr/86Sr to better understand mine inflow pathways and water-rock interactions.

Analysis of these indicators shows that deeper groundwaters have distinctly different characteristics in terms of dissolved metal ions. The deeper groundwater (e.g. mine seepage) is characteristically higher in minor ions such as Li, Ba and Sr compared to surface water and shallow groundwater (when normalised to chloride). These characteristics reflect long residence times and equilibrium established with the host groundwater minerals. Furthermore, different mine areas can be distinguished using water fingerprinting. Mine seepage and goaf drainage from Areas 3A and 3B have distinctly higher Li/Cl ratios than seepage and goaf water from Areas 1 and 2. This suggests that groundwater parameters within the coal measures are spatially variable and that variability is reflected initially in seepage samples, and subsequently in goaf water compositions.

### 2.12.3 MODERN WATER IN MINE INFLOW

The database currently includes over 700 analyses of tritium providing an indication of the presence of modern water (<70 years) in any given sample. This is useful, to a degree, for detecting components of modern water in groundwater entering the mine.

Potential sources of modern water ingress to the mine include modern water within strata and from surface waters and nearby reservoirs where there is a hydraulic connection to the goaf. Modern water, i.e. surface water, contributions to mine inflow have been assessed using the mine water balance together with analyses of tritium in mine seepage samples (HGEO, 2018d; HS, 2016b). Recently, the possibility of diffusion and/or an exchange or absorption process that removes some or all tritium from influent water before it reaches the goaf has been raised as a potentially confounding factor.

This efficiency of this removal process has not been quantified, and as such the advice from HGEO is that while the presence of tritium is indicative of modern water, the absence of tritium in goaf water samples does not indicate that there is no modern water.

**Table 2-8** summarises the flow-weighted mean for mine inflows using water fingerprinting and indicates the total estimate of modern water into Dendrobium Mine is approximately 6-14%.

These estimates are considered useful order of magnitude estimates. Uncertainties in the analysis include some modern water being introduced to the mine via town water supply and that component being recirculated through the goafs (particularly in Area 3A), as well as tritium potentially being removed via diffusion and ion exchange to strata/pore water, and considering this removal process, these % estimates should be taken to be minima.

**Table 2-8 Estimated % Modern Water entering Dendrobium Mine**

| MINE AREA | % modern water (50th %ile) | % modern water (90th %ile) |
|---|---|---|
| Area 1 | ≥10 | ≥17 |
| Area 2 | ≥25 | ≥33 |
| Area 3A | ≥11 | ≥27 |
| Area 3B | ≥0 | ≥5 |
| **Flow-weighted mean** | **≥6 %** | **≥11 %** |

Based on water fingerprinting and considering the discussion in **Table 2-3**, Area 2 is connected to the surface with surface water reaching the goaf within weeks of large rainfall events, while a relationship between Area 3B inflows and large rainfall events is developing, water fingerprinting suggests the groundwater collected within Area 3B is not statistically different, in terms of tritium concentration, to deep groundwater.

The percentages in **Table 2-8** should be considered in light of separate estimates (reported in IEPMC, 2018), made via hydrograph separation, from HGEO (2017) and Mackie (2017), which were that up to 78% or even 90% of inflow to Area 2 could be due to direct rainfall/surface water ingress.

The Area 3B tritium results are at odds with the PSM (2017) interpretation that there is vertical connection from seam to surface in Area 3B. HGEO's analysis of inflow hydrograph to Area 3B is that in the past two years, 12-20% of total inflow to that area occurs following rainfall peaks (**Section 2.7**).

The difference between this and the tritium results has not yet been reconciled (nor the difference between tritium results in Area 2 vs Area 3B), although could be associated with a tritium exchange mechanism that occurs between the surface and the goaf. The degree of connection in Areas 1 and 3A are between that of Area 2 and 3B, as noted in **Table 2-3**.

This is the subject of further and on-going investigation, as recommended by IEPMC (2018).

## 2.13 FRACTURING AND SEAM-TO-SURFACE CONNECTION

This section follows from the discussion in **Sections 2.8 and 2.9**, and the analysis of water quality (**Section 2.12**) and groundwater inflow (**Section 2.7**).

As discussed, seam-to-surface connection has been assessed via water finger-printing and hence the inferred proportion (%) of modern water detected in the mine (**Sections 2.12.2**, **2.12.3**). As a means of assessing historical and predicting likely future connectivity, HS has reviewed the depth of cover and the results of the various height of connected fracturing models (above) for each mine area, and compared those against the % modern water in the underground workings.

To complete this assessment, a regular grid was constructed in GIS to cover the mine areas and populated with the geological model, topography (LiDAR), surface elevations and longwall geometry (**Sections 1.1**-**1.2**). Then the depth of cover and different height of fracture estimates were calculated for each point in the grid, and summarised by mine area (i.e. Area 1, 2, 3A, 3B) and compared graphically against HGEO's analysis of modern water in goaf water samples. The results are presented in **Appendix C**, which should be considered alongside the following notes:

- Tammetta H (**chart C3**) can be calculated as < 0 (negative), which would indicate a height above ground surface, i.e. suggesting rapid connection to the surface.
- The analysis of the model in **chart C3** uses the depth to the top of each zone, rather than the height of these (H), as this normalises for the depth of cover.

**Appendix C** suggests that:

- Depth of cover (**chart C1**) is not the only factor governing seam-to-surface connection. The distribution of depth of cover in each area does not match the tritium analyses and inferred percentage of modern water by area.
- W/D (**chart C2**) is not the only factor governing seam-to-surface connection. The distribution of D/W in each area does not match the tritium analyses and inferred percentage of modern water by area.
- The distribution of Tammetta H (**chart C3**) suggests that Area 3B should be just as 'connected' as Area 2, and that Area 3A should have the weakest connection. This does not match the tritium analyses and inferred percentage of modern water.

The above is not meant to be a definitive assessment of the accuracy of the different models for assessing the height of connected fracturing; however, all methods or parameters tested in **Appendix C** suggest that the proposed Area 3C Longwalls 20 and 21 should be less connected to the surface than most, if not all, previous mining areas at Dendrobium.

However, in order to simulate and predict the effects of longwalls height of connected fracturing, the groundwater model relies on the relatively conservative position that there is connection from the seam to the surface fracturing zone, as suggested by PSM (2017) for the strata above > 300 m wide longwalls (see **Table 1-1**). See more on modelling methods of this behaviour in **Section 4.5.1**.

# 3 HYDROGEOLOGICAL CONCEPTUAL MODEL

## 3.1 EFFECTS OF LONGWALL MINING

To develop roadways and then extract a longwall panel, the coal seams must be dewatered, and this dewatering generally continues during operations to prevent flooding of roadways, longwalls and to maintain air circulation. Dewatering draws groundwater from the surrounding geological strata and potentially from surface water. In regulatory terms, this can constitute capture ("take") from one or more water sources.

After the panels of coal are extracted the overlying strata immediately above the extracted seam collapses into the void (forming the goaf). The strata above the goaf deform and fracture in response, and some level of subsidence can occur at the ground surface. **Section 3.2** describes the zones and modes of deformation.

## 3.2 SUBSIDENCE AND FRACTURING

Forster and Enever (1992) carried out studies at pillar and longwall mines in NSW and developed a conceptual model to describe a sequence of deformational zones above longwall and pillar extraction areas. Another conceptual model was provided by the Department of Planning (2008) and other authors have developed similar or alternative conceptual schemes. The zones adopted by HS, both in terms of the geomechanical behaviour and groundwater response, are listed in **Table 3-1**.

**Table 3-1 Conceptual Zones of Deformation adjacent to Longwalls**

| CONCEPTUAL ZONE | | | MILLS (2011) | TAMMETTA (2012) | DITTON (2014) | GEOMETRY |
|---|---|---|---|---|---|---|
| ⑦ | Surface Fracture Zone (i.e. surface cracking) | | | | D-zone | Depth of increased surface fracturing (due to lower depth of cover/confinement) <=20 m, with enhanced horizontal hydraulic conductivity. At Dendrobium, this may occur from the surface down to the Fractured Zone. |
| ③ | Zones of mostly horizontal shear **offset from the longwall panel footprint** | | | Disturbed Zone | | Offset from goaf, extending approx. 500 m from longwall edge (but subject to ongoing assessment). |
| | Constrained Zone | | Zone of no disturbance (#5) | | C-zone | Based on packer tests, not considered to occur above Area 3B. |
| ③ | Fractured Zone | upper zone of Disconnected Fracturing | Zone of stress relaxation (#4)<br>Zone of bedding plane dilation, some fracturing (#3) | | B-zone | ▫ 1.6 x panel width (W) (Mills, 2011);<br>▫ B/B95 - Ditton and Merrick (2014). |
| ② | | lower zone of Connected Fracturing | Zone of large downward movement (#2) | Collapsed Zone | A-zone | ▫ 1 x panel width (W) (Mills, 2012)<br>▫ H - Tammetta (2012) or<br>▫ A/A95 - Ditton and Merrick (2014). |
| ① | Caved Zone | | Zone of chaotic disturbance (#1) | | | ▫ 5-10 x t (Forster & Enever, 1992, Guo et al., 2007)<br>▫ 5-20 m (Mills, 2011). |
| | Mined Zone (extracted seam) | | | | | Mined seam thickness (***t***) listed in Sections 1.1-1.2 |
| ⑧ | Buckling/heaving of 'floor' strata, caused by unloading after panel extraction (Meaney, 1997; Karacan *et al.*, 2011) | | | | | Assumed to be in the order of 10-30 m. |

Numbers in circles, e.g. ①-⑧, correspond to zones on **Figure 5**.

Based on review of the existing conceptual models, e.g. Booth, 1986 and 2002; Holla and Barclay, 2000; Guo *et al.,* 2007; Mills, 2011; Tammetta, 2012; Ditton and Merrick, 2014, as well as analysis of data from Dendrobium, and discussion between HGEO, SCT, HS and IC, a conceptual model diagram has been developed (**Figure 5**). This is consistent with **Table 3-1** and is based mainly on the geotechnical zones proposed by Mills (2011), but with consideration of other published works. It is likely that in reality, the conceptual zones are not clearly distinguished, and would occur as a continuum with gradual changes between zones.

**Figure 5**, the summary in **Table 3-1**, and the following supporting text in this section describe our conceptual model of the changes that occur to the hydraulic conductivity and storage properties of the strata around Dendrobium Mine. In the following text, numbers in circles, e.g. ①-⑳, correspond to the zones on **Figure 5**.

The strata in the connected part of the fractured zone ①② would have a substantially higher vertical hydraulic conductivity⑱ than the undisturbed host rocks ⑤. This would encourage groundwater to move out of rock storage (elastic storage and drainable porosity) and drain downwards towards the goaf ⑬⑭⑮. Fracturing becomes gradually less well-connected (i.e. declining continuity between separate fractures) with increasing height above the seam, tending toward being vertically 'disconnected' ③; Kh increases due to the parting of bedding planes being enhanced more than Kv due to reduced frequency of (sub-)vertical fractures to act as vertical pathways. As a result, the vertical movement of groundwater would be enhanced but may not be significantly greater than under natural conditions ⑫. This is borne out by observations:

- at the Tahmoor Longwall 10A "HoF" (height of fracture investigation) borehole (SCT, 2014), it was clear that a downward gradient existed in the lower Hawkesbury Sandstone, but the vertical connectivity was not sufficient to alter groundwater levels in the mid/upper Hawkesbury Sandstone to any observable degree; and
- at Dendrobium, where water levels in shallow strata have been more affected than those at Tahmoor Longwall 10A, but positive pressures can still be maintained in the shallow strata (see **Section 3.2.1**), indicating an indirect connection (or a slow or low transmissivity pathway) to the fractured zone and goaf. That is, any fracturing below is insufficiently continuous or connected, or insufficiently transmissive, to cause drainage of groundwater from the upper zone via recharge or other sources.

At distances exceeding approximately 500 m from the mine, strata are assumed to be relatively unaffected ⑤, although minor enhancements to Kh may arise at specific horizons due to shearing along bedding planes. This enhancement is considered more likely in the upper parts of the strata offset from longwalls; in the lower sections above chain pillars the compression of overlying strata ⑥ is likely to restrict the potential for secondary porosity to develop, and may even reduce Kh in these areas.

At mines where the depth of cover greatly exceeds the longwall width, strata overlying the fractured zones may sag but not significantly fracture, resulting in a degree of hydraulic isolation of those fracture zones from the surface and near surface (⑦ - see below). This is referred to as the 'constrained zone' by Booth (1986) and others and the zone of vertical stress relaxation by Mills (2011). However, longwall geometries and depths of cover at Dendrobium are such that a constrained zone does not occur above the goaf, i.e. some degree of fracturing is observed through the sequence above these longwalls.

In the surface zone ⑦, fracturing of the surficial and near-surface strata can occur due to the effects of compression and tension on unconfined strata within and near to the subsidence trough.

Fracturing in the base or bed of watercourses has occurred at Dendrobium, most notably within streams directly mined under by Area 3B, e.g. WC21, Donalds Castle Creek to DCS2, as well as at other mines in the Southern Coalfield, e.g. along the Bargo River and Redbank Creek above Tahmoor and at Waratah Rivulet above Metropolitan Colliery. Down-slope movements and valley closure will enhance these strains and result in an increase in fracture frequency and/or width at these locations. Experience at Dendrobium and Appin mines suggests that 95% of observed fracturing occurs within the longwall footprint, about 99% within the footprint plus a further 50 m buffer (i.e. above or within the chain pillars), and a remaining 1% occur beyond that distance, such as impacts observed at LA4 (HGEO, 2017a).

Surface fracturing is likely to result in persistent or permanent changes to hydrology ⑨, such as WC21 ceasing to flow during recession periods. Leakage of water into the surface fracturing zone can result in effects on water quality (McNally and Evans, 2007).

Surface water flow that is redirected into and through near-surface fractures ⑨ may either be returned to surface drainage somewhere down-gradient ⑩, (in which case the net loss from the catchment is minimal), migrate downwards towards the goaf ⑬, or some combination of both. IC are monitoring water flows and planning tracer tests to further investigate this behaviour.

The strata movements and deformation that accompany subsidence would alter the hydraulic and storage characteristics of the host strata. As there would be an overall increase in rock hydraulic conductivity ⑱, groundwater levels can fall either due to actual drainage of water into the goaf ⑬⑭⑮⑯ or by an increase in storage capacity due to an increase in porosity ⑳ (Tammetta, 2016).

Fractures that are directly connected to the goaf would rapidly depressurise and form a pathway for seepage of pore water downwards towards the goaf. This does not mean that these areas contain no groundwater, but that there can be free drainage through the cracks and fractures ⑬. Desaturation can occur over time in this zone. As the matrix drains due to the presence of fractures, the declining moisture content in the matrix may result in lower (primary) hydraulic conductivity ⑲. Where the downward drainage of water in the fracture system encounters restrictions (partially closed fractures or fracture terminations), the fractures may fill or perch and would then drain at a rate dependant on the rock matrix or fracture hydraulic conductivity.

The zones of enhanced K, i.e. the deformation zones ①②③⑦, above the mine void/goaf on **Figure 5** is a schematic representation of monitoring data of post mining strata conditions at Dendrobium Mine and the conceptualised 'likely' case for the remainder of Area 3B. There are a number of models for estimating the height of the zone of connected fracturing (discussed briefly in **Section 2.8**, PSM (2017)). There are also methods and schemes for estimating change in K (e.g. Tammetta, 2014, Guo *et al.*, 2007), and both height and K are tested during groundwater model calibration (**Sections 4.5-4.6**).

Basal shear planes ④, as identified in the analysis of Walsh *et al.* (2014) and SCT (2015), can extend laterally in strata at an elevation of or just beneath the base of incised valleys. These features can be natural or a result of or enhanced by mining subsidence. It is possible that shear planes may act as a conduit for groundwater flow ⑪, and that these might enhance horizontal connection between watercourses and waterbodies (specifically the Avon and Cordeaux Reservoirs) with the fractured zone extending upward from the longwall goaf, therefore providing a rapid and transmissive pathway for surface water to enter the mine. It is unclear at what distance such shear planes might be able to connect a valley, including a reservoir, with the fractured zone above the goaf. However, data from Sandy Creek indicated that shear planes were mobilised when Longwall 8 was some 670 m from the valley (Walsh *et al.*, 2014), so conceptually there may be connection when the longwall edge is about 600 m from a watercourse or reservoir.

More recent testing at the Lake Avon monitoring bores (S2313, S2331 – see SCT, 2015; HGEO, 2016b,c), which are about 80 m from the edge of Longwall 12, did not detect any such shear zones (i.e. highly permeable discrete zones) in the pre- or post-mining strata. SCT then detected one at S2314, although "it is not considered to be a significant conduit for flow from the reservoir into the mine" (SCT, 2017). The development and/or enhancement of shear planes resulting from mining is the subject of ongoing research in Dendrobium Area 3B.

Aside from the discrete basal shear features ⑪, there is potential for the development or enhancement of Kh ④⑱ beyond the mine footprint. The extraction of a longwall results in the collapse and subsidence of overlying strata, causing both vertical and horizontal movement of overlying and nearby strata. Outside the longwall footprint, where such horizontal movements occur, the effect can be an enhancement of Kh through horizontally-bedded strata, especially in areas where the topographic relief is such that parts of the landscape (strata) are not supported or buttressed against such horizontal movements (SCT, 2015). Hydraulic conductivity testing at bores located between Area 3B longwalls and Lake Avon suggests that Kh might be enhanced 2-3 times, up to 14 times, the host (pre-mining) value (~0.3 log units) (**Section 2.11.1**). However, this is not definitive and possibly not significant as the post-mining permeabilities measured at S2331 lie within the expected range of (pre-mining) K.

While the degree of enhancement of Kh in areas offset from a longwall is unclear and subject to on-going research, it is considered prudent that the effects of an increase in Kh are modelled (**Section 4.5.3**). The distance from the longwall footprint that this effect occurs is not clear – bores S2313-S2331 are approximately 80 m from the nearest longwall edge. For the purpose of modelling, HS has assumed that this effect could occur with declining significance to about 500 m from the edges of the longwall footprint.

Within the mine workings, heave and buckling of the floor are relatively common observations during the removal of the coal seam or other strata. Upward flow through the floor is observed around the mine, and this is likely exacerbated by the deformation within and beneath the floor of the workings ⑧⑱.

This conceptual framework is in broad agreement with observed chemistry trends. Estimates of the modern water content for each mine area (see graph in **Figure 5, Appendix CB**) indicate that, to a first order approximation, the degree to which modern water contributes to the mine water balance (i.e. a measure of the degree of connection to the surface – more discussion in **Sections 2.12.3 and 2.13**) decreases with increasing depth of cover, assuming constant mining parameters. The depth of cover at Area 2 (median = 240 m) is such that it would suggest connected fracture networks ② intersecting with surface fracturing which would lead to greater connection (i.e. direct transfer of larger volumes of water/solute) and hence a greater proportion of modern water detected in the mine. By contrast, the depth of cover at Area 3B is significantly greater (median = 365 m), such that the connection with surface water systems has not been observed or inferred from water fingerprinting and it follows that a slower, less transmissive connection exists between the goaf and surface water systems. Depth of cover at Longwalls 20 and 21 is similar to that of Area 3B, at about 350 m.

### 3.2.1 INFLUENCE ON GROUNDWATER LEVELS

In general, the greatest drawdown effects occur in the strata immediately above the mined coal seam. Within and adjacent to the connected fracture zone ② which, at Area 3B includes the Scarborough and Bulgo Sandstones, and into the lower Hawkesbury Sandstone. The drawdown is often > 50 m or the strata become completely depressurised (pressure head is zero). Above the connected fractured zone (i.e. where fracturing is disconnected ③), the degree of drawdown becomes less towards the surface. Drawdown in the mid Hawkesbury

Sandstone is about 10-20 m, and in the shallower horizons of the Hawkesbury Sandstone it has been observed to be <5 m (e.g. at S2192-S2220 directly overlying Longwall 9).

Drawdown in Hawkesbury Sandstone decreases with distance from the extracted panels to approximately 5-10 m at a distance of 1 km from the longwall (based on observations in HS, 2014b or review of DEN131-S2009). Deeper in the sequence, e.g. the Bulli Seam, the 5-10 m drawdown occurs at about 2-3 km from extracted longwalls. Note that the responses described here are considered general or average responses only; responses in individual piezometers can vary depending on the conditions from one location to another.

There are no areas in the Dendrobium Mine where inflow has ceased, however it is expected that drawdown would persist until inflow ceases, and the mine re-fills and an equilibrium is re-established. The equilibrium groundwater levels may be at different levels to pre-mining conditions (either lower or higher), given the changes to permeability and porosity and consequent changes to recharge/discharge pathways or characteristics.

### 3.2.2 EFFECTS OF STRUCTURE: LINEAMENTS

Geological structures are mapped on **Figure 2**, and discussed in Section 2.1.

At Dendrobium, lineaments are rarely successfully correlated with a structure feature (fault, dyke) at seam level. Further, they have not caused difficulties to mine operations at Dendrobium, nor are mapped lineaments known to interact with water features (e.g. swamps, waterfalls) in a manner that suggest they exacerbate the risk of mining to such features or exacerbate the distance to which impacts manifest themselves (Section 2.1).

For reasons noted in Hebblewhite (2019), the Western Coalfield is different to the Southern Coalfield, and the experience at Dendrobium is different to that identified by IEPMC (2018) at Springvale Mine. MSEC (2019b) has indicated that subsidence anomalies along or around lineaments are obvious at Springvale Mine (in the Western Coalfield), with LiDAR mapping showing up to 30% more subsidence along these features, but that this behaviour is not evident at Dendrobium.

Therefore, based on current data, there is no need to explicitly represent such features in the regional groundwater model. However, if the extraction of these panels is approved, then there will be more investigation of geological conditions, including structures, by IC, and further knowledge can be incorporated into modelling as required.

# 4 GROUNDWATER MODEL

This section briefly describes the key aspects of the model used for this assessment of Longwalls 20 and 21. Other than the inclusion of Longwalls 20 and 21, no further changes have been made to the model, so it is essentially the same as reported in HS (2019) for Longwall 17.

## 4.1 MODEL MESH

The MODFLOW-USG model mesh or grid is identical to that of Coffey (2012) i.e. resolution varying between 50 m and 215 m (finest resolution in Longwalls 13-18 and nearest Lake Avon). There are 239 rows and 225 columns in the mesh, giving a total of 53,775 cells per layer. The active extent of the model is shown on **Figure 6**.

IEPMC (2018) noted that the migration to an 'unstructured' model mesh in MODFLOW-USG had 'stalled'. The development of an unstructured model is in the latter stages of development but will not be available in time for the Longwall 20 and 21 SMP Application.

## 4.2 MODEL GEOMETRY AND HYDROSTRATIGRAPHY

**Table 4-1** and **Figure 8** presents the model layering and stratigraphy adopted in this project, and is the same as that used for HS (2018). The geological layering within the model is based on the geological model supplied by IC which is defined by hundreds of exploration drill logs.

**Table 4-1 Model Layer Assignment**

| LAYER | STRATIGRAPHY | SECONDARY LITHOLOGY | COMMENT |
|---|---|---|---|
| 1 (or uppermost active) | Swamps | | Uniform 2 m thickness. |
| 2 | Hawkesbury Sandstone (upper) | Swamps | Mean thickness 80 m |
| 3 | Hawkesbury Sandstone (middle) | Swamps | |
| 4 | Hawkesbury Sandstone (lower) | Swamps / Crinanite | Mean thickness 25 m |
| 5 | Bald Hill Claystone | Garie/Newport Formations / Swamps / Crinanite | Mean thickness 20 m |
| 6 | Bulgo Sandstone (upper) | Crinanite | Mean thickness 40 m |
| 7 | Bulgo Sandstone (lower) | Crinanite | Mean thickness 74 m |
| 8 | Stanwell Park Claystone | Colo Vale Sandstone (Area 3B and west) / Crinanite | Mean thickness 10 m |
| 9 | Scarborough Sandstone | Crinanite | Mean thickness 38 m |
| 10 | Wombarra Claystone | Crinanite | Mean thickness 27 m |
| 11 | Coalcliff Sandstone | Wombarra Formation (Area 3B and west) | Mean thickness 15 m |
| 12 | Bulli Coal Seam | | Mean thickness 3 m |
| 13 | Lawrence & Loddon Sandstones | | Mean thickness 27 m |
| 14 | Wongawilli Coal Seam | | Mean thickness 21 m |
| 15 | Kembla Sandstone | | Mean thickness 53 m |
| 16 | lower Permian Coal Measures | | Mean thickness 167 m |
| 17 | Shoalhaven Group and older | | Mean thickness 250 m |

As noted in HS (2018), an additional model layer was added in 2017-18 to better accommodate the swamps at the surface above the Hawkesbury Sandstone or Narrabeen Group units.

There is a total of 914,175 cells, of which 501,447 are active. The MODFLOW-USG is written to taken advantage of the fact that only the 'active' nodes are written by Groundwater Vistas to the MODFLOW inputs files – the model layers do not have to be extensive across the entire model domain.

## 4.3 MODEL TEMPORAL DISCRETISATION

The temporal discretisation is the same as in the Longwall 17 (HS, 2019) model. The changes to the HS, 2016 discretisation included the addition of more 'stress periods' in order to better represent longwall progression for Longwalls 13-19 simulating the progressive extraction of each of those longwalls across 3-4 stress periods. For Longwalls 20 and 21, the adjusted temporal discretisation captures their extraction over 4 and 3 stress periods respectively. A table outlining the temporal discretisation is shown in **Appendix A**.

Furthermore, to capture the dynamics of very high rainfall periods, such as those leading to the 'inflow' events observed in Area 2 (**Section 2.7**), the key events have been identified and a series of shorter stress periods defined. These stress periods are designed to capture the intense rainfall event (e.g. a period of a few days or a week), the following period where the main inflow is measured, and then the recession period after that. Fifteen such high rainfall/inflow sequences or events are included in the model time period (**Appendix A**).

The third change to the model timing is in relation to SMP Condition 16 (**Table 1-3**), requiring model estimates of incidental baseflow capture for regular intervals to a point 30-years post-mining.

The downside to capturing this detail is a longer set of stress periods: 199, compared to 90 in the HS, 2016 (for Longwall 14-15) model to cover a similar total period, resulting in large model input and output files and longer model run times.

## 4.4 BOUNDARY CONDITIONS

Almost all the boundary conditions remain identical to the HS (2018) model. A summary of the boundary conditions is presented below, with emphasis on any changes.

### 4.4.1 LAKES - 'RIVER' BOUNDARIES

'River' boundaries conditions have been employed to represent the reservoirs, as in Coffey (2012) and HS (2014). The historical record of water levels in the Avon and Cordeaux Reservoirs has been employed, as in HS (2016a), but updated to include more recent data.

### 4.4.2 WATERCOURSES

As in HS (2018), River boundaries have been employed to represent watercourses which were previously simulated (HS 2014, 2016a) using the MODFLOW 'Stream-Flow Routing' [SFR1] package (Prudic *et al*., 2004). This was done because it increases the speed of the model simulation and assisted with the priority given to incorporating the off-goaf and surface cracking processes and the unexpectedly long model testing/calibration process. In future, the SFR package could be employed again, however IEPMC (2018) noted that the current approach is appropriate.

The watercourses simulated include variable stream stage, based on a timeseries of runoff from the water balance model (**Section 4.4.4**), for simulating gaining/losing conditions.

### 4.4.3 MINE DEWATERING - 'DRAIN' BOUNDARIES

'Drain' boundaries conditions have been employed to represent mining activity, as in previous modelling. These Drains were activated to fit the latest mine schedule (provided by IC) as per **Table 1-1** and **Figure 2** (with longwall progression as per **Appendix A**).

Additionally, drains have been employed for representing flow in the connected fracture zone. More on this method, in comparison to other methods, is presented in **Section 4.5.1**.

### 4.4.4 RECHARGE

The MODFLOW Recharge (RCH) package is used to simulate diffuse rainfall recharge, as per previous modelling. As in HS (2016a, 2018), temporal variation in rainfall recharge has been calculated based on a water balance calculated on a daily timestep and accounting for runoff, soil moisture deficit and recharge based on inputs of rainfall and potential evaporation.

The water balance model has been 'trained' or calibrated to match estimates of average or long-term recharge obtained from a number of literature sources and from analysis of Dendrobium data (**Table 4-2**). Noting the commentary in Advisian (2016), the method of analysis has been added to the table where this is known.

Table 4-2 Summary of Recharge and Baseflow Estimates

| Process | | HS, 2016b | Crosbie, 2015 | Coffey, 2012a,b | DPI, 2011 | Pells, 2013 | URS, 2007 |
|---|---|---|---|---|---|---|---|
| **Analysis method** | | Chloride mass balance baseflow separation, water table fluctuation. | Chloride mass balance in shallow groundwater. | Baseflow separation, water table fluctuation. | Unknown | Unknown | water table fluctuation |
| **RECHARGE** | % LTA rain | 6.5% | 3 - 8.5% | 2.7 or 6% | 6% | 5% | 3-10%* |
| | mm/yr | 65 | 40-100 | | | 50 | |
| **BASEFLOW** | BFI % | 15% (10-40%) | no estimate | 8% | no estimate | no estimate | |
| | mm/yr | 40 (25-110) | no estimate | | no estimate | no estimate | |
| | % LTA rain | 4 (2.5-11%) | no estimate | 0.5-3% | no estimate | no estimate | |

LTA: Long-term Average; BFI : Baseflow Index. * URS stated that local variation might be 2-16%, but "realistic range" is 3-10%.

The average recharge as calculated by the water balance model for the areas of rock outcrop is equivalent to about 7% of long-term average rainfall. As Advisian (2016) concluded, the weight of evidence from multiple studies is that recharge to the Hawkesbury Sandstone is within a range of 0-8.5% of LTA rainfall. Within the groundwater model, recharge is zoned in the model in a similar fashion to that in Coffey (2012) and HS (2014, 2016a), based on average rainfall declining from the coast/escarpment to the northwest.

Estimates of rainfall recharge to the swamps are not available but are conceptualised as being significantly more than that to the rock outcrop. As a result, the water balance model for the swamp areas was set to produce a timeseries of recharge of about 330 mm/a, equivalent to 25-30% of long-term average rainfall.

#### Enhanced recharge above longwalls

Conceptually, the presence of subsidence cracking at the surface and increased permeability/porosity in near surface strata could lead to increased infiltration of rainfall to shallow groundwater systems above and around the footprint of longwalls (McNally and Evans, 2007; Advisian, 2016).

The issue with modelling this process is that the degree of enhancement is unknown. HS is not aware of any estimates of the increase in recharge. HS inspected water quality and water level data from bores to assess whether freshening or increased water table rise were discernible in shallow groundwater, and whether this would allow some quantification of any change. Such freshening was not discerned within the electrical conductivity dataset. While inspection of water table fluctuation does show changes in the post-mining environment, the fluctuation of water tables is governed by recharge, porosity and permeability, and it is likely that all of these parameters are modified by longwall mining, making it difficult to quantify.

During the model calibration process in HS (2018), HS tested infiltration recharge being enhanced by 2-5 times (i.e. 12-30% of long-term average rainfall) for the area above extracted longwalls. The impact assessment models presented in this assessment (**Section 4.8**) use a factor of 2.5. There is uncertainty about the magnitude of this conceptual process.

### 4.4.5 EVAPOTRANSPIRATION

The water balance model described in the previous section also provides estimates of evapotranspiration in the soil zone, and whether there is an excess of potential evaporation on each day during the sequence. The excess evaporation is then averaged across model stress periods and applied to the MODFLOW model via the Evapotranspiration package. The potential rate of evapotranspiration from groundwater is approximately 700 mm/yr for the outcropping rock at Dendrobium, and approximately 300-400 mm/yr for swamps.

Rooting depths (‘extinction depths’) were set at 1.9 m for swamps (which aligns with swamp sediment depth data) and 3-6 m for other areas. The extinction depth for the treed areas is lower than in HS (2016), based on calibration to shallow groundwater levels.

The potential rate of evapotranspiration from shallow water tables, or the rooting depths, were not changed in the post-mining environment.

## 4.5 MODELLING OF DEFORMATION AND FRACTURING

Within groundwater models, simulation of mining-induced changes to the hydraulic properties of rock strata within and above the mined zone has typically been limited to simulating the connected fracture zone. HS are aware of three methods for simulating the connected fractured zone in groundwater models, and these are discussed in **Section 4.5.1**.

Additionally, other zones and mechanisms are simulated in this groundwater model, based on conditions of approval (**Section 1.3, Table 1-3**) and the DPE study (**Sections 2.9-2.11**), and the representation of these is discussed in **Section 4.5.2**.

All the methods tested, and the combination of methods for different processes, have some weakness, either in conceptual terms or with software or practical ability (e.g. model stability, model performance). This is not to say that these hurdles cannot be overcome in the future, although model practicality is an important requirement.

### 4.5.1 ZONE OF CONNECTED FRACTURING

The development of a network of fractures extending up from the longwall as a result of mining subsidence is typically simulated in three ways, as tabulated below.

Table 4-3 Typical methods used to simulate fracturing

| METHOD | DESCRIPTION | ADVANTAGES | DISADVANTAGES |
|---|---|---|---|
| **Time-varying hydraulic properties** | Time-varying material properties (within the MODFLOW TVM or TMP packages) can be used to simulate the zones of fracturing and deformation within mine workings and the other fractured zones above longwall panels. Specifically, this package is used to increase hydraulic conductivity (horizontal – Kh and vertical - Kv) as well as storage properties (Sy) due to mining. Changes to specific storage (Ss) are also possible.<br>This method is also possible by using 'time-slices', essentially a chain of models run end-to-end in time. | The main advantage of this method is that it represents the change in permeability and porosity properties, and the degree of enhancement of these properties can be calibrated by using mine inflow and heads. This then allows a more 'seamless' simulation of the longwall extraction phase, the period after that when mine workings remain dewatered, and the post-closure period. | Requires a method for estimating/calibration Kh, Kv and porosity properties.<br>Model stability is frequently an issue, especially if using pseudo-soils or upstream weighting numerical methods. Models where the height of the connected fracture zone is relatively low compared to overburden thickness seem to be more stable.<br>Some practitioners do not like the idea of simulating the fracture network as an equivalent porous medium governed by Darcian flow. |
| **'Stacked Drains'** | A set of Drain boundary conditions are set through the strata above longwall panels to represent the depressurisation and drainage of groundwater in this zone.<br>The Drains are set in each model layer up to a user-specified height, with conductance terms used to represent permeability.<br>The Drains are activated as each longwall is extracted. The Drains could be left active into the future to provide conservative estimates of the effects of the mine on the catchment water balance, or can be inactivated when mine dewatering ceases. | This method does not require an estimate of enhanced permeability or porosity to be made, although some would argue that the conductance term needs to be estimated.<br>Models using this method tend to be significantly faster and more stable than those employing the other two methods. *This is an important factor in the subsequent use of this method in this study.* | This method is a short-cut, in that it fixes the groundwater pressures within a user-specified zone, rather than allowing the numerical model to simulate groundwater pressures in response to changes in permeability and porosity. Changes to hydraulic properties may still need to be simulated using another method, in conjunction with the 'Stacked Drains'.<br>Because this method fixes groundwater heads, it does not allow groundwater pressures to build up in the goaf and fractured zone after mine dewatering has ceased, unless the 'Stacked Drains' are removed altogether. Because of this weakness in honouring the conceptualised changes in hydraulic properties, this method must be replaced with one of the other two methods to more appropriately simulate the long-term recovery of the groundwater system. |
| **Connected Linear Networks (CLN)** | CLNs are a feature of the most recent versions of MODFLOW, and allow a discrete conduit with a size independent to the main model grid, to be represented.<br>CLNs can be used to simulate horizontal, vertical and angled conduits. This method was employed in HS (2016a) to simulate the vertical conduits connecting the mined seam to the overlying strata. | The chief advantage is that it can simulate the interaction between the two conceptualised flow domains – the host strata in the groundwater model cells and the fracture network developed through the strata.<br>Like the time-varying properties method, this method should be applicable to both active mining and post-closure period. | Requires estimates of geometry of the CLN. Each CLN should represent the bulk volume of connected fractures, but that is a difficult parameter to estimate, as is the conductivity of the conduit.<br>Model stability was an issue in HS (2016b), although less so in the testing conducted in this phase of work. |

For the modelling, two rules have been applied to carry out a conservative impact assessment, as per discussion with the Dr. Frans Kalf of Kalf and Associates, the model Peer Reviewer. These were that:

- The Tammetta (2012) empirical model has been used to estimate the height of connected fracturing for all modelled longwalls, based on the local conditions (panel width, depth of cover, cutting height). The Tammetta model has been used as it is typically the more conservative (Galvin, 2017b); and
- Seam-to-surface connection has been enforced for all model cells that lie along the centre-line of any 305 m wide panels (**Table 1-1**), consistent with the interpretation by PSM (2017) for Longwall 9.

The resultant modelled profile of seam, surface and the height or depth of the main fracturing zones are shown in **Appendix D**. There are areas where the Tammetta H will intersect the surface cracking zone or ground surface, even without the imposition of seam-to-surface fracturing for the 305 m wide longwalls.

The chief issue encountered in this project is that while each method could be calibrated to inflow during the active longwall extraction phase in each separate mine area (see discussion in **Section 4.6.4**), all methods struggled to match the period after longwalls had been extracted but while dewatering still occurs. Specifically, the very peaky inflow to Area 2 (*after* Longwall 5) and muted peaks in Area 3A (*after* Longwall 8) were difficult to simulate – as a result of the time taken to achieve the current degree of calibration, the ‘Stacked Drains’ method has been employed because model run times are about half that of other methods, the model is much more stable, and because early on it gave better results for matching the peakiness of Area 2 inflows. Discussion with the Peer Reviewer has confirmed that the use of ‘Stacked Drains’ to simulate the connected fracture zone should provide a conservative impact assessment.

The ‘Stacked Drains’ have been set with a conductance that declines with height above the mined seam, with conductances varying, as a result of calibration, from 13 above the seam down to 2 $m^2$/d.

A secondary issue is that adding different deformation processes, i.e. surface cracking and off-goaf permeability enhancement, affects the performance of all the above methods in simulating flow into the mine workings, especially the peaky or flashy hydrograph of Area 2.

### 4.5.2 SURFACE CRACKING ZONE

The simulated surface cracking zone depth was set at 10 x longwall cutting height (t) above longwall panels. This means that the surface cracking zone above Dendrobium is simulated as being about 34 m (Area 1), up to 45 m (Longwalls 10-12) in Area 3B, and about 39 m for proposed Longwalls 20 and 21 in Area 3C (**Appendix D**). There will be some difference in the model application given the granularity (thickness) of model layers compared to the scale of 10 x t.

This representation of the surface cracking zone was set as having a horizontal hydraulic conductivity as 3 times that of the host material and vertical hydraulic conductivity that is 50% greater than the host strata. Higher factors were initially tried during model calibration, and these resulted in less peaky inflow hydrographs. It is hypothesised that higher factors could be used successfully in conjunction with lower ‘host’ (natural) hydraulic conductivities, although this should be tested after the recommended further analysis of hydraulic conductivity (see Recommendations, **Section 7.2**).

### 4.5.3 OFF-GOAF (VALLEY CLOSURE)

This has been simulated by increasing horizontal hydraulic conductivity of the strata between the longwalls and the nearest ‘deep’ valley (**Figure 4**). This has been done by selected model cells within a certain distance or buffer (less than 100 m from the longwall, less than 300 m and less than 600 m) and assigning a Kh value or Kh multiplier to each buffer area, with the multiplier declining with distance from the longwall. The modelled timing of the permeability enhancement is simplistic, with the enhancement due to a group of longwalls being imposed at one time, e.g. Longwalls 9-13 are imposed in stress period 106, while Longwalls 14-15 are imposed in stress period 117. It could be possible to improve this in the future.

Initially, the factors selected were x15, x5 and x3, however given the issues during calibration to do with enhanced permeability flattening the inflow hydrograph, the model was then run using factors of x4, x3 and x2. Subsequently, HGEO (2018b) revised the estimate of how Kh enhancement should be simulated in order to carry out a conservative assessment of the potential connection between Lake Avon and the goaf, and so an absolute value of 5E-2 m/d is simulated for cells lying within 300 m, with multipliers of x2 used beyond 300 m. Kh enhancement is simulated in the strata from the base of the nearest valley, e.g. in the lower Hawkesbury Sandstone along Wongawilli Creek around Longwalls 20 and 21, and above.

### 4.5.4 UNDERLYING (FLOOR) STRATA

Deformation (buckling) in floor strata is caused by unloading. This has been simulated with a horizontal hydraulic conductivity factored up to 5, and vertical hydraulic conductivity increased by a factor of 2. This has been applied to the model layer immediately below the mined seam.

### 4.5.5 DISTRIBUTION OF INCREASED POROSITY

The extraction of the longwall results in an increase in porosity in the subsurface (i.e. removal of 3.9 m of coal). Subsidence at the surface reduces the volume available (see example on the left-hand side of **Table 4-4**). The subsequent deformation in the strata between the seam floor and the surface results in some re-distribution of that porosity through the sequence.

Advisian (2016) made the following summary: “In areas nearer the zone of extraction, such as the caved zone, both vertical and horizontal cracking is thought to be substantial and therefore significant increases in vertical and horizontal permeability are expected, as well as increases in porosity.” PB (2015) stated that the greatest strain occurred below their lowest extensometer (i.e. below the Bulgo Sandstone).

**Table 4-4 Modelled Enhancement of Porosity / Specific Yield**

| VOID SPACE CALCULATION | |
|---|---|
| **PARAMETER** | **VALUE** |
| Mined height | 3.9 m |
| Subsidence | 0.8 m (pillar);^<br>2.5 m (centre)^ |
| Void space created | 1.5 m (averaged) |
| | = 3.9-1.5 = 2.4 m |
| | |
| Depth of Cover | 350 m |
| Average increase in porosity | =2.4 / 350 = 0.007 = 0.7% |

| MODELLED POROSITY ENHANCEMENT | | | | | |
|---|---|---|---|---|---|
| | | **HOST** | | **POST-MINING** | |
| Layer | Thickness* | Sy | Void (m) | Sy | Void (m) |
| Wombarra Fm (L11) | 15 m | 0.004 | 0.06 m | 0.033 | 0.495 m |
| Bulli Seam (L12) | 2.5 m | 0.016 | 0.04 m | 0.06 | 0.15 m |
| LRSS (L13) | 28 m | 0.005 | 0.14 m | 0.05 | 1.5 m |
| Wongawilli Seam (L14) | 4 m ** | 0.015 | 0.06 m | 0.15 | 0.6 m |
| Total | | | 0.3 m | | 2.65 m |
| Difference | | | =2.65-0.3 = 2.3 m | | |

^ taken from MSEC, 2017. *End of Panel for LW12*; * example thickness; ** working section only

In the current model, the Sy increase has been concentrated on the mined seam, the caved zone and the lower parts of the connected fractured zone, as outlined in the right-hand columns of **Table 4-4**.

**Table 4-4** shows good agreement between the 'calculation' of void space created and the example distribution of void space in the groundwater model. It is acknowledged that porosity can be created or enhanced higher in the profile, and possibly in a non-systematic fashion (e.g. as in PB, 2015). However, HS has taken the view that most of the Sy enhancement will occur in the zones near the mined seam (as per Advisian, above) and that as long as the model approximates the total porosity enhancement, then the role of this in delaying the recovery of groundwater levels should be taken into account.

### 4.5.6 OTHER WORKINGS

Within roadways and bord and pillar areas, horizontal hydraulic conductivity was set to 10 m/d, and vertical hydraulic conductivity to 0.002 m/d.

## 4.6 MODEL CALIBRATION

### 4.6.1 APPROACH

Manual calibration methods were used to alter the hydraulic conductivity (horizontal and vertical), and specific yield of modelled layers or zones. The model is parameter-rich, with many host permeabilities and storage parameters, recharge, boundary condition conductances to be modified. In addition, the height / depth / lateral extent of the various zones of deformation and the degree of deformation within those all work in different ways to affect model behaviour.

Calibration has focussed on replicating observed mine inflow and groundwater levels, while constraining the hydraulic conductivity with the large dataset of packer and core test results available at Dendrobium and supported by data from neighbouring mines (Appin, Tahmoor).

A key difference in this model, compared to the previous HS and Coffey models is that calibration has been attempted for inflow to each mine area (Areas 1, 2, 3A and 3B). This is viewed as important given the different character of inflow to each area.

Given the size and complexity of the model, and timeframe between the release of the PSM study (in September, 2017) and requirement for model update in late 2017 (as in **Section 1.3**), HS used a local-scale model, based on the regional model but with boundaries much closer to the Dendrobium Mine, in order to test different methods for representing connected fracturing, as well as different heights/parameters within deformed zones. The results of this were then passed back to the regional model for the overall 'impact assessment'. The model was revised in early 2018 based on Agency and Peer Review (Kalf and Associates, 2018) comments to make it more conservative with respect to subsidence and deformation processes.

### 4.6.2 MODEL PERFORMANCE

The full regional model takes about 15-20 hours to run with the 'Stacked Drains' implementation of the connected fractured zone, and about 30-50 hours with other methods.

The head close criterion specified in the MODFLOW-USG SMS solver was 0.05 m. The mass balance error at the end of the MODFLOW-USG simulation was reported as <0.05%. The model uses the 'upstream weighting' method for simulating unsaturated conditions (similar to the 'pseudo-soil' function in MODFLOW-SURFACT), although testing was conducted with this and with the Richards Equation for unsaturated flow. Some previous versions of the model have used Richards Equation (e.g. HS, 2014; 2016a).

The statistical calibration to groundwater levels and the calibration to inflows has declined with the incorporation of a conservative height of connected fracturing and off-goaf / valley-bulging mechanism.

### 4.6.3 GROUNDWATER LEVELS

The location of boreholes and piezometers used for groundwater level calibration are mapped in **Figure 7** (with more detailed maps in **Appendix E**). As per Condition of Approval 16(b) (**Table 1-3**), a large dataset of groundwater levels has been collated across a total of 698 target instruments (bores, piezometers) at which approximately 40,000 observations have been used to assess model calibration to groundwater levels.

Of those sites/piezometers, 630 are piezometers in 'deep' bores. From the sub-daily or daily data recorded at those sites, HS have aggregated those data into over 38,250 aggregated medians by model stress period. The modelled heads are plotted against observed heads on **Figure 9**. With respect to the scatter on the X:Y plot shown on this figure, the key reasons for the scatter are:

- difficulty in matching the timing of drawdown. The model may match the pre-mining head quite well, and also the final post-mining head reasonably well, but during the period of drawdown, it is easy for the model to be out by 100 m or more because it either draws down too quickly or too slowly compared to observed.
- longwall progression and therefore commencement of significant impacts at a monitoring point occurs over small time increments compared to model stress periods.
- potentially incorrect layer assignment. Some VWPs located in the mid-Bulgo Sandstone may be assigned to the lower Bulgo Sandstone but could be validly assigned to the upper Bulgo Sandstone.
- incorrect or suspect data which has not been identified.
- incorrect or imperfect parameterisation of the model re: K and S parameters, either on a local or larger-scale.
- the 'Stacked Drains' method fixes the head in the connected fracture zone at zero pressure – pressures are often maintained (see **Figure 12** and **Figure 13**) but the preference is that the model configuration be such that a conservative impact assessment is achieved.

HS has used water levels from 98 'shallow' piezometers, almost all of which are located in swamp deposits (as mapped for IC or based on OEH mapping), although some are not located in such features. From this dataset, given that these shallow bores are responsive to short-term rainfall events, we have derived target values for calibration by taking a value within the first third, second third and last third of each month resulting in over 2,500 'targets' for calibration.

The size of the dataset has meant that data 'cleaning' or the application of 'weights' has not occurred. We have made steps to have clearly erroneous data corrected (e.g. provided instructions to the data managers to fix some calculated heads obtained from some of the VWPs, such as occasional miscalculation between groundwater level, mAHD and pressure head, m).

The SRMS error for the correlation between observed data and the transient model groundwater levels is 12.2% and just outside the often-quoted example of 10% (MDBC, 2001; Barnett *et al.,* 2012), however considered acceptable for a model of this scale and complexity, in a fractured rock environment, and considering the accuracy of the VWPs and the size of the dataset. The mean residual groundwater level is -22 m.

Calibration hydrographs for the entire dataset are presented in **Appendix E**. The match between modelled and observed hydrographs is generally good, with the main issue being that while the overall scale of drawdown is often quite well matched, the timing of drawdown is not always matched, and this can lead to large residuals in the calibration. This could be due to the real timing of mine development versus the 'blocky' timing of model stress periods but is more likely related to local-scale variation in permeability and porosity, or geotechnical behaviour that cannot be captured in a regional model (e.g. multiple caving/subsidence events related to (multiple) longwall extraction).

Modelled groundwater levels are plotted against observed pressures for two sites in or near Area 3C: S1910 on the western edge of the proposed Longwall 20 roadways (**Figure 10**); S1892 between Area 3A and the proposed Longwall 21 (**Figure 11**) – locations marked on **Figure 7**. Observed groundwater levels are plotted in solid lines, with a corresponding modelled series in a dashed line of the same colour.

From **Figure 10** and **Figure 11**, the key features are:

- Relatively good correlation between observed and modelled head values for the Hawkesbury Sandstone) at both bores.
- Pre-mining levels do not show enough separation between layers from the Bald Hill Claystone and below, especially at S1910 with most model layers clustered at 330-340 mAHD while observed heads are 260-330 mAHD.
- The model tends to simulate the timing of drawdown incorrectly, generally being too slow but sometimes too quick to reach the minimum observed groundwater level following mining. The difference in timing means that groundwater level residuals (the 'error' in modelled vs observed values) is often 100-200 m during the period when groundwater level declines are occurring. However, the total observed groundwater drawdowns in the coals seams and the overlying strata are quite well matched by the model (i.e. the final groundwater levels for piezometers at S1910 after the passing of Longwall 9 are a good match to observed when considering that many piezometers can be sheared off before the maximum drawdown is achieved).
- Modelled groundwater levels at S1910 predicted a peak in the Wongawilli Seam reaching a maximum head of >1000 m in 2009, before declining fairly rapidly back to realistic values. This is a model artefact, and something that occurs occasionally when simulating changes in specific yield (due to coal extraction and subsidence) in these groundwater models.

A second method of assessing groundwater level calibration is via comparison of groundwater pressure profiles. Observed and modelled pressures for two sites are presented: the paired site S2192-S2220 above Longwall 9 (**Figure 12**) and S1911 at Longwall 13 (**Figure 13**). On these plots recorded or observed pressures for specific dates are plotted in solid lines, with a corresponding modelled series in a dashed line of the same colour. From these it can be seen that:

- Pre-mining pressures are relatively well matched at both sites, being better at S2192 in Longwall 9, **Figure 12** (blue and green series).
- Following extraction of Longwall 9 and then again as Longwall 10 passed, piezometers in the replacement bore S2220 sheared, and so do not provide information below 140 m (**Figure 12**). The upper piezometers show the maintenance of pressures in the range 0-5 m$H_2O$ (the piezometer at 50 m) to about 15 m (in the piezometer at 140 m). The model simulates the pressures in the upper horizon (3 m$H_2O$ pressure head in model layers 2 and 3 (midpoints at 15 and 60 m respectively), but then simulates <1 m$H_2O$ pressure through the sequence below that (due to the 'Stacked Drains' method).

- **Figure 13** shows that as mining approached S1911, pressures in the units below the Bald Hill Claystone, i.e. Bulgo Sandstone and lower, dropped significantly, especially in the sandstones. Pressures in some of these fell to zero, while in the claystones pressures declined a little, but were maintained as positive. The model overestimates the decline, simulating near zero pressures from the lower Hawkesbury Sandstone down.

Overall, the model overestimates the degree of drainage of groundwater from the strata above and around the longwalls. This is due to the 'Stacked Drains' method. In reality, areas where fracturing is not connected and/or where host permeabilities are low, drainage would be delayed or even incomplete - this is likely the reason for the staggered pressure head profile observed in S1911 (**Figure 13**).

### 4.6.4 MINE INFLOW

**Figure 14** and **Figure 15** present the model calibration to the 'observed' groundwater inflow to the underground mine, as calculated by IC's site water balance. The groundwater model results have been calculated considering time-weighted averages, with reference to model output times (**Section 4.3** and Mackie, 2013).

Comments on **Figure 14** are as follows:

- Area 1 – modelled inflows are generally too high, including during the 'active' extraction phase (Longwalls 1 and 2). Following that, the peaks that occurred during Longwalls 3 and 4 are not matched. The consistent long-term trend is matched appropriately, although again the modelled inflow is too high.
- Area 2 – the model simulates too much groundwater inflow during Longwalls 3-5, although the pattern of peaks and troughs appears reasonable. After the active extraction phase, the model does simulate the peakiness of inflows to Area 2, although it does not capture the peak inflow rate. While this represents an improvement on previous modelling at Dendrobium (which was not able to capture this behaviour), the peakiness has declined with the use of a greater height of fracturing model compared to other model runs that used the lower heights to represent connected fracturing.
- Area 3A – as with all areas, the model overestimates inflow to the underground workings while longwall extraction is in progress, and then does not capture the peaks, typically one or two per year, after the active phase.
- Area 3B – The model again overestimates inflow during the early longwalls (9-10) but is a better match of the inflow during Longwalls 11-13.

Further to the above, during model calibration, the one local-scale model that did capture this behaviour also overestimated inflow to Areas 2 and 3B by a factor of 2 and 4 respectively, and it did not include simulation of off-goaf and surface cracking. Once those behaviours were added, the peakiness of both areas reduced significantly. Thus, while it should be possible to replicate the short-term peaks of Area 2, the slower peaks of Area 3A and the inflow to Area 3B within a single model run with a consistent model of the height/degree of connected fracturing, there remains uncertainty about the combination of host permeabilities and the representation of the various deformation zones that would better replicate observed inflow and groundwater levels.

Overall, the modelled total mine inflow **Figure 15A** appears to be a reasonable match to observed, and is generally higher than the observed data, and therefore should be considered conservative with respect to volumetric impacts, such as groundwater take and baseflow capture from watercourses.

## 4.7 CALIBRATED MODEL PARAMETERS

**Table 4-5** presents the calibrated model aquifer parameters, the same as in HS (2018).

**Table 4-5 Calibrated Model Aquifer Parameters**

| Layer | Hydro-stratigraphic unit | Kh (m/d) | Kv (m/d) | Kv/Kh | Ss (m$^{-1}$) | Sy |
|---|---|---|---|---|---|---|
| 1-4 | Swamps | 1 | 5.00E-02 | 0.050 | 0.01 | 0.3 |
| 2 | upper Hawkesbury Sandstone | 2.50E-02 | 1.20E-05 | 0.001 | 5.00E-03 | 0.05 |
| 3 | mid Hawkesbury Sandstone | 9.00E-03 | 1.00E-04 | 0.011 | 1.00E-06 | 0.025 |
|  | (deeper, under ridge lines) | 9.00E-03 | 1.00E-05 |  |  |  |
| 4 | lower Hawkesbury Sandstone | 2.00E-02 | 3.00E-05 | 0.002 | 1.00E-06 | 0.012 |
|  |  | 1.00E-03 | 1.00E-05 | 0.01 |  |  |
| 5 | Crinanite (upper) | 5.00E-02 | 3.00E-03 | 0.06 | 5.00E-04 | 0.01 |
| 5 | Bald Hill Claystone | 1.50E-03 | 3.00E-06 | 0.002 | 1.00E-06 | 0.006 |
|  |  | 3.00E-4 | 3.00E-06 | 0.01 |  |  |
| 5-11 | Crinanite | 1.00E-04 | 5.00E-05 | 0.5 | 9.00E-06 | 0.003 |
| 6 | Bulgo Sandstone (upper) (Area 2) | 2.00E-02 | 2.00E-05 | 0.017 | 9.00E-07 | 0.008 |
|  |  | 6.00E-03 | 2.00E-06 | 0.001 | 9.00E-07 | 0.008 |
|  |  | 8.00E-04 | 1.00E-06 | 0.001 |  |  |
|  | (deepest, west/north) | 3.00E-04 | 1.00E-06 | 0.003 |  |  |
| 7 | Bulgo Sandstone (lower) (Area 2) | 1.00E-02 | 2.00E-05 | 0.002 | 8.00E-07 | 0.007 |
|  |  | 6.00E-03 | 6.00E-06 | 0.001 |  |  |
|  |  | 8.00E-04 | 3.00E-06 | 0.004 |  |  |
|  | (deepest, west/north) | 1.00E-04 | 2.00E-06 | 0.02 |  |  |
| 8 | Stanwell Park Claystone | 6.00E-04 | 4.00E-06 | 0.007 | 7.00E-07 | 0.005 |
| 8 | Stanwell Park Claystone – sandy facies | 1.00E-03 | 3.25E-05 | 0.033 |  |  |
|  | (deepest, west/north) | 6.00E-05 | 2.00E-06 | 0.033 |  |  |
| 9 | Scarborough Sandstone | 4.00E-03 | 5.00E-06 | 0.001 | 6.00E-06 | 0.01 |
|  |  | 4.00E-04 | 1.00E-06 | 0.003 |  |  |
|  | (deepest, west/north) | 1.00E-04 | 1.00E-06 | 0.01 |  |  |
| 10 | Wombarra Claystone | 3.00E-04 | 5.00E-06 | 0.017 | 5.00E-07 | 0.0035 |
|  |  | 7.00E-05 | 5.00E-06 |  |  |  |
| 11 | Coalcliff Sandstone | 4.00E-04 | 7.00E-06 | 0.018 | 4.00E-07 | 0.004 |
| 12 | Bulli Coal Seam | 7.00E-04 | 2.50E-05 | 0.036 | 1.00E-06 | 0.016 |
| 13 | Lawrence & Loddon Sandstones | 3.00E-04 | 9.00E-06 | 0.03 | 3.00E-07 | 0.005 |
| 14 | Wongawilli Coal Seam | 5.00E-03 | 9.00E-06 | 0.002 | 1.00E-06 | 0.015 |
|  |  | 8.00E-04 | 7.00E-06 |  |  |  |
| 15 | Kembla Sandstone | 2.50E-04 | 3.00E-05 | 0.12 | 3.00E-07 | 0.0045 |
| 16 | lower Permian Coal Measures | 8.00E-05 | 1.28E-05 | 0.16 | 3.00E-07 | 0.004 |
| 17 | Shoalhaven Group | 1.00E-05 | 1.80E-06 | 0.18 | 3.00E-07 | 0.004 |

NOTES:
1. Kh – Hydraulic conductivity (horizontal); Kv – Hydraulic conductivity (vertical); Kv/Kh – Ratio of vertical to horizontal hydraulic conductivity; Ss – Specific storage; Sy – Specific yield.

*Source: E:\ \DENDROBIUM\Model\Vistas\DenV7TR012.gwv*

Model parameters are all within expected ranges based on analysis of the packer and core testing databases (i.e. close to arithmetic mean and harmonic mean for horizontal and vertical hydraulic conductivities respectively) and do not represent a marked departure from previous modelling (see Coffey, 2012a; HS, 2014, 2016a, 2016b). Two of the main adjustments include:

- Hydraulic conductivity of the Wongawilli Seam has been zoned by depth and reduced to 0.005-0.0008 m/d, which is a better match to the packer test data.
- Zonation of the Hawkesbury Sandstone, Bald Hill Claystone and Bulgo Sandstone has been applied, to represent higher permeabilities measured in packer tests around Area 2 and the eastern edge of Area 3A (where the Bald Hill and Bulgo are at or near the surface), and lower permeabilities measured in Area 3B.

## 4.8 MODEL REVIEW

The Dendrobium Regional Groundwater Model has evolved from that of Coffey (2012) through numerous iterations and updates (HS, 2014, 2016, 2018), and further work to improve the model is on-going, as recommended by IEPMC (2018).

The model, as reported on in SMP applications for Dendrobium has been reviewed a number of times by NSW Government Agency staff (e.g. WaterNSW, DSC, OEH and DPE) and the IEPMC.

The Dendrobium Regional Groundwater Model has been the subject of Peer Review by Kalf and Associates (in 2018), who has made specific comments and recommendations about the analysis of data, the development of the conceptual model, as well as features of the numerical model including the need for conservative representation of the zone of connected fracturing and reviewed the method for including basal shears and valley closure processes.

Kalf and Associates is engaged on an on-going basis for review of the model described in this report and for future model development, including the development of an unstructured model which will be documented in a separate report.

# 5 PREDICTIVE MODELLING

The mine plan and schedule for Longwalls 20 and 21 are presented in **Table 1-1** and **Appendix A**. To assess the effects of the proposed Longwalls 20 and 21 a number of predictive scenarios have been applied and these are summarised in **Table 5-1**.

Table 5-1 Summary of Predictive Scenario Design

| Scenario | RUN | NAME | DENDROBIUM | CONNECTED FRACTURED ZONE METHOD | OTHER MINES | COMMENT |
|---|---|---|---|---|---|---|
| **A** | v7TR020 | Full Impact | All Area 3C (LW 20-21), 3B, 3A and other longwalls | 'Stacked Drains', with connected fracturing as per calibration (Appendix D) | All | Represents pre-mining conditions.<br>Important to note the long history of mining in this area. |
| **B** | v7TR021 | Dendrobium, no LW 20-21 | All Areas except Area 3C. | 'Stacked Drains', with connected fracturing as per calibration (Appendix D) | All | Comparison against Scenario A gives effects of LW 20-21. |
| **C** | v7TR022 | Baseline – No Dendrobium | None | None | All | Represents conditions of no Dendrobium for Impact Assessment |
| **D** | v7TR023 | Baseline – Natural ('Null') | None | None | None | 'Null run' as per Barnett *et al*, 2012. |

Each predictive run simulates the period to 2200 (as per Condition of Approval), which is detailed in **Appendix A**.

All the runs in **Table 5-1** were carried out, and results of these compared to assess the effects of Dendrobium (as a whole) and the incremental effects of Longwalls 20 and 21. However, given the amount of model output that could be generated, only the key results, notably fluxes, have been discussed in detail in the following sections. This includes whole-of-mine and incremental effects of Longwalls 20 and 21 on leakage from Lake Avon (**Section 5.4**), leakage from Lake Cordeaux (**Section 5.5**) and surface water take from watercourses (**Section 5.6**). The mine inflow predictions (**Section 5.3**) show mine inflow through time, including through the remainder of Area 3B, 3A and then Longwalls 20 and 21.

As with the modelling done in HS (2018), the predictive period includes variation in rainfall recharge, based on the calculated historical patterns. Generally, stress periods are set at two per year for the predictive period, with a recharge rate for typical wet and typical dry periods used alternately, with some occasional variation to cater for more extreme conditions (although not including multi-year droughts). It is for this reason that peaks and troughs in inflow are modelled in subsequent sections.

During the calibration process and revision of the model, and during previous modelling assessments, a variety of methods, permeability parameter sets and fracture zone heights have been used. The configuration of the model used in the impact assessments is considered to be conservative with respect to the height of connected fracturing, the method used to represent fracturing and the off-goaf permeability enhancement.

## 5.1 MODEL PERFORMANCE

As noted before, the predictive model run times were about 20 hours. The conjunctive use of 'Stacked Drains' (for the connected fracture zone) has meant that model speed has improved on previous versions of the model, yet the run time remains somewhat impractical.

Model stability has improved by not using TVM or CLNs for the connected fracture zone, although in our opinion both those methods possess conceptual advantages over the ‘Stacked Drains’ method and are worthy of further consideration and testing.

All predictive runs had overall mass balance errors of <0.04% which is acceptable based on the recommended threshold of 1-2% of Barnett *et al* (2012). Some timesteps, typically those at the beginning of a stress period, have higher mass balance errors. This is due to the enhancement of specific yield, Kh or Kv in many cells, and often in cells containing the ‘Stacked Drains’ in those periods.

## 5.2 SIMULATED GROUNDWATER BALANCE

The modelled regional groundwater balance is summarised in **Table 5-2** to provide context to the major processes represented by the groundwater model. The water balance presented here is the average from 1990-2053, and includes Dendrobium (including Longwall 16), historical mining around Dendrobium, and the parts of Tahmoor and the Appin Mine that lie within the active model domain (see **Figure 6**).

**Table 5-2 Modelled water balance**

| MODFLOW component | Process | In | Out |
|---|---|---|---|
| RECHARGE | rainfall recharge | 130.5 | 0.0 |
| RIVER LEAKAGE | watercourses, reservoirs | 84.5 | 62.5 |
| ET | evapotranspiration | 0.0 | 181.6 * |
| DRAINS | mine inflow | 0.0 | 9.6 |
| HEAD DEP BOUNDS | regional GW flow | 2.1 | 0.0 |
| CONSTANT HEAD | flow to ocean, estuaries | 0.1 | 0.1 |
| STORAGE | groundwater storage | 91.4 (reduction in GWLs) | 55.3 (rise in GWLs) |
|  | **Total** | **308.5** | **309.5** |

* ET is high because it represents spring flow along escarpment. Results are from model run v7TR020.

Rainfall recharge is the dominant input, while baseflow to watercourses/springs and evapotranspiration are the dominant outputs. Mine inflow constitutes approximately 8% of the recharge.

## 5.3 PREDICTED MINE INFLOW

**Figure 15A** presents the predicted Dendrobium Mine inflow from 2005 until 2025, capturing the complete period for all longwalls including Longwalls 20 and 21. This shows that the current and conservative representation of vertically-connected fracturing and off-goaf permeability enhancement results in relatively high inflows compared to observed. The highest average annual inflow to the mine is predicted to be approximately 14 ML/d.

**Figure 15B** shows that inflow to Longwalls 20 and 21 is predicted to peak at approximately 6 ML/d, averaging about 4 ML/d.

## 5.4 SIMULATED LEAKAGE FROM LAKE AVON

The scenario v7TR020 (**Table 5-1**) includes enhanced permeability in the off-goaf areas, considered to simulate broad scale valley closure (valley bulging) mechanisms. This has been used to provide estimates of leakage from the reservoir.

### Whole of Mine effects

The maximum leakage from Lake Avon, as a result of mining at Dendrobium, is predicted to be 0.26 ML/d, with an average for the period 2014-2050 being 0.06 ML/d. This is less than DSC's prescribed tolerable limit for Lake Avon (1 ML/d), and is in the middle of estimates from previous regional models in Coffey, 2012, HS, 2014, HS, 2016a (see **Table 5-3**), of which the highest was in HS, 2016a.

Additional estimates have been made in HGEO (2017d). HGEO used an uncalibrated site-scale numerical model to simulate a number of hydraulic conductivity (Kh) cases based on pre- and post-mining Hawkesbury Sandstone permeability in bores S3214 and S2331, which are adjacent to Lake Avon. That model focusses on horizontal flow between the reservoir and the fractured zone within the Hawkesbury Sandstone, as well as considering the scenario of a permeable zone along the Elouera Fault. The estimates produced by HGEO are included in **Table 5-3** alongside the other estimates.

Table 5-3 Estimates of induced leakage from Lake Avon

| Reference | Scenario (if relevant) | Seepage from Lake [ML/d] | Comment |
|---|---|---|---|
| HGEO, 2017d | 3 Kh cases with Elouera Fault | 0.040, 0.16 and 0.929 | Local scale, horizontal flow only, no calibration |
| HGEO, 2017d | 3 Kh cases without fault | 0.039, 0.16 and 0.928 | |
| HS, 2018 | As described in this report | 0.25 | Regional scale, calibrated against inflow, groundwater level and constrained by permeability data |
| HS, 2016a | Buffer distance = 250 m | 0.47 | |
| HS, 2016a | Buffer distance = 300 m | 0.41 | |
| HS, 2014 | | 0.13 | |
| Coffey, 2012 | Panels 250 m from L. Avon | 0.15 | |

More discussion on the differences between estimates made by the regional models (by Coffey and HS) and the local model (by HGEO) is provided in HS (2018).

### Incremental effects

The incremental leakage due to the extraction of Longwalls 20 and 21 is estimated to be <0.001 ML/d (peak). This small incremental leakage, effectively nil, is due to the distance from the proposed longwalls to Lake Avon (see Section 1.2.2).

## 5.5 SIMULATED LEAKAGE FROM LAKE CORDEAUX

### Whole of Mine effects

The simulated maximum leakage from Lake Cordeaux as a result of Dendrobium mining operations was predicted to be 0.08 ML/d (modelled average for the period 2005-2050 is 0.06 ML/d). Again, this is lower than DSC's prescribed tolerable limit for Lake Cordeaux (1 ML/d), and lower than previously predicted.

### Incremental effects

The incremental leakage due to Longwalls 20 and 21 is <0.001 ML/d, effectively nil.

## 5.6 SIMULATED 'INCIDENTAL TAKE' FROM WATERCOURSES

### Whole of Mine effects

Condition 16(c) (**Table 1-3**) required estimates of baseflow capture to be provided in 5-yearly intervals out to 30-years after the proposed completion of Longwalls 16-18. HS has adopted the same approach for this assessment of Longwalls 20 and 21.

The results from the MODFLOW budget files have been extracted from the predictive scenarios, and net difference, the 'take' from surface water, calculated based on a number of zones as defined by the WSP *for the Greater Metropolitan Region Unregulated River Water Sources 2011* (Section 1.4). These are summarised in **Table 5-4** in ML/year. These zones within (or are the total predicted take for) the *Upper Nepean River Tributaries Headwaters Management Zone.*

For conceptual understanding of the model results short-term losses at high flows can be greater than the average loss.

**Table 5-4 Predicted reduction in surface water quantity [ML/yr]**

| 5-year interval | Donalds Castle Ck | Wongawilli Creek [includes WC15] | Total – Upper Nepean River Tributaries Headwaters |
|---|---|---|---|
| 2011-15 | 36 | 68 | 364 |
| 2016-20 | 398 | 208 | 1372 |
| 2021-25 | 397 | 175 | 1471 |
| 2026-30 | 316 | 138 | 1217 |
| 2031-35 | 242 | 116 | 906 |
| 2036-40 | 197 | 112 | 714 |
| 2041-45 | 157 | 100 | 573 |
| 2046-50 | 113 | 86 | 472 |
| 2051-55 | 91 | 84 | 470 |

LW17 SMP model estimates and LW20-21 incremental

As shown in **Table 5-4** in the future, the total annualised surface water take from the *Upper Nepean River Tributaries Headwaters Management Zone* is predicted to vary between 400 and 1470 ML/yr (up to 4 ML/d, as an average), which is calculated for the full development of Areas 1, 2, 3A, 3B and Longwalls 20 and 21.

### Incremental effects

Longwalls 20 and 21 are predicted to result in some 'take' from watercourses, as summarised in **Table 5-5**. Only the zones affected are included in **Table 5-5**.

**Table 5-5** indicates a very small effect on the Lake Cordeaux zone due to the upper part of the LC5 catchment overlying Longwall 21 (see **Figure 7**). Donalds Castle Creek and Wongawilli Creek are both predicted to experience higher rates of loss (**Table 5-5**) due to the proximity of those watercourses to Longwalls 20 and 21, with various tributaries of Wongawilli Creek directly overlying the longwalls (WC20, WC23, WC24 and WC25 - **Figure 7**).

Table 5-5 Incremental Surface Water Take – Longwalls 20 and 21 [ML/yr]

| 5-year interval | Lake Cordeaux Zone | Wongawilli Creek | Donalds Castle Creek |
|---|---|---|---|
| | | (within the Upper Nepean River Tributaries Headwaters Management Zone) | |
| 2011-15 | 0 | 0 | 0 |
| 2016-20 | 0 | 0 | 0 |
| 2021-25 | 1 | 70 | 52 |
| 2026-30 | 2 | 56 | 3 |
| 2031-35 | 2 | 65 | 3 |
| 2036-40 | 1 | 65 | 5 |
| 2041-45 | 1 | 67 | 6 |
| 2046-50 | 1 | 45 | 7 |
| 2051-55 | 1 | 22 | 3 |

Source: E:\DENDROBIUM\Model\GWModel\Processing\ZoneBudgetU\SWtake_Dendv7TR020-021.xlsx

## 5.7 SIMULATED GROUNDWATER LEVELS

As required by Condition 17(a) (**Table 1-3**), a variety of methods of presenting modelled groundwater levels are provided in the following sections.

### 5.7.1 CONTOUR MAPS – GROUNDWATER LEVEL

**Figure 16**, **Figure 17** and **Figure 18** present modelled water levels for four 'layers' in the geological sequence at different times in the model simulation. These layers are:

- Water table (calculated as the water level in the uppermost saturated model layer, i.e. uppermost saturated stratigraphic unit);
- lower Hawkesbury Sandstone (model layer 4);
- lower Bulgo Sandstone (model layer 7); and
- Wongawilli Coal seam (model layer 14).

**Figure 16** shows the modelled pre-mining conditions, **Figure 17** shows the conditions as simulated at the end of Longwall 21, and **Figure 18** shows the simulated groundwater levels in approximately 2200 (i.e. over 150 years after the end of mining in Area 3B).

Comparison of **Figure 16** and **Figure 17** allows visual assessment of the effects of Dendrobium Mine, including Longwalls 20 and 21, on water levels in those units, significant drawdown in the Wongawilli Seam (up to 340 m within the footprint of Longwall 20), lower Bulgo (approx. 150 m) and lower Hawkesbury Sandstone (20-40 m). The water table, as described above, is also disturbed by about 10 m in some locations around Area 3B and Longwalls 20 and 21.

Drawdown or depressurisation is predicted to occur at some distance outside the footprint of the longwalls. e.g. predicted heads in the lower HBSS (Layer 4) are about 300 mAHD at a point 1 km north of Longwall 21 on **Figure 16**, and have declined to 280 m on **Figure 17**. At a similar location, the depressurisation in the Bulgo Sandstone (Layer 7) is simulated to change from 320 mAHD (**Figure 16**) down to 260 mAHD in **Figure 17**. The drawdown in the Wongawilli Seam is about 120 m at the same point.

Comparison of **Figure 18** with **Figure 16** suggests the water table and lower Hawkesbury will have recovered to close to pre-mining levels. The water levels in the Bulgo Sandstone and

Wongawilli Seam are predicted to remain depressed compared to pre-mining conditions (see **Section 5.7.3**).

### 5.7.2 CROSS-SECTIONS – PRESSURE HEAD

Two cross-sections of modelled groundwater pressures, in metres (m $H_2O$) are presented in **Figure 19** (model row 109) and **Figure 20** (model column 106). Each figure has a thumbnail map showing the cross-section locations in relation to the mine plan. These sections show the development of pressures from pre-mining (steady state) model conditions, through the operation of Dendrobium to Longwalls 20 and 21 and then through to a post-mining recovery phase.

These figures show the relatively conservative nature of the stacked Drains method for representing groundwater drainage in the connected fracture zone. In reality, delayed and incomplete drainage is expected due to the variable connection and somewhat random or tortuous nature of the fracture network, while each model cell within the simulated connected fracture zone is subject to zero pressure (complete drainage) due to the imposition of a Drain boundary condition.

Visual comparison of the pressure head sections in **Figure 19** and **Figure 20** shows that the model simulates complete depressurisation above the longwalls, and drawdown, often significant, at some distance from the longwall footprint. For example, comparison of the sections of **Figure 19** shows:

- 200 m of depressurisation at seam level, approx. 1 km from longwalls.
- 30-50 m depressurisation in the mid-Bald Hill Claystone, 1 km from longwalls.
- Up to 10 m of depressurisation in the mid Hawkesbury, 1 km from longwalls.

Other points to note are:

- **Figure 19** shows some depressurisation from the extraction of Area 3B to the west of Longwalls 20 and 21 (the cross-section passes within 100 m of Longwall 9).
- Depressurisation of about 100 m$H_2O$ at seam level beneath Lake Cordeaux (**Figure 19**), but less than 10 m$H_2O$ in the shallow strata directly beneath the lake (see lake losses, Section 5.5).
- Depressurisation due to other mines (Elouera, BSO) is simulated and shown on **Figure 20**.

The final panel in both **Figure 19** and **Figure 20** shows the predicted pressure head during the simulated recovery phase, approximately 175 years after the extraction of Longwall 21. In the area surrounding the mine workings the model predicts persistent depressurisation (i.e. partial recovery), especially for the deeper units.

Incremental drawdown of groundwater (as reduction in pressure head) can be assessed by comparing pressure head sections, specifically the upper three sections on **Figure 19** and middle two sections on **Figure 20**,  which show pre-Longwall 20, pre-Longwall 21 and post-Longwalls 20 and 21 groundwater pressures.

### 5.7.3 HYDROGRAPHS – GROUNDWATER LEVELS

Hydrographs of modelled groundwater levels through the geological sequence are provided in **Figure 21** and **Figure 22**. These show groundwater levels through time at several nominal locations surrounding Longwalls 20 and 21 (these are referred to as 'monitoring wells' but are simply dummy locations used to inspect model results).

The figures show the degree of drawdown and illustrates the recovery of water levels is predicted to be partial (in many cases). Recovery is predicted to be faster in the upper layers and slower in deeper units (e.g. typically in all strata below the Bald Hill Claystone).

The key points from each hydrograph are as follows:

- At a location 250 m north of Longwall 21 (**Figure 21A**):
    - Water levels in the Bulli and Wongawilli Seams are predicted to experience around ~250 m of drawdown as a result of mining, with approximately 100-150 m of that occurring due to Longwalls 20 and 21. This impact is predicted to continue longer than other strata with these coal seams recovering by ~10 m above the lowest drawdown by the end of the model.
    - Above the seams, all layers up to the Bald Hill Claystone (BHCS) are predicted to experience significant drawdown due to both mining and incrementally due to Longwalls 20 and 21. For example, an additional ~20 m of drawdown is predicted to occur in the Bald Hill Claystone following the start of Longwall 21. Recovery to pre-Longwall 20 and 21 levels is predicted to be achieved by ~2070.
    - It is difficult at this scale to discern the drawdown in the Hawkesbury Sandstone. The model simulates a 7 m drawdown in the lower Hawkesbury Sandstone (3 m drawdown post Longwall 21).
- At a location adjacent to Donalds Castle Creek, west of Longwall 20 (**Figure 21B**):
    - Approximately 200 m of drawdown has been predicted for the Wongawilli and Bulli Seams as a result of mining activity, of which about 130 m is simulated as occurring after Longwalls 20 and 21.
    - A relatively constant decline has been simulated for water levels in the Bulgo and Scarborough Sandstones from the beginning of Area 3B mining, with the greatest drawdown predicted to occur about 30 years after the completion of mining at Longwall 21. Approximately 30 m of recovery is modelled to occur in the upper Bulgo Sandstone by the end of the model run, about 60 m below simulated pre-mining water levels.
    - Modelled drawdown in the lower Hawkesbury Sandstone is about 25 m up to the commencement of Longwalls 20 and 21, with a further 25 m due Longwalls 20 and 21. Recovery is predicted to be about 30 m (approximately 50%) of the total drawdown.
    - 6 m of drawdown has been simulated for the mid Hawkesbury Sandstone and recovery is predicted to be complete, although taking 80-100 years.
    - The model predicts no drawdown in the upper Hawkesbury Sandstone at this location which is adjacent to the creek.
- At a location on Wongawilli Creek nearest the edge of Longwall 20 (**Figure 22A**):
    - Drawdown in the Bulli and Wongawilli Seams is estimated to be about 30 m due to mining before Longwalls 20 and 21, and then a further 250 m is predicted due

  - to Longwalls 20 and 21. Approximately 70 m of water level recovery is predicted for the Wongawilli Seam, and 60 m for the Bulli.
  - The Bulgo Sandstone is predicted to experience between 70-100 m drawdown with greater impacts estimated for the lower Bulgo. The upper Bulgo should recover more than the lower, with the model predicting 60 m recovery by 2200, whereas the lower Bulgo should recover 50 m in that time.
  - The lower Hawkesbury Sandstone is present at surface in this location (at the centre of the Wongawilli Creek valley). The model does not predict any drawdown at this location, although this may be masked by induced leakage from the watercourse (the result capture of stream flow is discussed in Section 5.6).
- Location at (under) Swamp 125, 700 m north of Longwall 20 (**Figure 22B**):
  - The model predicts gradual drawdown (10 m) in the Wongawilli and Bulli Seams to the beginning of Longwall 20, then more rapid drawdown (120 m) after Longwalls 20 and 21). Approximately 8-10 m of recovery has been modelled by the end of this model period.
  - The Bulgo Sandstone is estimated to experience incremental drawdown of 30 m (upper) and 70 m (lower) following mining of Longwalls 20 and 21 (over the 15-20 m drawdown due to previous mining at Dendrobium). Recovery of water levels in the range of 10 m is predicted to occur by 2200.
  - The lower Hawkesbury Sandstone is predicted to experience ~40 m of drawdown following the end of mining at Longwall 21. A 10 m recovery is predicted to occur within a year and with an additional 10 m by 2200.
  - The upper horizons in the Hawkesbury are predicted to experience less drawdown. The drawdown in the mid-Hawkesbury Sandstone is predicted to be 8 m to the beginning of Longwall 20, then a further 2 m (incremental) due to Longwalls 20 and 21. Drawdown in the upper Hawkesbury Sandstone is predicted to be 1 m of drawdown over the life of mining at Dendrobium (pre-Longwall 20), with ~2 m occurring following the completion of Longwall 21.
  - No mining-related drawdown has been predicted to occur in model layer 1 (Swamp 125), which is unsurprising given the distance from the longwalls.

### 5.7.4 GROUNDWATER DRAWDOWN AT GROUNDWATER BORES

The nearest Groundwater Works from the Pinneena database are described in Section 2.4. The maximum predicted drawdown at each of these sites has been determined and is listed in **Table 5-6**. For reference, the *Aquifer Interference Policy* (2012) deems the threshold for ‘minimal harm’ to be 2 m. The model suggests that none of the nearest bores would be adversely affected by the extraction of Longwalls 20 and 21 (or Dendrobium as a whole).

**Table 5-6 Maximum Predicted Drawdown at Groundwater Works**

| GW works # | Depth | Strat | Layer | Predicted max drawdown (m) due to: | |
|---|---|---|---|---|---|
| | | | | Dendrobium | Longwalls 20 & 21 |
| GW112386 | 6-24 m | HBSS | 4 | 0.1 | 0 |
| GW040945 | 110-170 m | HBSS | 4 | <0.05 | 0 |
| GW068119 | 9-19 m | Shoalhaven Grp | 17 | 0 | 0 |
| GW102528 | 17-169 m | HBSS | 3, 4 | 0 | 0 |

X:\HYDROSIM\DENDROBIUM\Model\GWModel\Processing\Drawdown\BoreDDN_Assessment_LW20-21.xlsx

# 6 MONITORING AND MITIGATION

IC have installed a combination of Time-Domain Reflectometry and multi-level piezometers directly above Longwalls 14 and 15 (as per the conditions in **Table 1-3**).

If access is possible, then two ‘shallow sandstone’ monitoring bores are recommended for installation between the longwalls and Wongawilli Creek, preferably within the Wongawilli Creek valley. These should be installed in the Hawkesbury Sandstone and upper Bulgo Sandstone. These could be compared with data-logged surface water sites that record surface water levels. These paired sites would allow the analysis of groundwater-surface water dynamics pre- and post-mining, an important concept given the recent (2017-18) low-flow conditions along one reach of Wongawilli Creek. If access along the valley is not possible, then consideration of a deeper bore installed with instruments located at and just above and below the elevation of the creek near the longwalls could provide useful data.

Carry out at least one round of surface water flow observations (e.g. “dry / no observed flow”, “flowing - trickle”, as per current surface water inspections) along tributaries WC20, WC22, WC23, WC24, and LC5 during dry conditions to establish whether these tributaries flow under dry conditions or have persistent baseflow. Based on recent weather data and forecasts, 2019 will continue to provide further opportunity to understand baseline stream flow conditions in dry conditions.

Further surface water gauging sites should be considered for baseline and impact assessment monitoring:

- further downstream of the current DCU gauge, and downstream of Longwall 20 and other possible/future mining areas, i.e. closer to the confluence with Cordeaux River.
- on tributary LC5, although flow depletion due to mining induced impacts from the proposed longwalls is expected to be minimal. However, this watercourse has recently had monitoring installed (LC5S1), and the aim of this site was to be a ‘reference site’ for surface water monitoring. While the effect of mining on flows at LC5S1 is likely to be very small, an alternative reference site could be installed to avoid doubt. HS has discussed alternatives with ICEFT.

Install shallow piezometers in swamps to be impacted by future mining to obtain >2 years baseline records in those features.

# 7 CONCLUSIONS

The numerical groundwater model has been modified from previous modelling (Coffey, 2012; HS 2013, 2014, 2016a, 2018). As per HS (2018) this was due to the requirement to simulate deeper surface cracking, as well as off-goaf or valley closure mechanisms for permeability enhancement, that called for simplifications to the model configuration including the use of MODFLOW Rivers (not Streams) as well the use of ‘stacked Drains’ to simulate the connected fracture zone.

This model is now assessed for calibration against a large dataset of groundwater levels from more than 600 target locations, as required by the Conditions of Approval. Further, HS (2018) calibrated the model to mine inflow in each mine area as well as the total inflow and groundwater levels, as well as constraining the model to field testing of permeability.

The following results were obtained from the revised groundwater model:

- The model is conservative with respect to historical inflow to the Dendrobium Mine. The model simulates the dynamic patter of area-by-area and total mine inflow with reasonable accuracy. This provides confidence that the assessment of associated changes in the catchment water balance is conservative.

- Dendrobium Mine inflows or groundwater make is predicted to be slightly more than predicted previously, peaking at about 13.5 ML/d, and with the inflow to Longwalls 20 and 21 averaging about 4 ML/d of the total during 2022-2023.
- In the case of the Avon Reservoir, the simulated incremental leakage from the reservoir storage due the extraction of Longwalls 20 and 21 is effectively zero. Predicted losses due to Dendrobium, with and without Longwalls 20 and 21 are less than DSC's prescribed tolerable limit. Alternative modelling approaches to estimating leakage from Lake Avon are made by SCT and Hgeo (various reports), as presented to the DSC and other agencies.
- Leakage from Cordeaux Reservoir is also predicted to be less than the prescribed tolerable limit. The incremental rate due to Longwalls 20 and 21 is effectively zero.
- Incidental baseflow capture has been estimated using the groundwater model and tabulated as required in **Table 5-4**. The predicted take from the Upper Nepean Tributaries Headwaters Management Zone is up to 1470 ML/yr, while the incremental take due to Longwalls 20 and 21 is up to about 120 ML/yr (**Table 5-5**).
- The nearest registered groundwater work is 4.8 km north-east of Dendrobium Area 3B. Drawdown due to Dendrobium mining is predicted to be <0.1 m at this monitoring bore. No other groundwater works are predicted to be affected to any degree and none meet the 2 m threshold in the Aquifer Interference Policy.
- The nearest High Priority Groundwater Dependent Ecosystem (GDE), as defined in the relevant WSP (Section 1.4) is the Macquarie Rivulet Estuary which is over 16 km from Dendrobium Area 3C (**Figure 6**). No drawdown effects will occur at this location as a result of mining at Dendrobium.

Assessment against the Aquifer Interference (AI) Policy is summarised in **Table 7-1**.

**Table 7-1 Summary of AI Policy Assessment – Fractured and Porous Rock**

| | |
|---|---|
| **Aquifer** | Sydney Basin Porous Rock (Nepean Groundwater Source, Management Zone 2) |
| **Category** | Highly Productive |
| **Level 1 Minimal Impact Consideration** | **Assessment** |
| **Water Table**<br>Less than or equal to a 10% cumulative variation in the water table, allowing for typical climatic "post-water sharing plan" variations, 40 m from any:<br>- high priority groundwater dependent ecosystem; or<br>- high priority culturally significant site;<br>listed in the schedule of the relevant water sharing plan.<br>OR a maximum of a 2 m water table decline cumulatively at any water supply work. | The relevant Water Sharing Plan is the 'Greater Metropolitan Groundwater Sources' (dated 1 October 2011).<br>There are no High Priority Groundwater Dependent Ecosystems (GDEs) listed in this WSP within 15 km of Dendrobium Areas 1-3B and Longwalls 20 and 21. Hence there are no known risks of mine development to such sites.<br>There are no Culturally Significant Sites in the Study Area listed in the WSP. Hence there are no known risks of mine development to such sites.<br>There is minimal risk of drawdown in excess of the water supply work drawdown criterion within the Permo-Triassic or shallow strata (based on the distance to registered groundwater works).<br>**Level 1 minimal impact consideration classification.** |
| **Water pressure**<br>A cumulative pressure head decline of not more than a 2m decline, at any water supply work. | There is a very minor risk of depressurisation in excess of the water supply work drawdown criterion within the Permo-Triassic strata (at GW040945, GW112386).<br>**Level 1 minimal impact consideration classification.** |
| **Water quality** | Mining-induced changes to the hydraulic properties and depressurisation of the strata in the Dendrobium Mine area may result in mixing of potentially chemically different groundwater between overlying and underlying units. However, it is considered unlikely that this will result in changes to the beneficial uses of groundwater in the Permo-Triassic rock units. The risk of water quality impacts decreases with distance from the mine footprint.<br>**Level 1 minimal impact consideration classification.** |

## 7.1 LICENSING

The predicted licensing requirements for groundwater are not predicted to change with the extraction of Longwalls 20 and 21. That is, predicted maximum annual groundwater take from any of the following sources would not change:

- Sydney Basin Nepean Sandstone MZ1.
- Sydney Basin Nepean Sandstone MZ2.
- Sydney Basin South.

Currently held licences, including allocations granted in 2019, would be sufficient to cover the predicted maximum groundwater take.

Surface water take is predicted to increase by about 120 ML/yr in the *Upper Nepean River Tributaries Headwaters Management Zone*, with a maximum predicted take of 1470 ML/yr in the 5 years following extraction of Longwalls 20 and 21. Surface water take would not change in other zones as a result of extraction of Longwalls 20 and 21.

## 7.2 RECOMMENDATIONS

Recommendations for future monitoring, data analysis and modelling are as follows:

- The existing *Groundwater Monitoring and Modelling Plan* (HS, 2015a) should be updated, given the considerable expansion of the extent and scope of the monitoring network since 2015.
- Multivariate analysis of permeability. It became apparent during the calibration process for HS (2018) that the focus on the extent and degree of strata deformation in trying to achieve model calibration may be misplaced, with a focus on variation in ‘host’ permeability (e.g. variation due to lithology/facies, weathering/structure or related to depth) providing for improved calibration results. HS has compiled much of IC’s permeability data, however some older data needs to be transferred into database format, and HS are progressing with further analysis that should assist in informing the numerical model. Reporting on this will occur in a forthcoming groundwater assessment.
- Associated with this and noting the valid comment by IEPMC (2018) regarding the apparent divergence in hydraulic conductivity parameters used in the modelling for Dendrobium and for Metropolitan Mine, the model values used in the current Dendrobium model are well constrained by packer test data. However, further analysis across the Southern Coalfield would be useful, i.e. including data from Appin Mine, Tahmoor Mine, Metropolitan Mine, Russell Vale Mine, and that held by WaterNSW.
- Values of specific storage used in the modelling should be reviewed, with geotechnical parameters used to derive or constrain specific storage values. This may have little bearing on the near-surface impact assessment predictions but may improve calibration to groundwater levels in some of the deeper layers.
- Consideration of the timing of fracture zone development might assist in calibration to inflow. It may be that the overestimation of inflow during the early period of each mine area, and subsequent underestimation after the active extraction phase, is due in part to delayed deformation in the goaf as subsequent longwalls pass. FLAC2D modelling may assist with understanding this.

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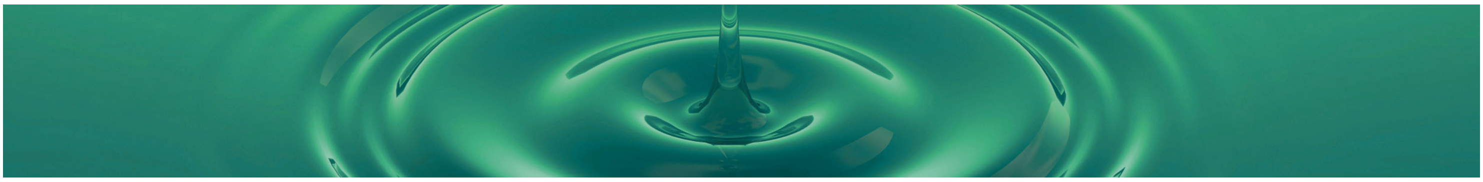

# FIGURES

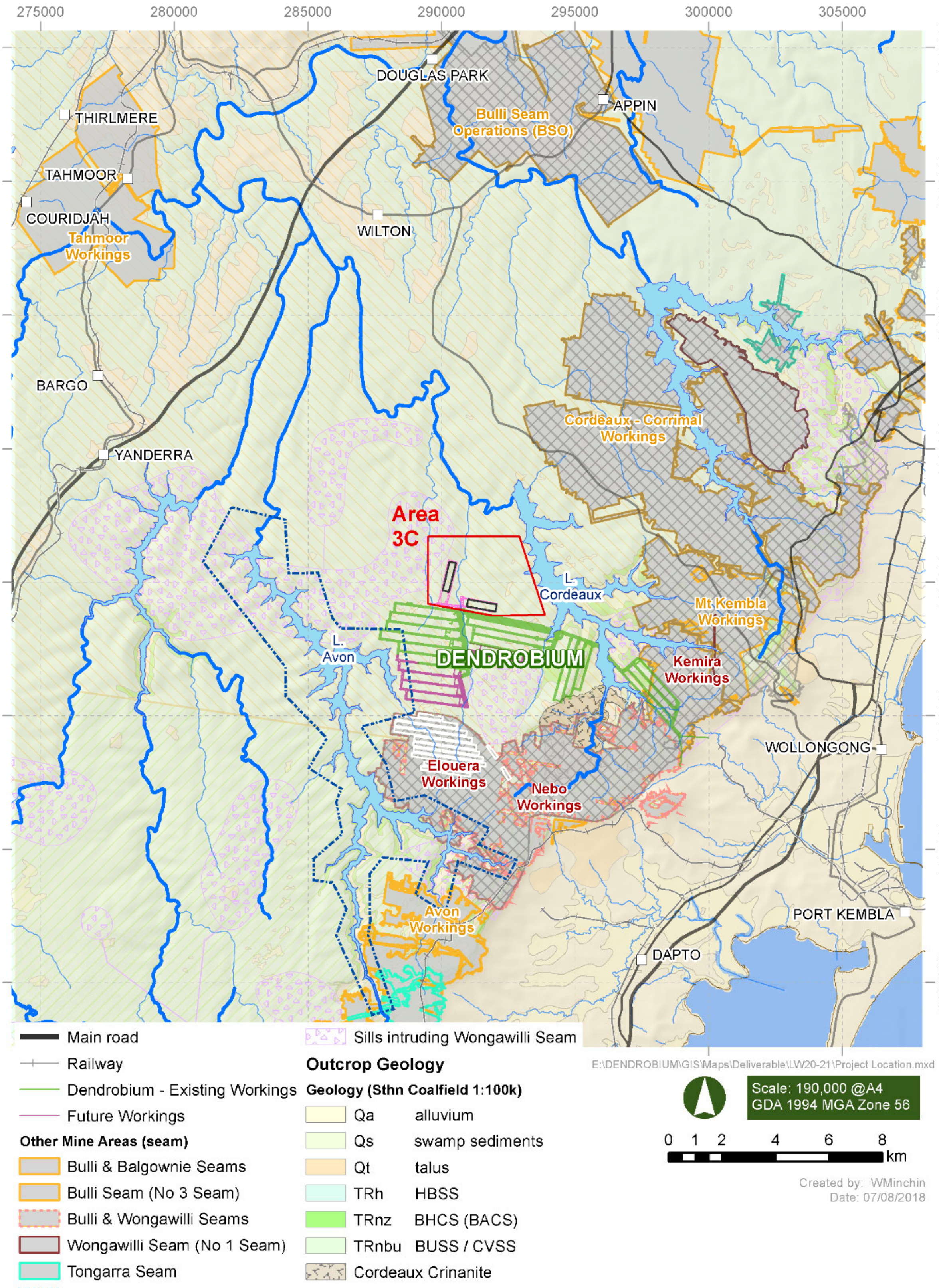

**Figure 1** **Project Location**

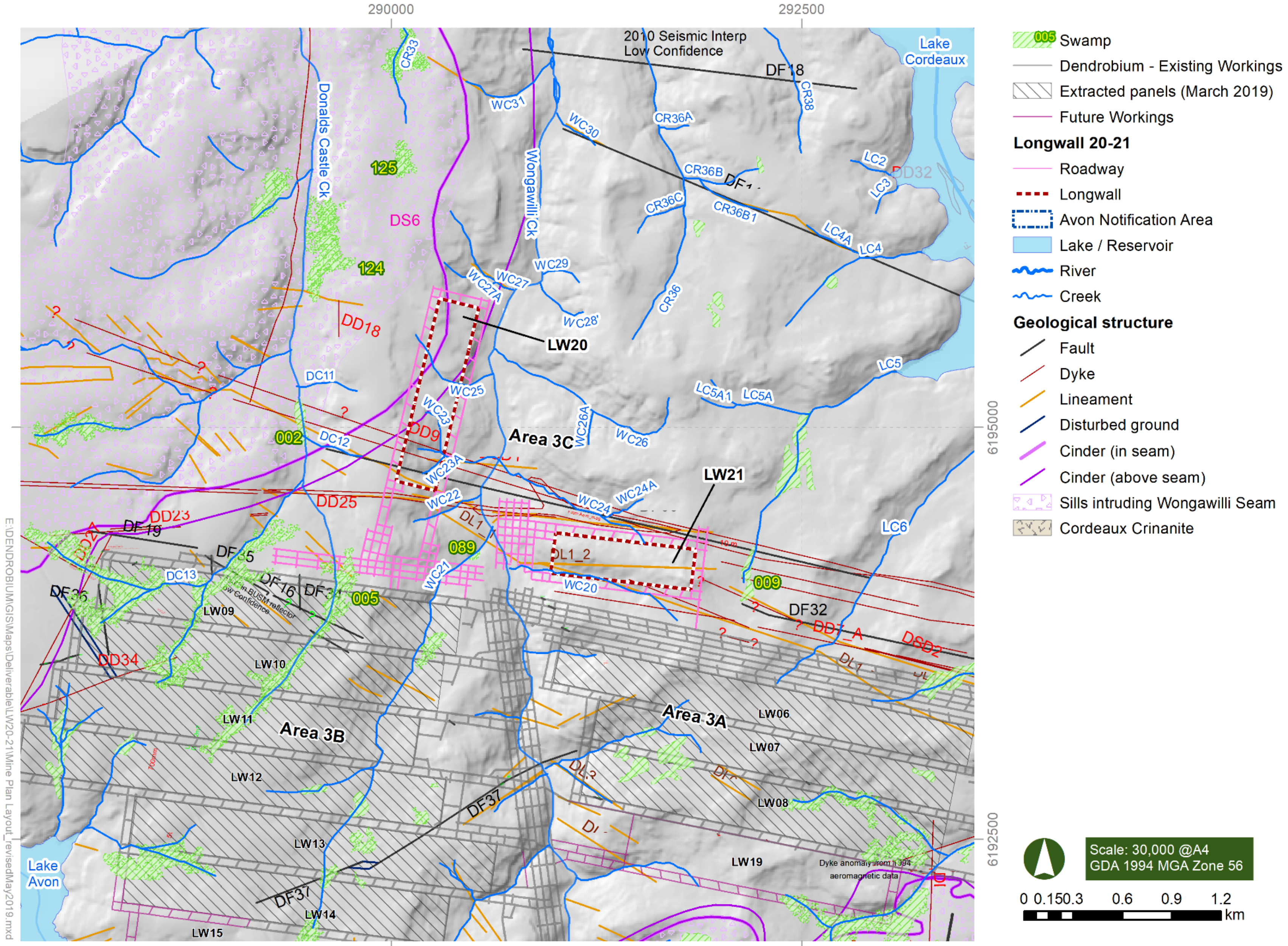

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**Figure 2** Plan of Proposed Area 3C Longwalls 20 and 21

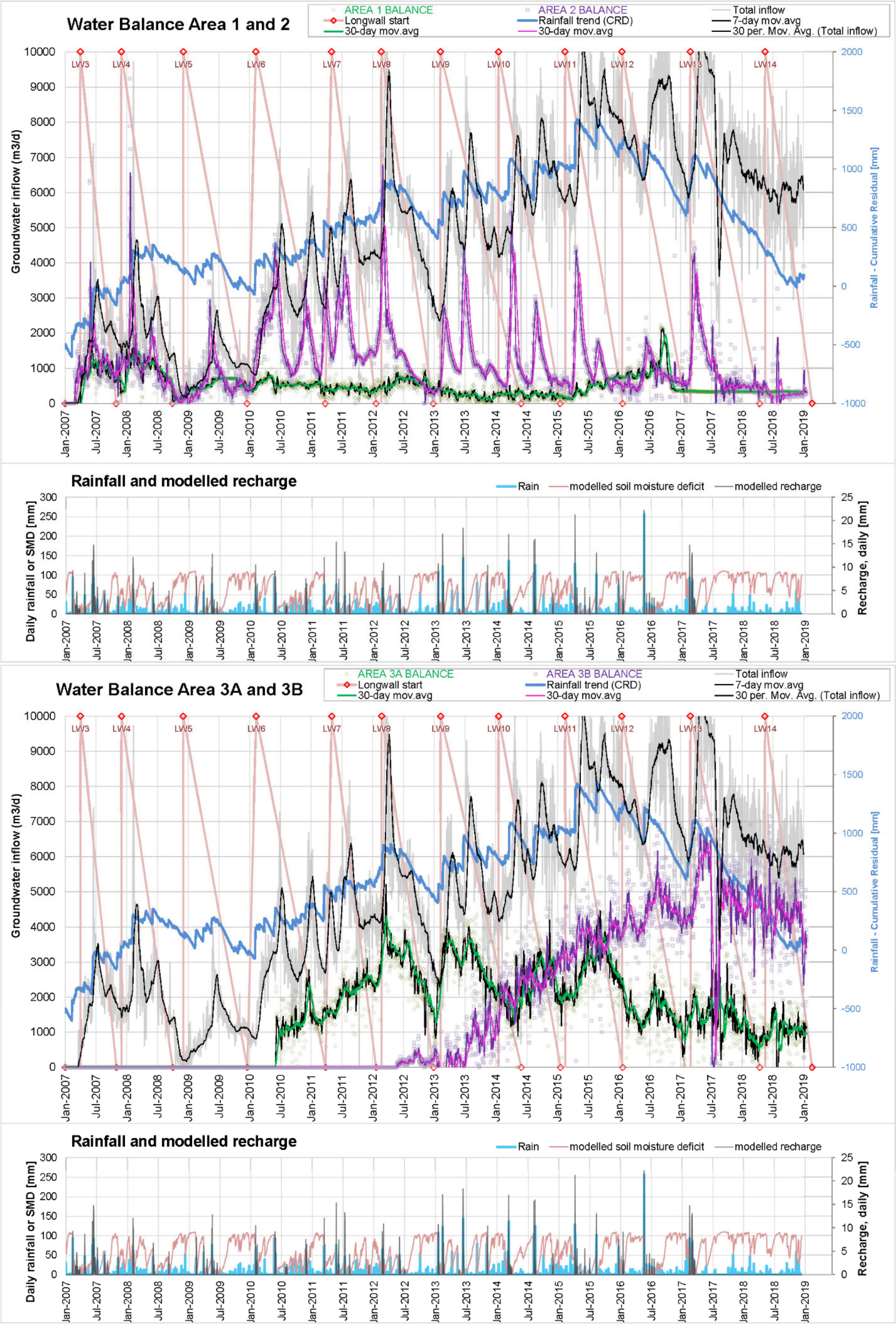

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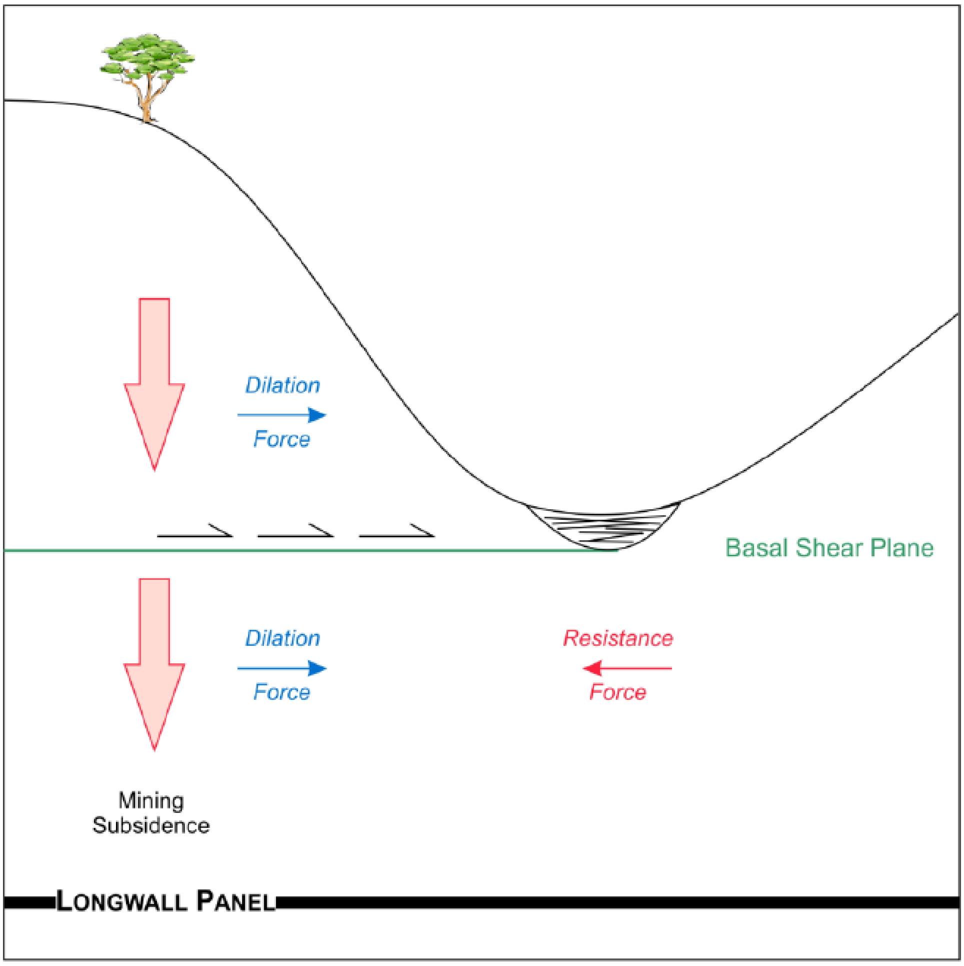
**Figure 3 Groundwater Inflow Trends by Mine Area**

A)



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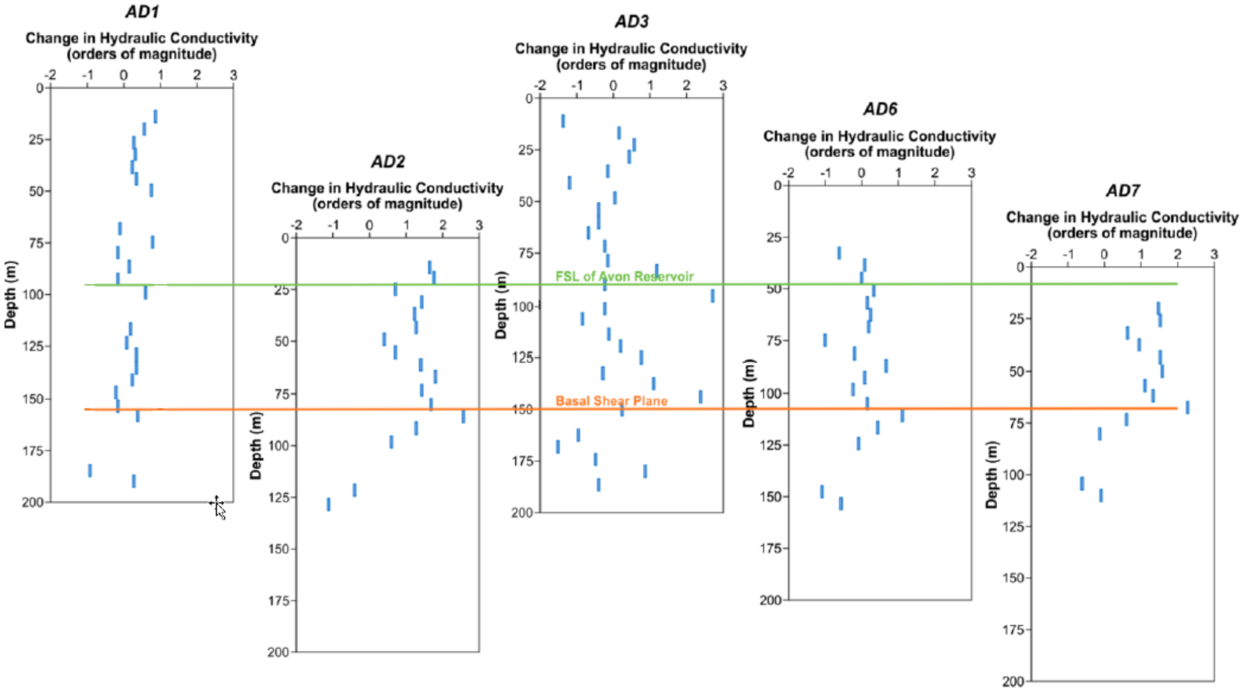
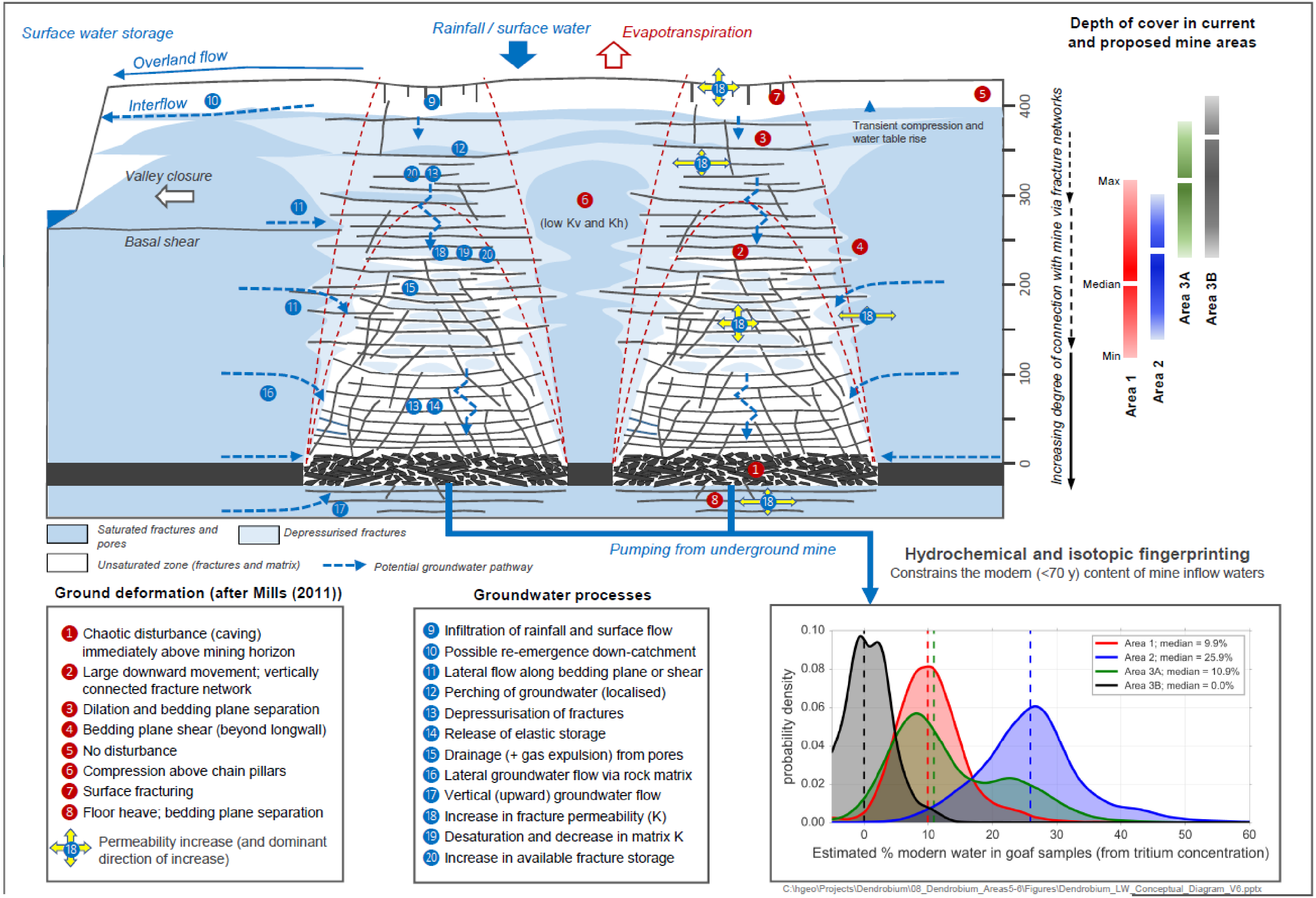


Figure 4: Changes in Hydraulic Conductivity Indicated by Packer Testing Pre to Post Mining

**Figure 4** A) Basal shear conceptual model and B) analysis of Kh changes (from SCT).



**Ground deformation (after Mills (2011))**

- ① Chaotic disturbance (caving) immediately above mining horizon
- ② Large downward movement; vertically connected fracture network
- ③ Dilation and bedding plane separation
- ④ Bedding plane shear (beyond longwall)
- ⑤ No disturbance
- ⑥ Compression above chain pillars
- ⑦ Surface fracturing
- ⑧ Floor heave; bedding plane separation
- ⑱ Permeability increase (and dominant direction of increase)

**Groundwater processes**

- ⑨ Infiltration of rainfall and surface flow
- ⑩ Possible re-emergence down-catchment
- ⑪ Lateral flow along bedding plane or shear
- ⑫ Perching of groundwater (localised)
- ⑬ Depressurisation of fractures
- ⑭ Release of elastic storage
- ⑮ Drainage (+ gas expulsion) from pores
- ⑯ Lateral groundwater flow via rock matrix
- ⑰ Vertical (upward) groundwater flow
- ⑱ Increase in fracture permeability (K)
- ⑲ Desaturation and decrease in matrix K
- ⑳ Increase in available fracture storage

Figure 5 Conceptual model: geotechnical and hydrogeological effects of mining at Dendrobium

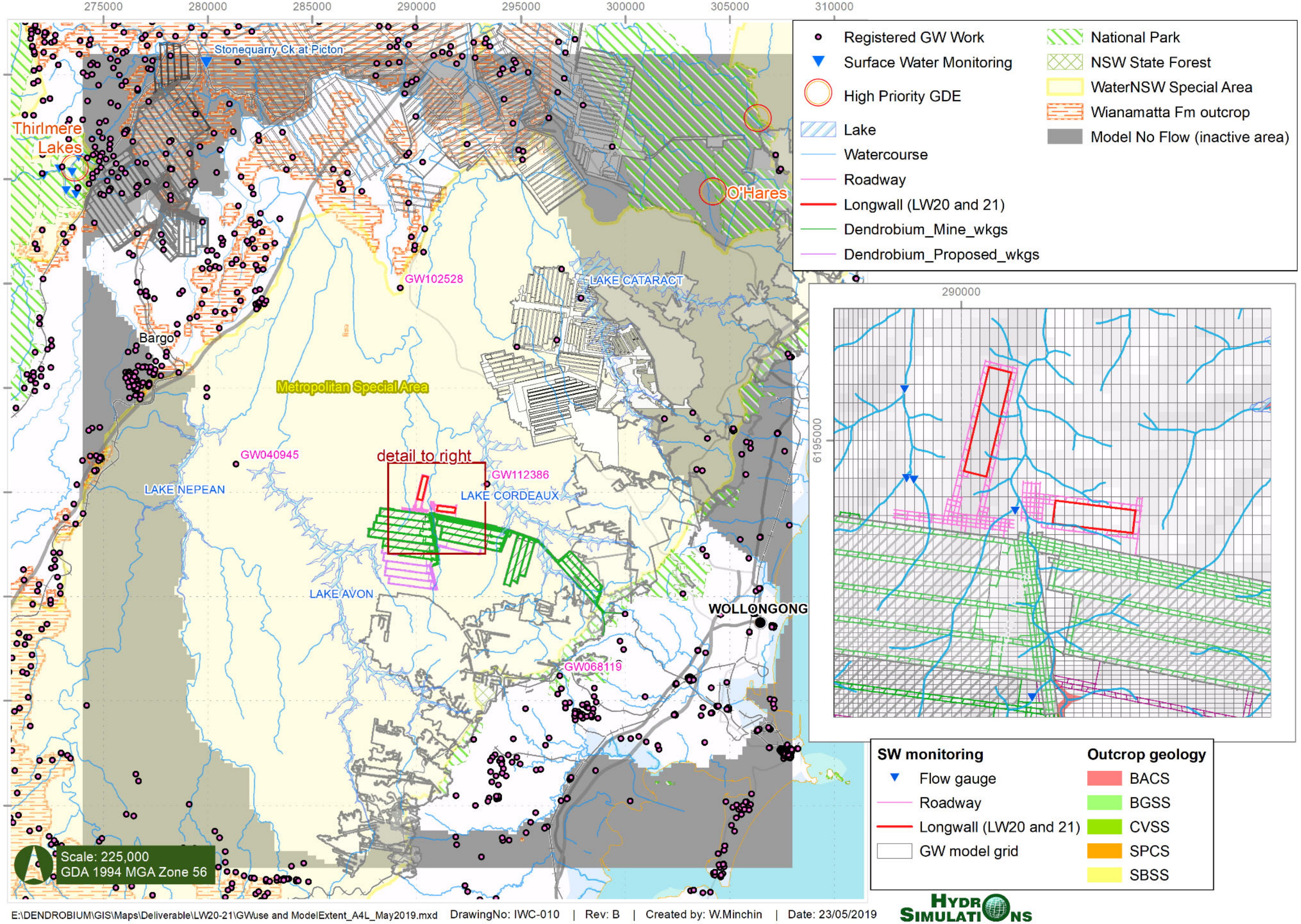


**Figure 6** **Groundwater Users and Groundwater Model Extent**

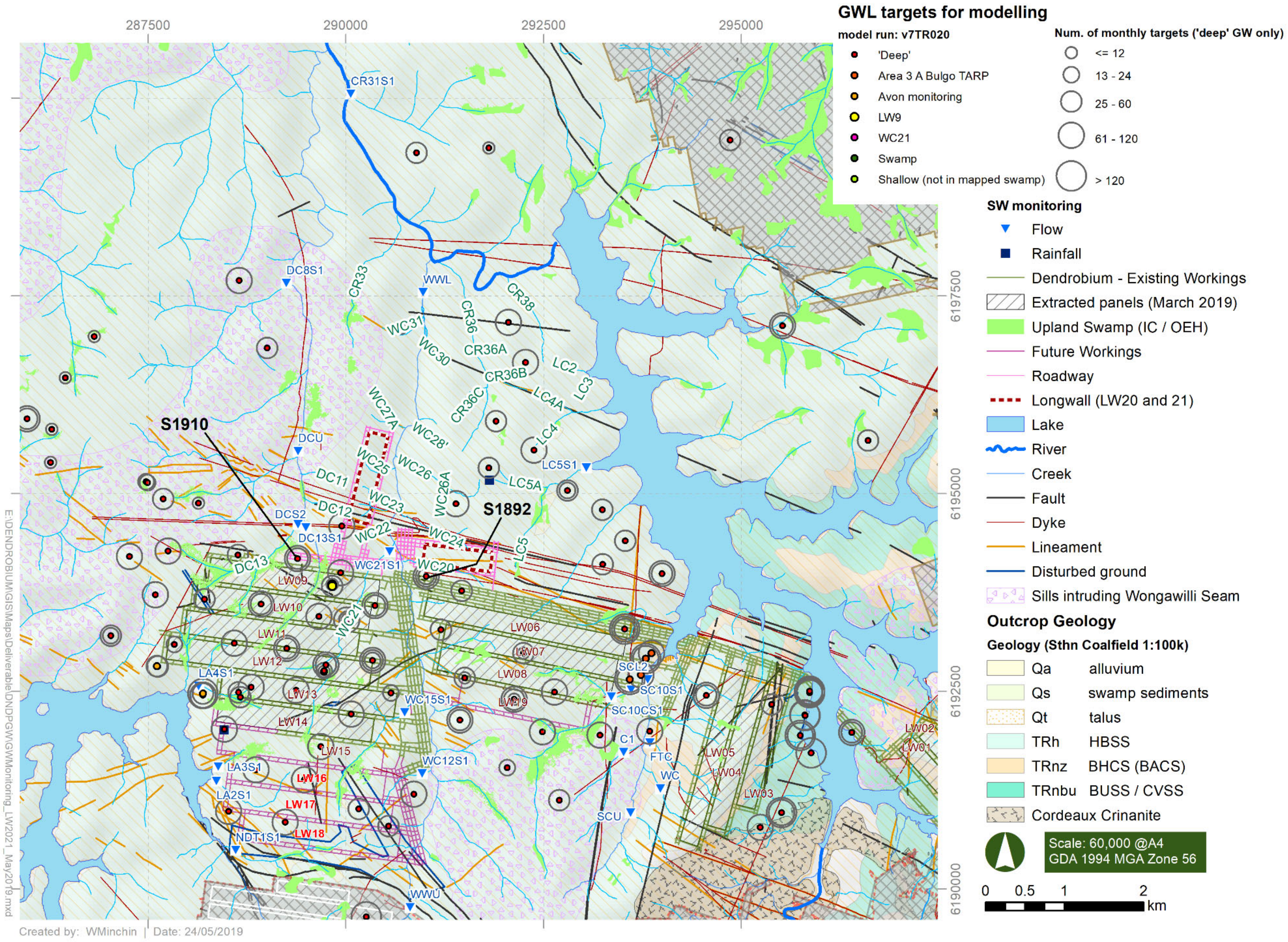


Figure 7 Monitoring and Calibration Locations

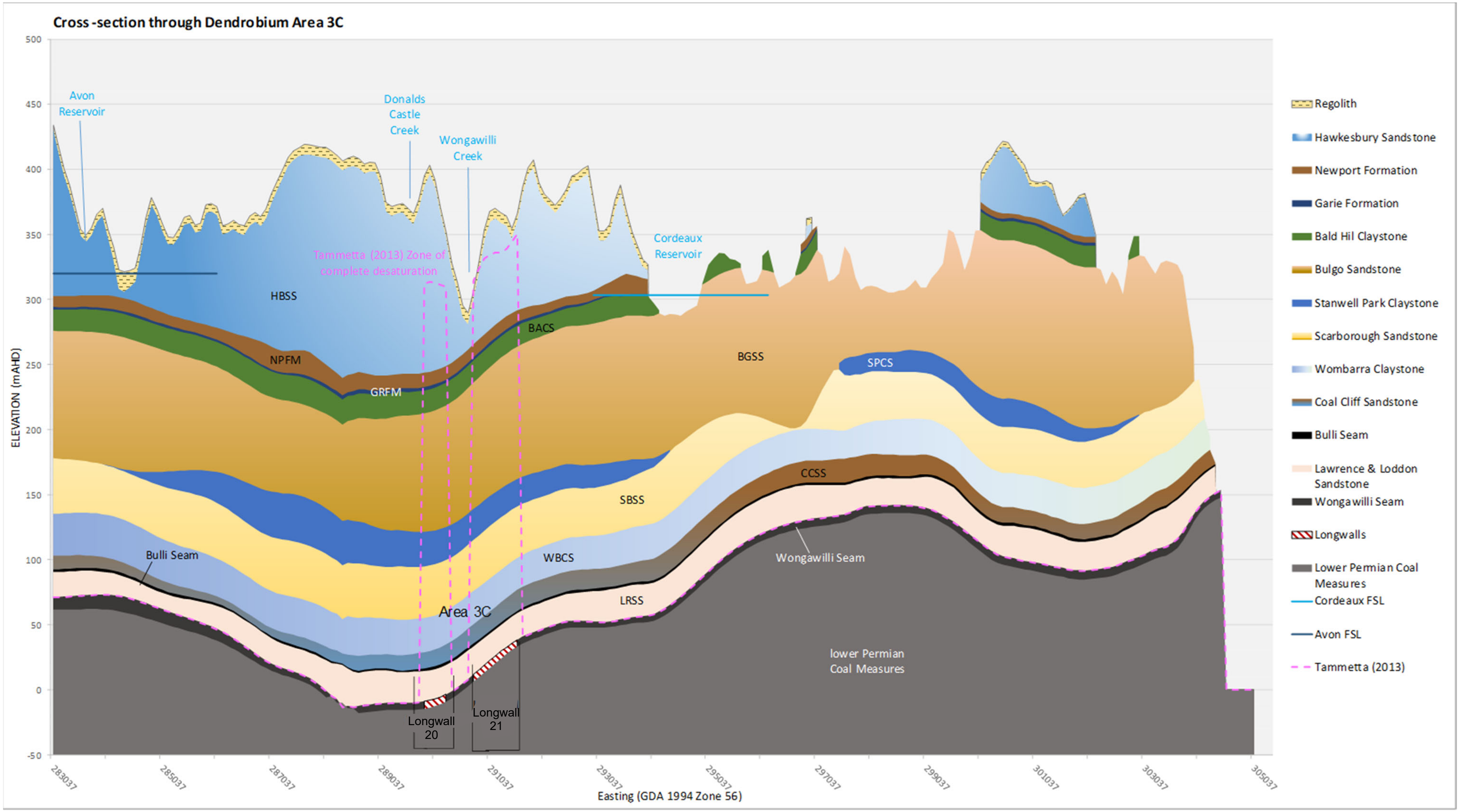


**Figure 8** Geological cross-section through Dendrobium Mine

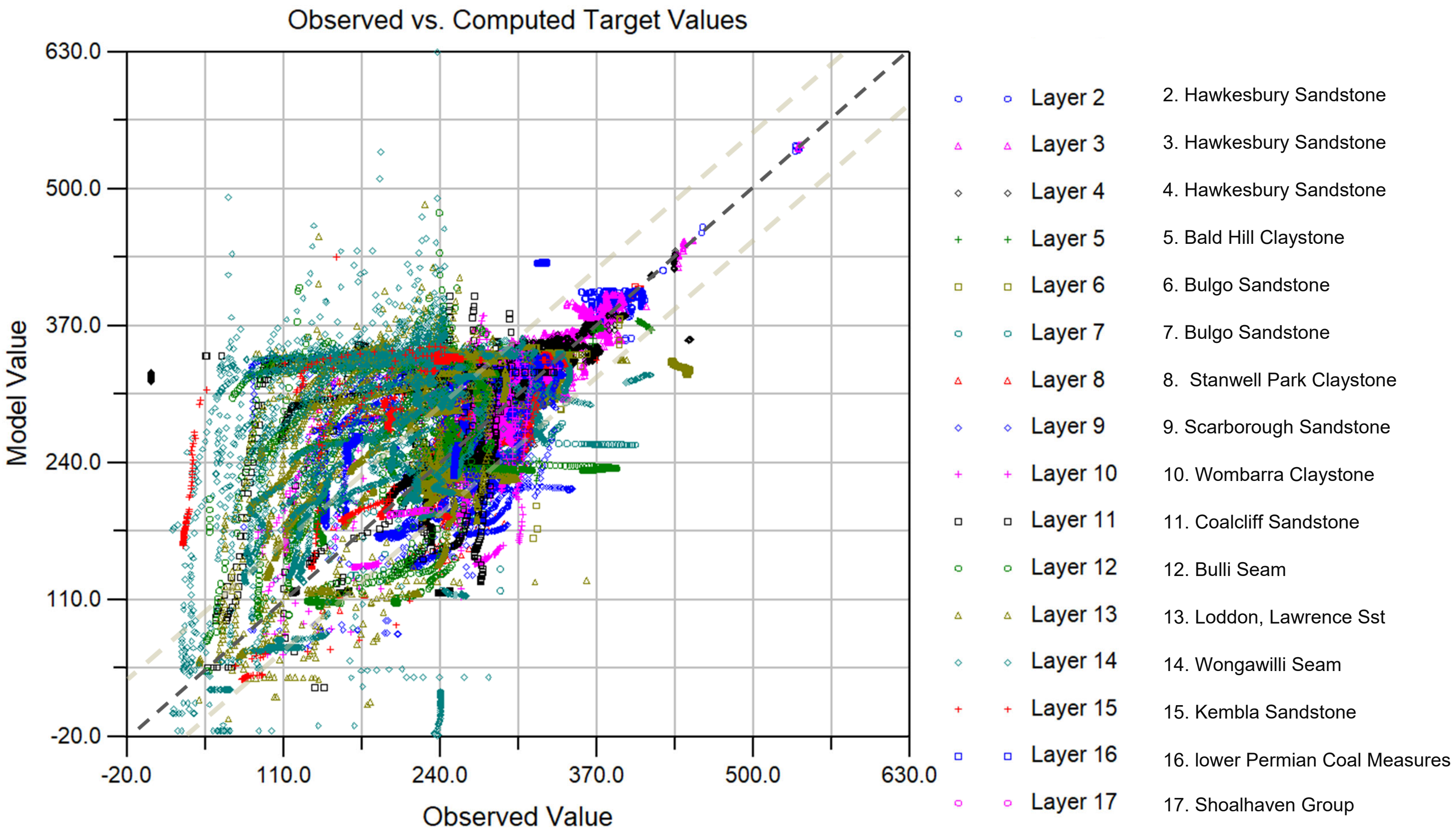


**Figure 9** **Summary of groundwater level calibration**

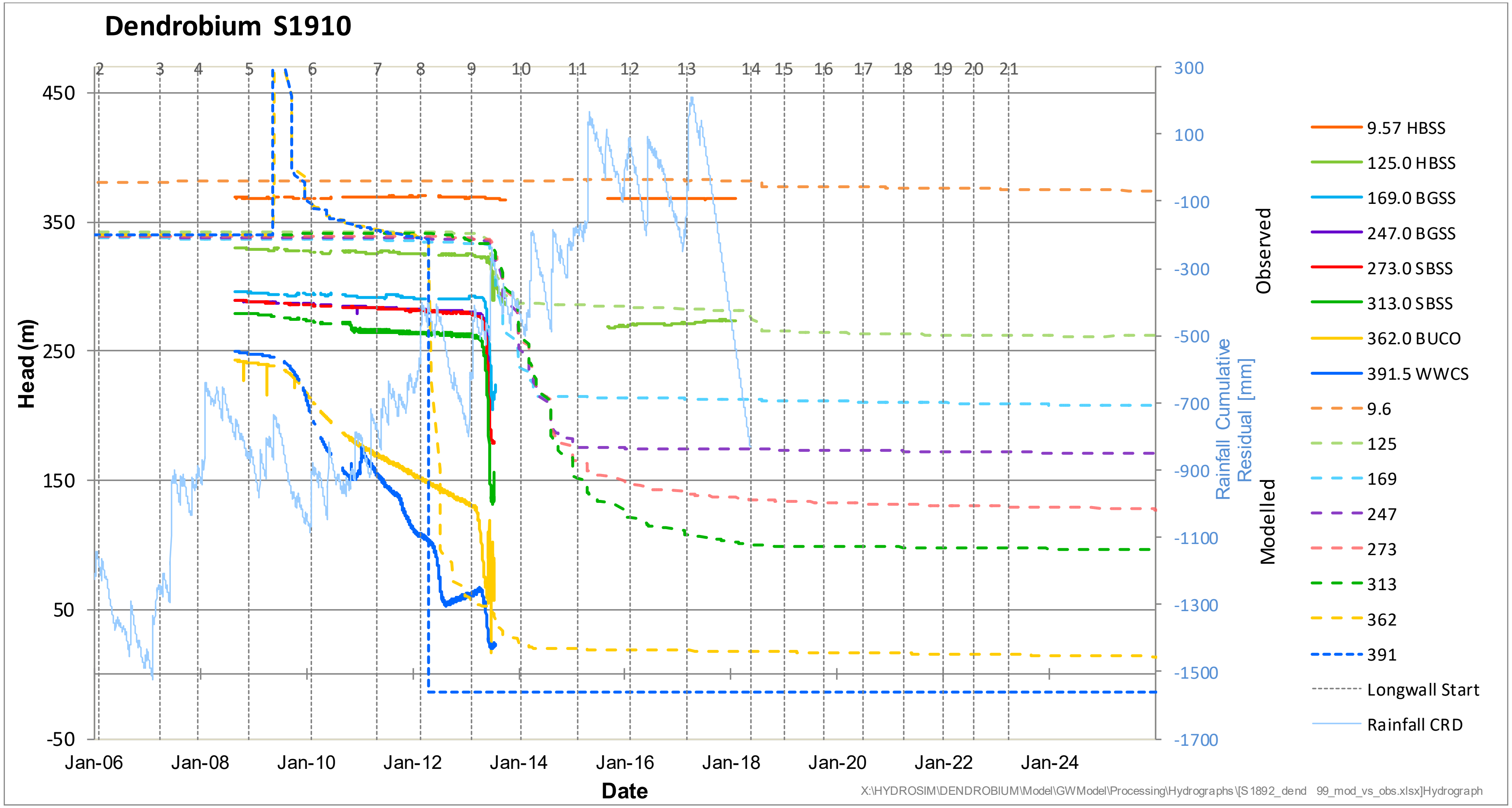


**Figure 10** Comparison of observed and modelled groundwater levels at bore S1910

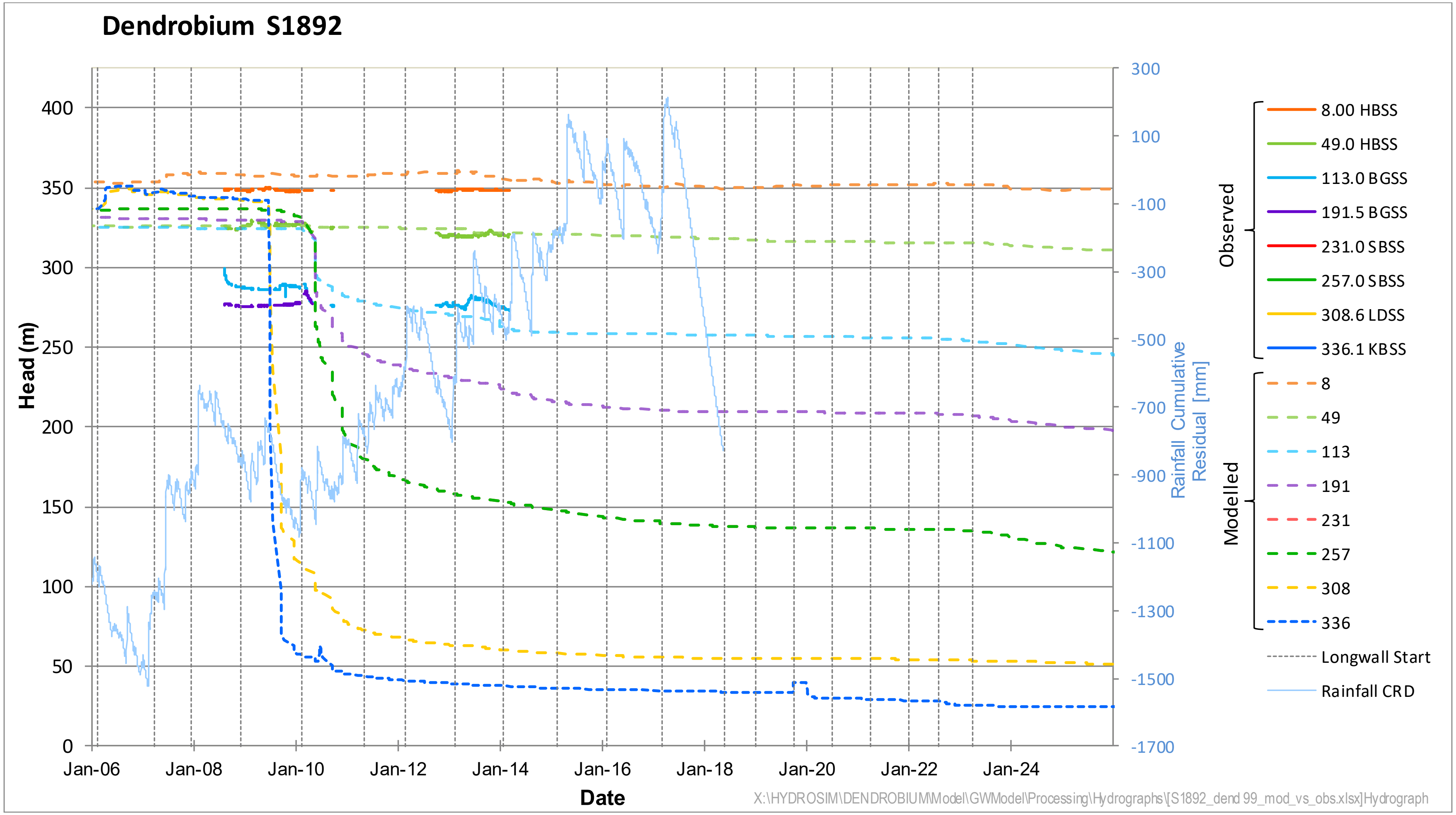


**Figure 11** Comparison of observed and modelled groundwater levels at bore S1892

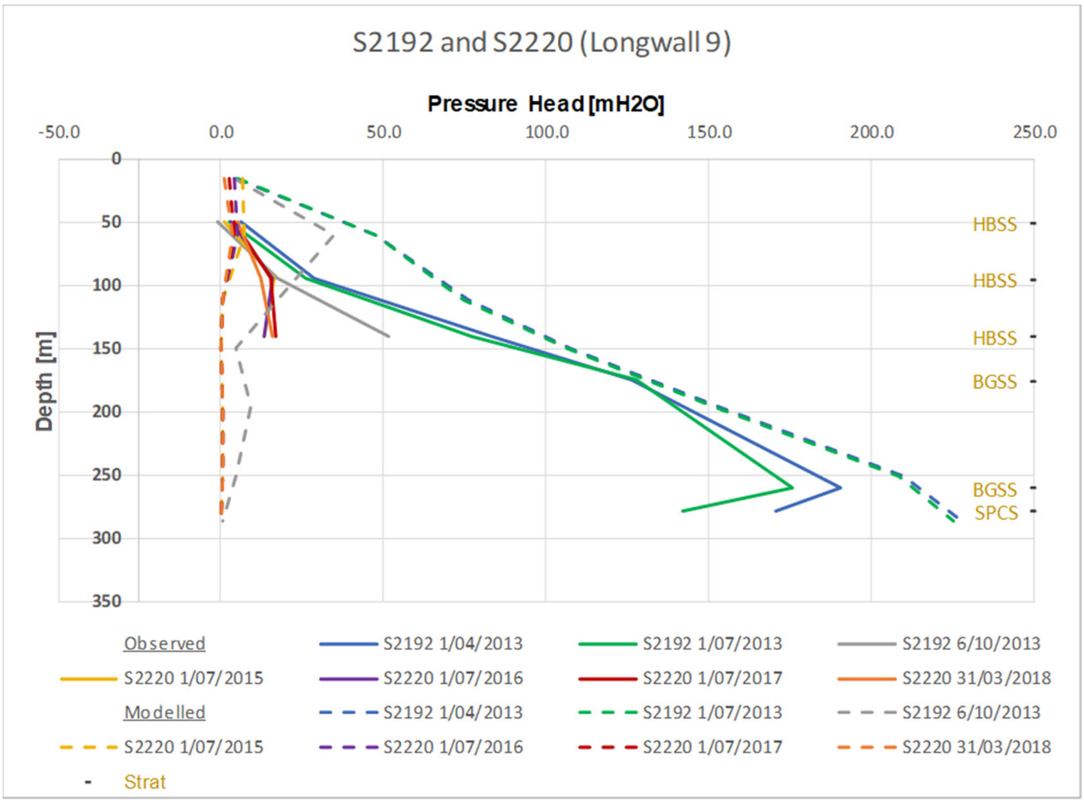


**Figure 12** Modelled and observed groundwater pressures: Area 3B, Longwall 9

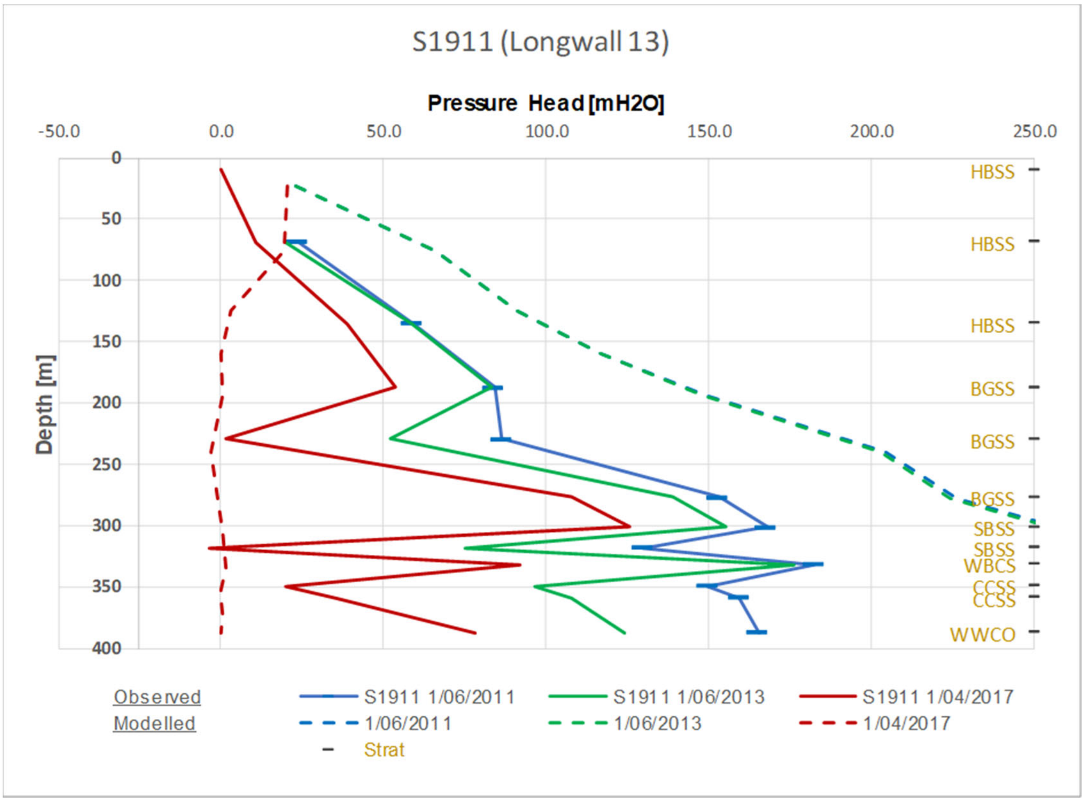


**Figure 13** Modelled and observed groundwater pressures: Area 3B, bore S1911

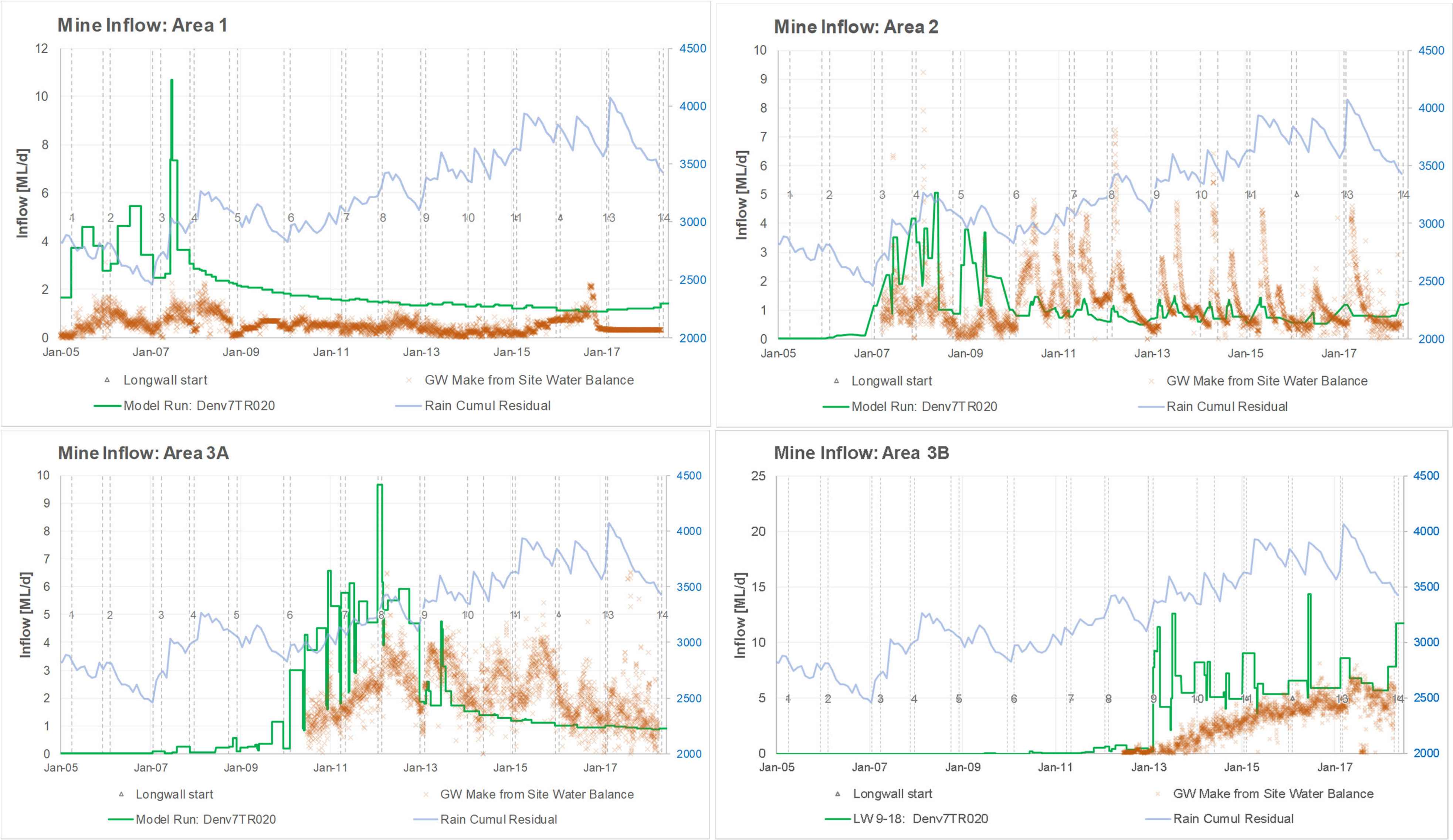


**Figure 14** **Mine inflow calibration – by Mine Area**

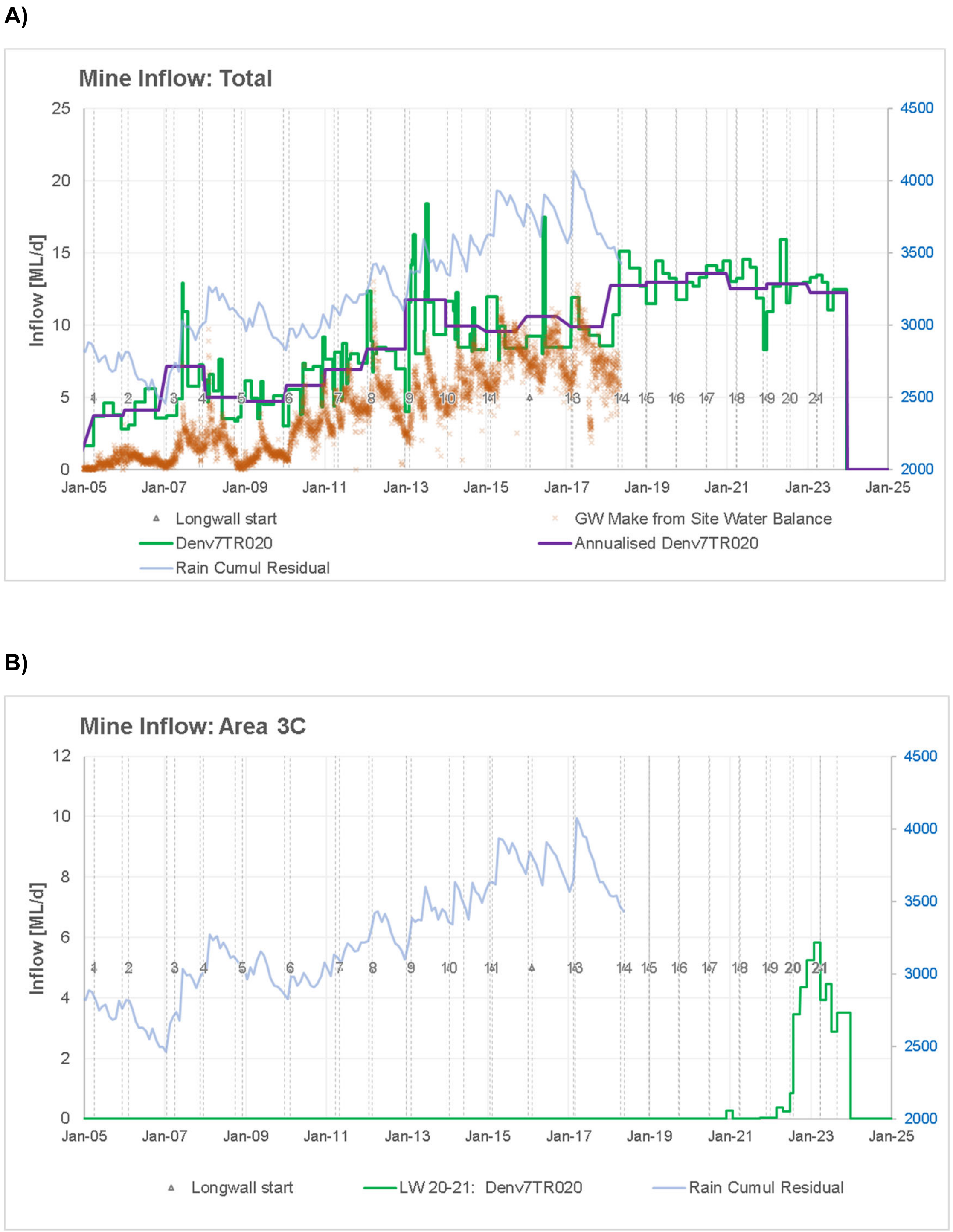


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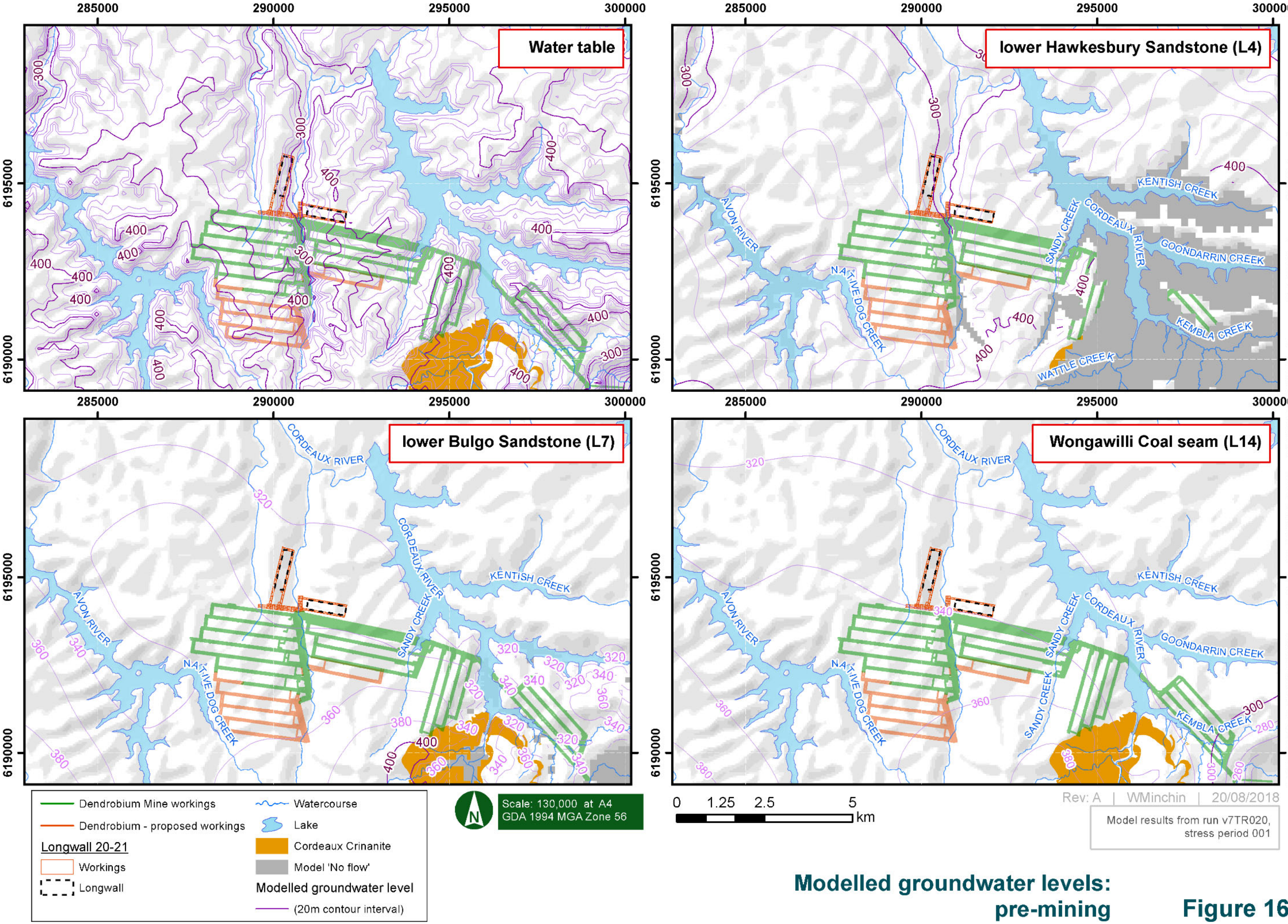
**Figure 15** Mine inflow calibration and prediction: A) whole of mine and B) Area 3C



Rev: A | WMinchin | 20/08/2018

Model results from run v7TR020, stress period 001

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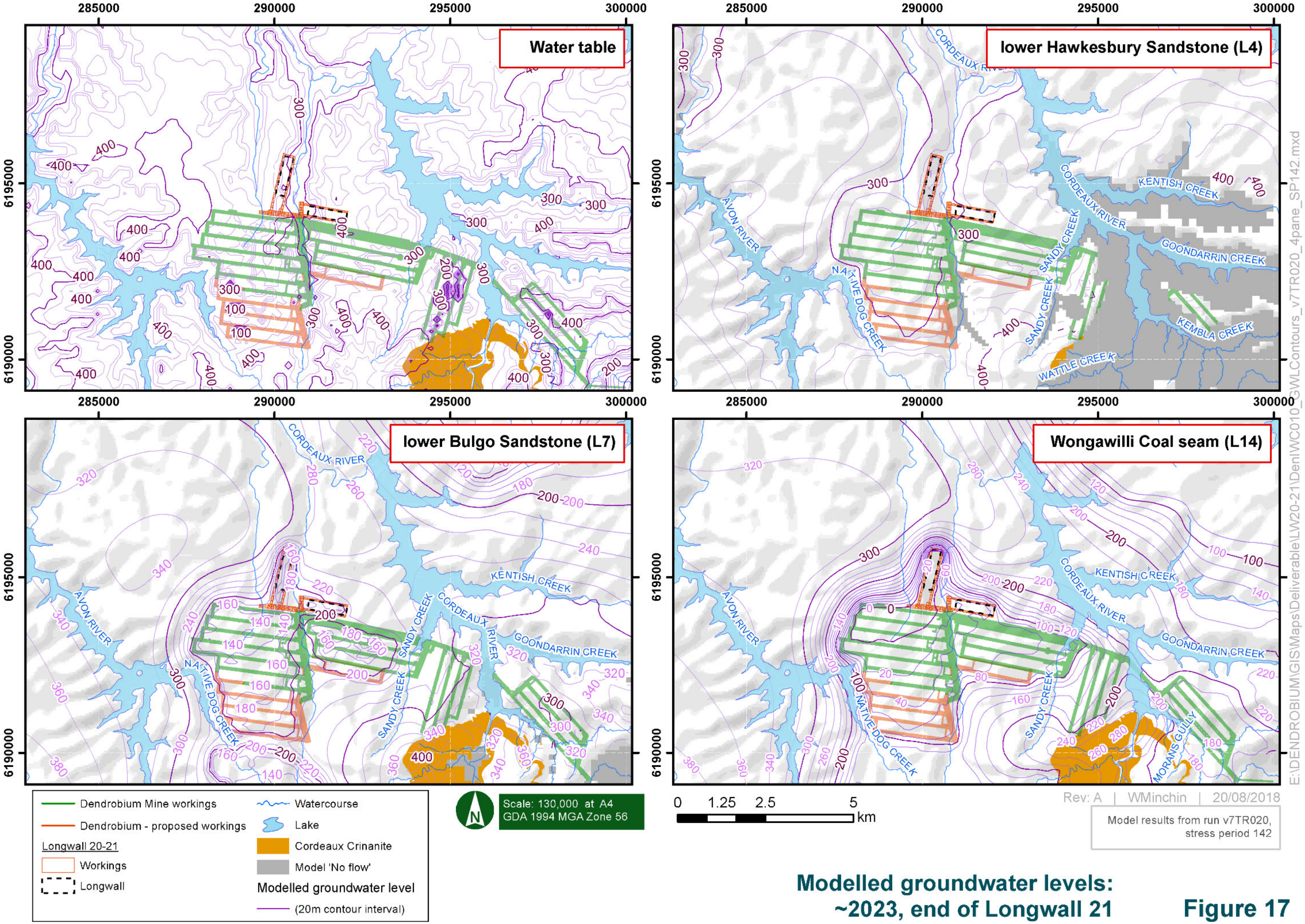
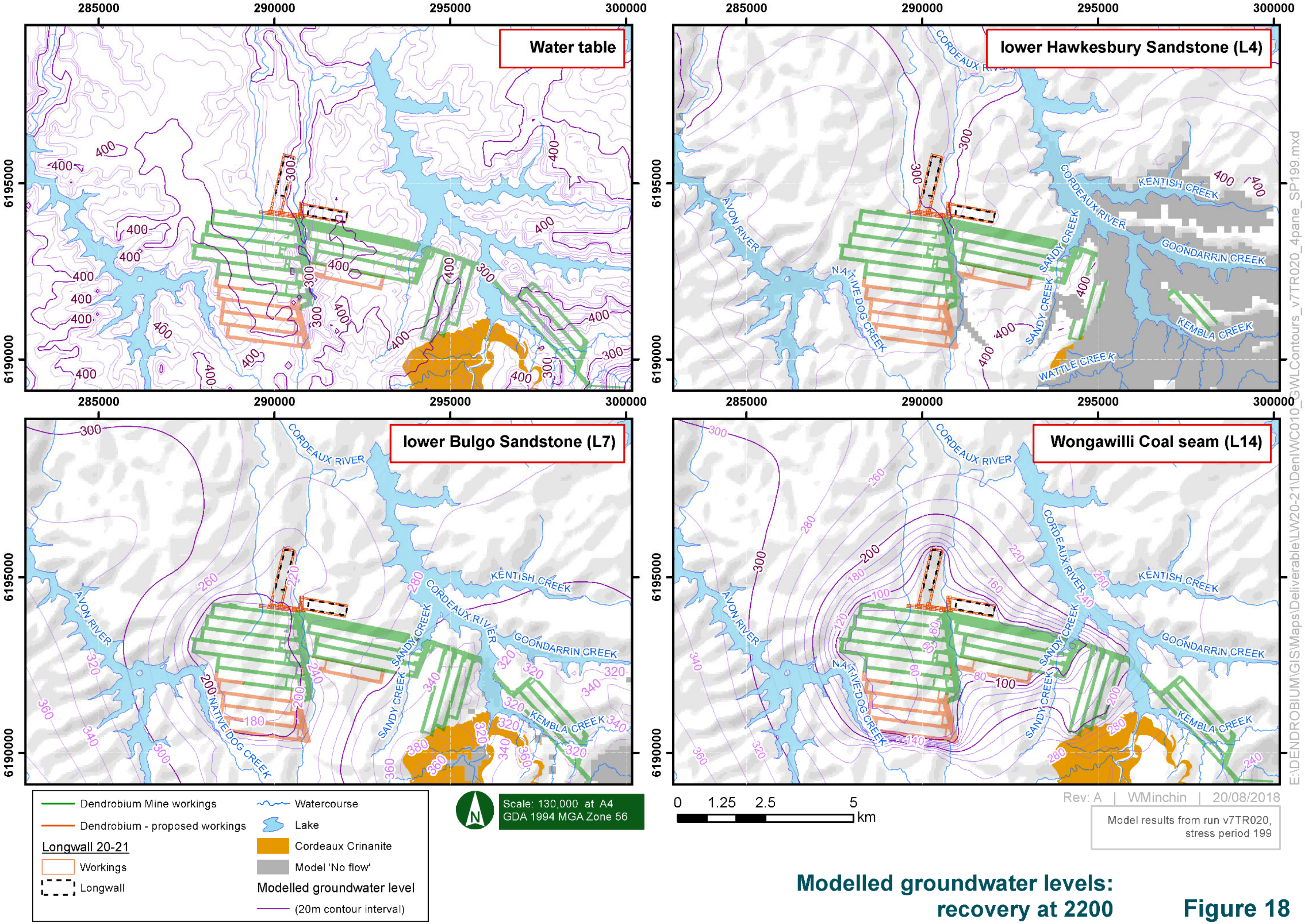
## Modelled groundwater levels: pre-mining

**Figure 16**



**Modelled groundwater levels: ~2023, end of Longwall 21**

**Figure 17**



Scale: 130,000 at A4
GDA 1994 MGA Zone 56

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Model results from run v7TR020,
stress period 199

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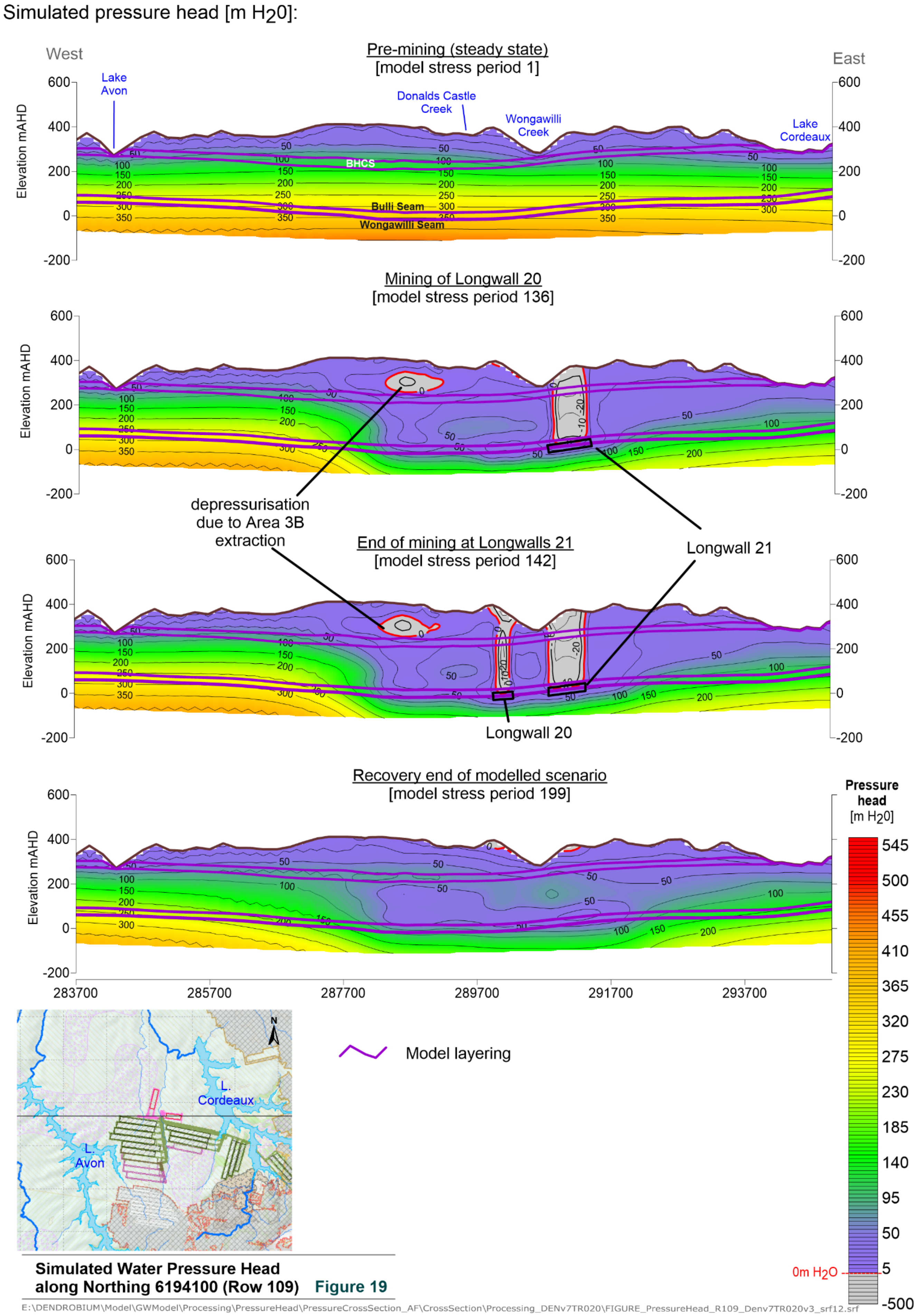
Modelled groundwater levels:
recovery at 2200

Figure 18



**Simulated Water Pressure Head along Northing 6194100 (Row 109)** **Figure 19**

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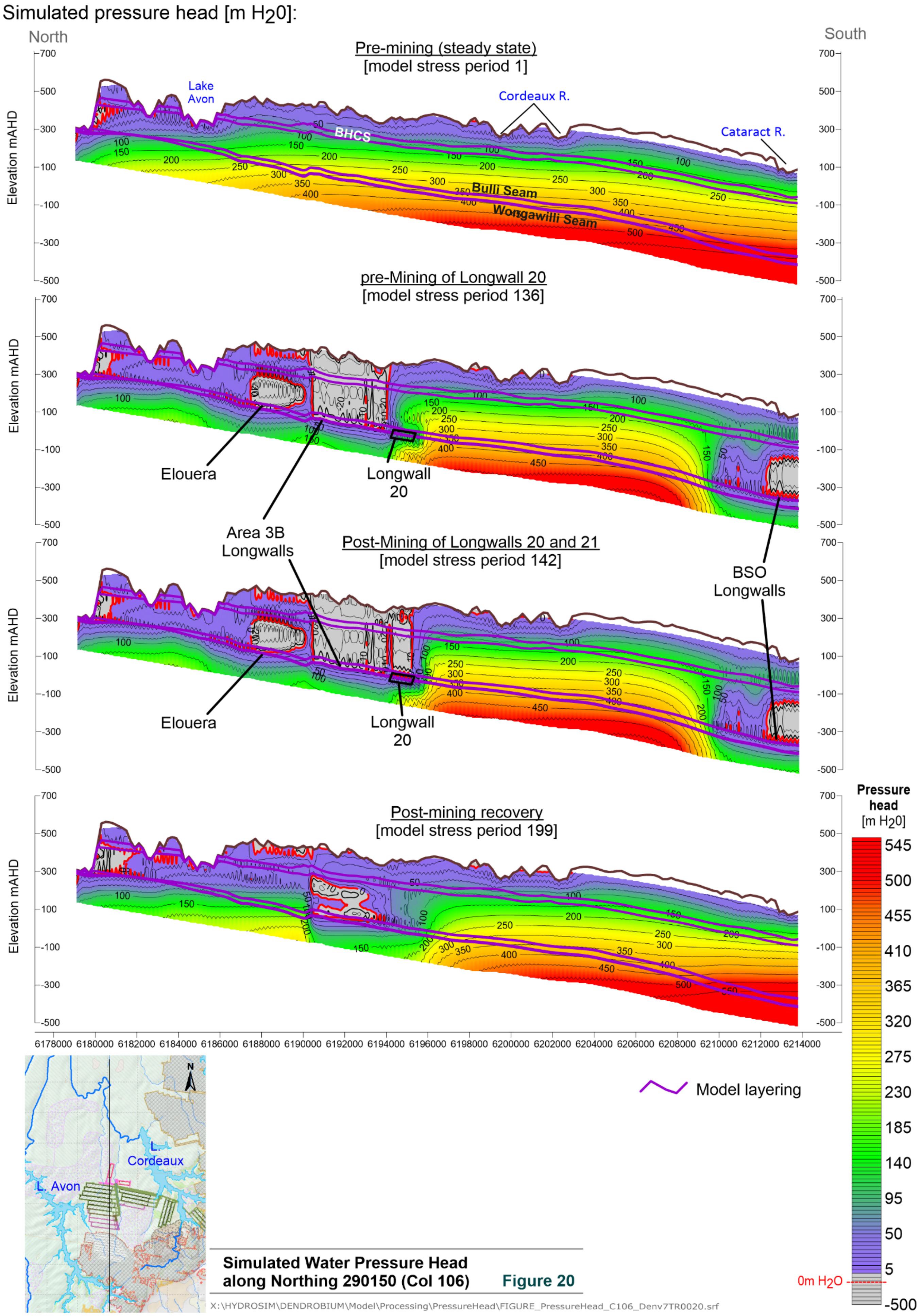

**Simulated Water Pressure Head along Northing 290150 (Col 106)** **Figure 20**

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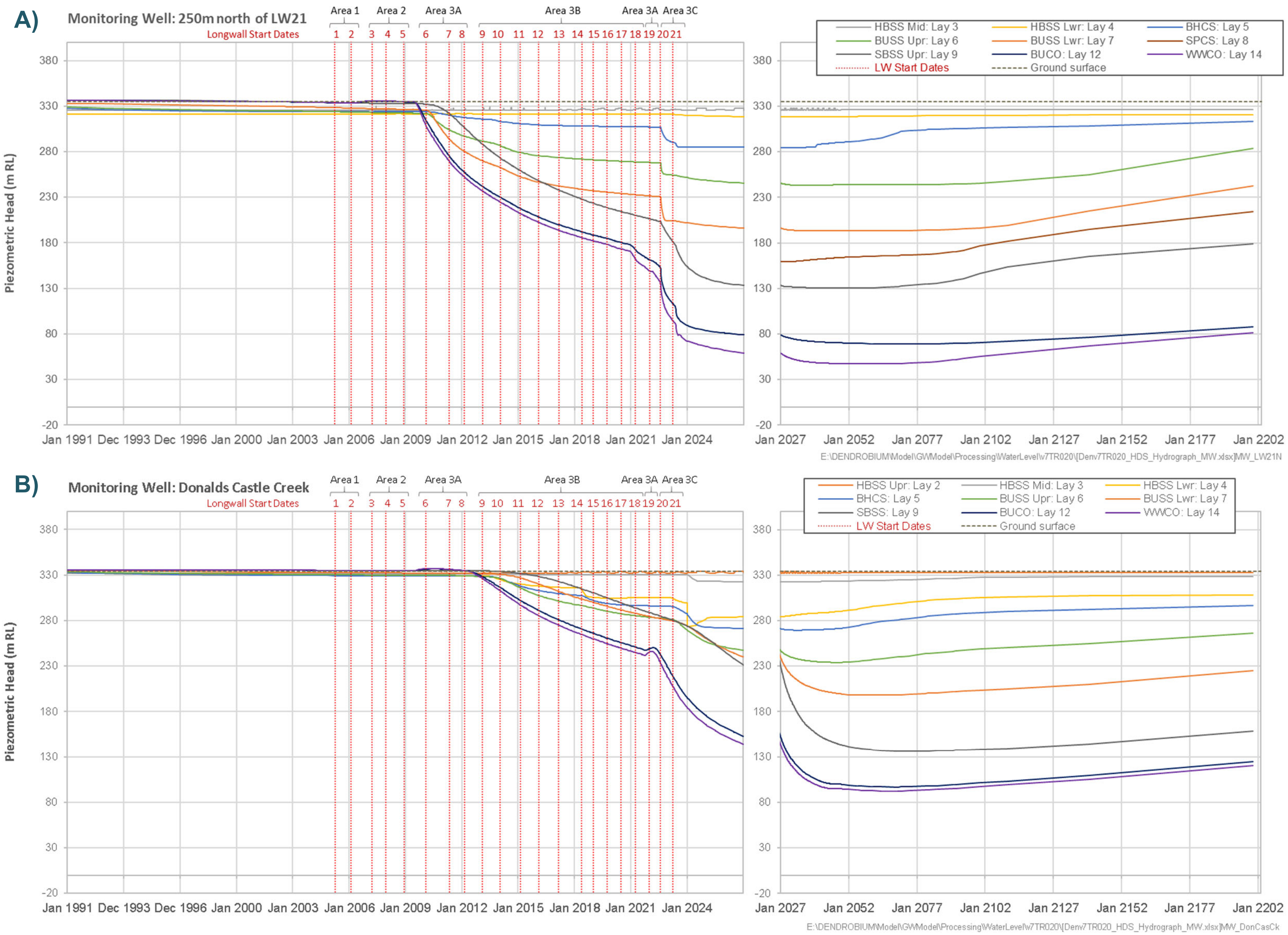

**Figure 21** **Modelled groundwater level hydrographs for Area 3C**

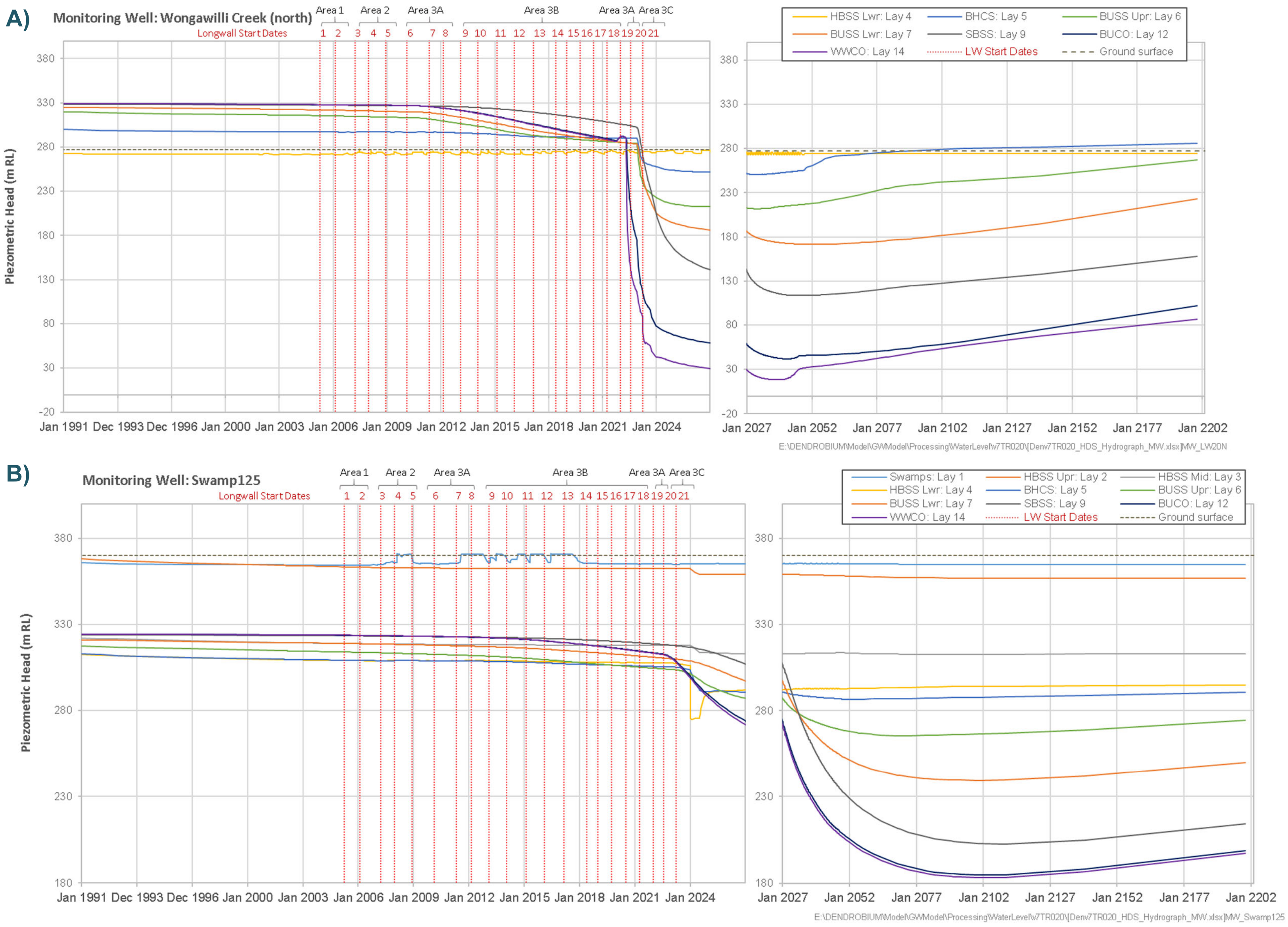

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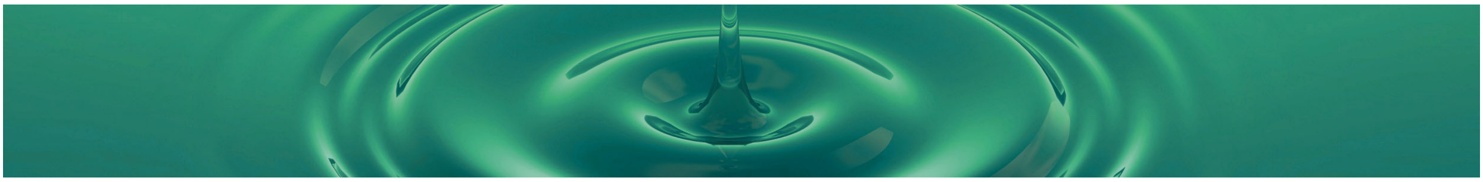
**Figure 22 Modelled groundwater level hydrographs for Area 3C**



# APPENDIX A MODEL TIMING

| StressPeriod | Days | Date From | Date To | Scheduled Mining | Comment / Rainfall-Inflow behaviour |
|---|---|---|---|---|---|
| 1 | Steady state | | | | |
| 2 | 730 | 1/01/1990 | 31/12/1991 | | |
| 3 | 3608 | 1/01/1992 | 16/11/2001 | | |
| 4 | 20 | 17/11/2001 | 6/12/2001 | | |
| 5 | 20 | 7/12/2001 | 26/12/2001 | | |
| 6 | 20 | 27/12/2001 | 15/01/2002 | | |
| 7 | 40 | 16/01/2002 | 24/02/2002 | | |
| 8 | 100 | 25/02/2002 | 4/06/2002 | | |
| 9 | 100 | 5/06/2002 | 12/09/2002 | | |
| 10 | 100 | 13/09/2002 | 21/12/2002 | | |
| 11 | 200 | 22/12/2002 | 9/07/2003 | | |
| 12 | 200 | 10/07/2003 | 25/01/2004 | | |
| 13 | 200 | 26/01/2004 | 12/08/2004 | | |
| 14 | 232 | 13/08/2004 | 1/04/2005 | Start LW1 | |
| 15 | 90 | 2/04/2005 | 30/06/2005 | | |
| 16 | 90 | 1/07/2005 | 28/09/2005 | End LW1 | |
| 17 | 74 | 29/09/2005 | 11/12/2005 | | |
| 18 | 60 | 12/12/2005 | 9/02/2006 | Start LW2 | |
| 19 | 60 | 10/02/2006 | 10/04/2006 | | |
| 20 | 95 | 11/04/2006 | 14/07/2006 | | |
| 21 | 95 | 15/07/2006 | 17/10/2006 | End LW2 | |
| 22 | 96 | 18/10/2006 | 21/01/2007 | Start LW3 | |
| 23 | 99 | 22/01/2007 | 30/04/2007 | | |
| 24 | 44 | 1/05/2007 | 13/06/2007 | | A2rain1 |
| 25 | 4 | 14/06/2007 | 17/06/2007 | | A2week1 |
| 26 | 8 | 18/06/2007 | 25/06/2007 | | A2inflow1 |
| 27 | 43 | 26/06/2007 | 7/08/2007 | End LW3 | |
| 28 | 100 | 8/08/2007 | 15/11/2007 | | |
| 29 | 33 | 16/11/2007 | 18/12/2007 | Start LW4 | |
| 30 | 47 | 19/12/2007 | 3/02/2008 | | A2 Rain2 |
| 31 | 6 | 4/02/2008 | 9/02/2008 | | A2 week2 |
| 32 | 8 | 10/02/2008 | 17/02/2008 | | A2 inflow2 |
| 33 | 36 | 18/02/2008 | 24/03/2008 | | |
| 34 | 50 | 25/03/2008 | 13/05/2008 | | |
| 35 | 32 | 14/05/2008 | 14/06/2008 | End LW4 | |
| 36 | 110 | 15/06/2008 | 2/10/2008 | | |
| 37 | 31 | 3/10/2008 | 2/11/2008 | | |
| 38 | 30 | 3/11/2008 | 2/12/2008 | Start LW5 | |
| 39 | 31 | 3/12/2008 | 2/01/2009 | | |
| 40 | 60 | 3/01/2009 | 3/03/2009 | | |
| 41 | 60 | 4/03/2009 | 2/05/2009 | | |
| 42 | 17 | 3/05/2009 | 19/05/2009 | | A2rain3 |
| 43 | 5 | 20/05/2009 | 24/05/2009 | | A2week3 |
| 44 | 8 | 25/05/2009 | 1/06/2009 | | A2inflow3 |
| 45 | 22 | 2/06/2009 | 23/06/2009 | | |
| 46 | 88 | 24/06/2009 | 19/09/2009 | End LW5 | |
| 47 | 90 | 20/09/2009 | 18/12/2009 | | |
| 48 | 53 | 19/12/2009 | 9/02/2010 | Start LW6 | |
| 49 | 105 | 10/02/2010 | 25/05/2010 | | A2rain4 |
| 50 | 10 | 26/05/2010 | 4/06/2010 | | A2week4 |
| 51 | 8 | 5/06/2010 | 12/06/2010 | | A2inflow4 |
| 52 | 22 | 13/06/2010 | 4/07/2010 | | |
| 53 | 75 | 5/07/2010 | 17/09/2010 | | |
| 54 | 72 | 18/09/2010 | 28/11/2010 | | A2rain5 |
| 55 | 9 | 29/11/2010 | 7/12/2010 | | A2week5 |
| 56 | 8 | 8/12/2010 | 15/12/2010 | | A2inflow5 |

| StressPeriod | Days | Date From | Date To | Scheduled Mining | Comment / Rainfall-Inflow behaviour |
|---|---|---|---|---|---|
| 57 | 22 | 16/12/2010 | 6/01/2011 | | |
| 58 | 71 | 7/01/2011 | 18/03/2011 | | A2rain6 |
| 59 | 4 | 19/03/2011 | 22/03/2011 | End LW6 | A2week6 |
| 60 | 8 | 23/03/2011 | 30/03/2011 | StartLW7 | A2inflow6 |
| 61 | 60 | 31/03/2011 | 29/05/2011 | | A2rain7 |
| 62 | 4 | 30/05/2011 | 2/06/2011 | | A2week7 |
| 63 | 8 | 3/06/2011 | 10/06/2011 | | A2inflow7 |
| 64 | 38 | 11/06/2011 | 18/07/2011 | | A2rain8 |
| 65 | 5 | 19/07/2011 | 23/07/2011 | | A2inflow8 |
| 66 | 8 | 24/07/2011 | 31/07/2011 | | A2inflow8 |
| 67 | 22 | 1/08/2011 | 22/08/2011 | | |
| 68 | 69 | 23/08/2011 | 30/10/2011 | End LW7 | |
| 69 | 85 | 31/10/2011 | 23/01/2012 | Start LW8 | |
| 70 | 35 | 24/01/2012 | 27/02/2012 | | A2rain9 |
| 71 | 11 | 28/02/2012 | 9/03/2012 | | A2week9 |
| 72 | 8 | 10/03/2012 | 17/03/2012 | | A2inflow9 |
| 73 | 31 | 18/03/2012 | 17/04/2012 | | |
| 74 | 85 | 18/04/2012 | 11/07/2012 | | |
| 75 | 85 | 12/07/2012 | 4/10/2012 | End LW8 | |
| 76 | 86 | 5/10/2012 | 29/12/2012 | | |
| 77 | 41 | 30/12/2012 | 8/02/2013 | Start LW9 | |
| 78 | 11 | 9/02/2013 | 19/02/2013 | | A2rain10 |
| 79 | 12 | 20/02/2013 | 3/03/2013 | | A2week10 |
| 80 | 8 | 4/03/2013 | 11/03/2013 | | A2inflow10 |
| 81 | 22 | 12/03/2013 | 2/04/2013 | | |
| 82 | 80 | 3/04/2013 | 21/06/2013 | | A2rain11 |
| 83 | 9 | 22/06/2013 | 30/06/2013 | | A2week11 |
| 84 | 8 | 1/07/2013 | 8/07/2013 | | A2inflow11 |
| 85 | 22 | 9/07/2013 | 30/07/2013 | | |
| 86 | 48 | 31/07/2013 | 16/09/2013 | End LW9 | |
| 87 | 106 | 17/09/2013 | 31/12/2013 | Start LW10 | |
| 88 | 77 | 1/01/2014 | 18/03/2014 | | A2rain12 |
| 89 | 13 | 19/03/2014 | 31/03/2014 | | A2week12 |
| 90 | 8 | 1/04/2014 | 8/04/2014 | | A2inflow12 |
| 91 | 22 | 9/04/2014 | 30/04/2014 | | |
| 92 | 107 | 1/05/2014 | 15/08/2014 | | A2rain13 |
| 93 | 12 | 16/08/2014 | 27/08/2014 | | A2week13 |
| 94 | 8 | 28/08/2014 | 4/09/2014 | | A2inflow13 |
| 95 | 22 | 5/09/2014 | 26/09/2014 | End LW10 | |
| 96 | 106 | 27/09/2014 | 10/01/2015 | Start LW11 | |
| 97 | 96 | 11/01/2015 | 16/04/2015 | | A2rain14 |
| 98 | 16 | 17/04/2015 | 2/05/2015 | | A2week14 |
| 99 | 8 | 3/05/2015 | 10/05/2015 | | A2inflow14 |
| 100 | 45 | 11/05/2015 | 24/06/2015 | End LW11 | |
| 101 | 196 | 25/06/2015 | 6/01/2016 | Start LW 12 | |
| 102 | 149 | 7/01/2016 | 3/06/2016 | | rain15 |
| 103 | 7 | 4/06/2016 | 10/06/2016 | | |
| 104 | 20 | 11/06/2016 | 30/06/2016 | End LW 12 | |
| 105 | 233 | 1/07/2016 | 18/02/2017 | Start LW 13 | |
| 106 | 71 | 19/02/2017 | 30/04/2017 | | |
| 107 | 92 | 1/05/2017 | 31/07/2017 | | |
| 108 | 92 | 1/08/2017 | 31/10/2017 | End LW 13 | |
| 109 | 120 | 1/11/2017 | 28/02/2018 | Start LW 14 | |
| 110 | 61 | 1/03/2018 | 30/04/2018 | | |
| 111 | 92 | 1/05/2018 | 31/07/2018 | | |
| 112 | 92 | 1/08/2018 | 31/10/2018 | End LW 14 | |

| StressPeriod | Days | Date From | Date To | Scheduled Mining | Comment / Rainfall-Inflow behaviour |
|---|---|---|---|---|---|
| 113 | 61 | 1/11/2018 | 31/12/2018 | Start LW 15 | |
| 114 | 90 | 1/01/2019 | 31/03/2019 | | |
| 115 | 61 | 1/04/2019 | 31/05/2019 | | |
| 116 | 61 | 1/06/2019 | 31/07/2019 | End LW 15 | |
| 117 | 61 | 1/08/2019 | 30/09/2019 | Start LW 16 | |
| 118 | 92 | 1/10/2019 | 31/12/2019 | | |
| 119 | 59 | 1/01/2020 | 28/02/2020 | | |
| 120 | 62 | 29/02/2020 | 30/04/2020 | End LW 16 | |
| 121 | 61 | 1/05/2020 | 30/06/2020 | Start LW 17 | |
| 122 | 92 | 1/07/2020 | 30/09/2020 | | |
| 123 | 61 | 1/10/2020 | 30/11/2020 | | |
| 124 | 62 | 1/12/2020 | 31/01/2021 | End LW 17 | |
| 125 | 59 | 1/02/2021 | 31/03/2021 | Start LW 18 | |
| 126 | 61 | 1/04/2021 | 31/05/2021 | | |
| 127 | 61 | 1/06/2021 | 31/07/2021 | | |
| 128 | 61 | 1/08/2021 | 30/09/2021 | End LW 18 | |
| 129 | 61 | 1/10/2021 | 30/11/2021 | | |
| 130 | 31 | 1/12/2021 | 31/12/2021 | Start LW 19 | |
| 131 | 59 | 1/01/2022 | 28/02/2022 | LW20-21 development | |
| 132 | 61 | 1/03/2022 | 30/04/2022 | End LW 19 | |
| 133 | 61 | 1/05/2022 | 30/06/2022 | | |
| 134 | 31 | 1/07/2022 | 31/07/2022 | | |
| 135 | 61 | 1/08/2022 | 30/09/2022 | Start LW 20 | |
| 136 | 61 | 1/10/2022 | 30/11/2022 | | |
| 137 | 62 | 1/12/2022 | 31/01/2023 | | |
| 138 | 59 | 1/02/2023 | 31/03/2023 | End LW 20 | |
| 139 | 50 | 1/04/2023 | 20/05/2023 | Start LW 21 | |
| 140 | 51 | 21/05/2023 | 10/07/2023 | | |
| 141 | 52 | 11/07/2023 | 31/08/2023 | End LW 21 | |
| 142 | 122 | 1/09/2023 | 31/12/2023 | | |
| 143 | 182 | 1/01/2024 | 30/06/2024 | | |
| 144 | 184 | 1/07/2024 | 31/12/2024 | | |
| 145 | 181 | 1/01/2025 | 30/06/2025 | | |
| 146 | 184 | 1/07/2025 | 31/12/2025 | | |
| 147 | 181 | 1/01/2026 | 30/06/2026 | | |
| 148 | 184 | 1/07/2026 | 31/12/2026 | | |
| 149 | 181 | 1/01/2027 | 30/06/2027 | | |
| 150 | 184 | 1/07/2027 | 31/12/2027 | | |
| 151 | 182 | 1/01/2028 | 30/06/2028 | | |
| 152 | 184 | 1/07/2028 | 31/12/2028 | | |
| 153 | 181 | 1/01/2029 | 30/06/2029 | | |
| 154 | 184 | 1/07/2029 | 31/12/2029 | | |
| 155 | 181 | 1/01/2030 | 30/06/2030 | | |
| 156 | 184 | 1/07/2030 | 31/12/2030 | | |
| 157 | 181 | 1/01/2031 | 30/06/2031 | | |
| 158 | 184 | 1/07/2031 | 31/12/2031 | | |
| 159 | 182 | 1/01/2032 | 30/06/2032 | | |
| 160 | 184 | 1/07/2032 | 31/12/2032 | | |
| 161 | 181 | 1/01/2033 | 30/06/2033 | | |
| 162 | 184 | 1/07/2033 | 31/12/2033 | | |
| 163 | 181 | 1/01/2034 | 30/06/2034 | | |
| 164 | 184 | 1/07/2034 | 31/12/2034 | | |
| 165 | 181 | 1/01/2035 | 30/06/2035 | | |
| 166 | 184 | 1/07/2035 | 31/12/2035 | | |
| 167 | 182 | 1/01/2036 | 30/06/2036 | | |
| 168 | 184 | 1/07/2036 | 31/12/2036 | | |

| StressPeriod | Days | Date From | Date To | Scheduled Mining | Comment / Rainfall-Inflow behaviour |
|---|---|---|---|---|---|
| 169 | 181 | 1/01/2037 | 30/06/2037 | | |
| 170 | 184 | 1/07/2037 | 31/12/2037 | | |
| 171 | 181 | 1/01/2038 | 30/06/2038 | | |
| 172 | 184 | 1/07/2038 | 31/12/2038 | | |
| 173 | 181 | 1/01/2039 | 30/06/2039 | | |
| 174 | 184 | 1/07/2039 | 31/12/2039 | | |
| 175 | 182 | 1/01/2040 | 30/06/2040 | | |
| 176 | 184 | 1/07/2040 | 31/12/2040 | | |
| 177 | 181 | 1/01/2041 | 30/06/2041 | | |
| 178 | 184 | 1/07/2041 | 31/12/2041 | | |
| 179 | 181 | 1/01/2042 | 30/06/2042 | | |
| 180 | 184 | 1/07/2042 | 31/12/2042 | | |
| 181 | 181 | 1/01/2043 | 30/06/2043 | | |
| 182 | 184 | 1/07/2043 | 31/12/2043 | | |
| 183 | 182 | 1/01/2044 | 30/06/2044 | | |
| 184 | 184 | 1/07/2044 | 31/12/2044 | | |
| 185 | 181 | 1/01/2045 | 30/06/2045 | | |
| 186 | 184 | 1/07/2045 | 31/12/2045 | | |
| 187 | 181 | 1/01/2046 | 30/06/2046 | | |
| 188 | 184 | 1/07/2046 | 31/12/2046 | | |
| 189 | 181 | 1/01/2047 | 30/06/2047 | | |
| 190 | 184 | 1/07/2047 | 31/12/2047 | | |
| 191 | 366 | 1/01/2048 | 31/12/2048 | | |
| 192 | 365 | 1/01/2049 | 31/12/2049 | | |
| 193 | 1096 | 1/01/2050 | 31/12/2052 | Approx. 30-year post A3C mining (as per Condition of Approval) | |
| 194 | 2556 | 1/01/2053 | 31/12/2059 | | |
| 195 | 3653 | 1/01/2060 | 31/12/2069 | | |
| 196 | 3652 | 1/01/2070 | 31/12/2079 | | |
| 197 | 3653 | 1/01/2080 | 31/12/2089 | | |
| 198 | 3652 | 1/01/2090 | 31/12/2099 | | |
| 199 | 36525 | 1/01/2100 | 1/01/2200 | | |

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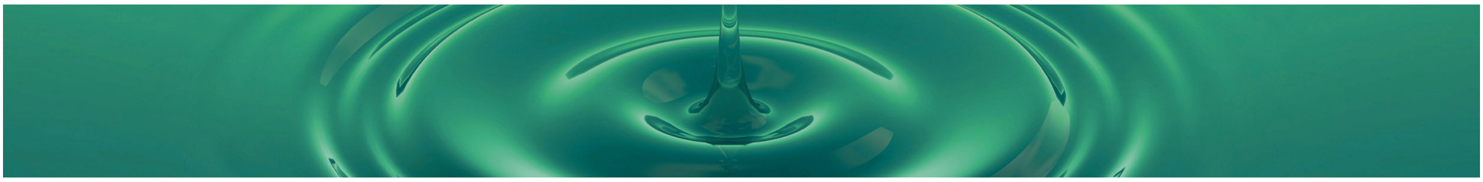
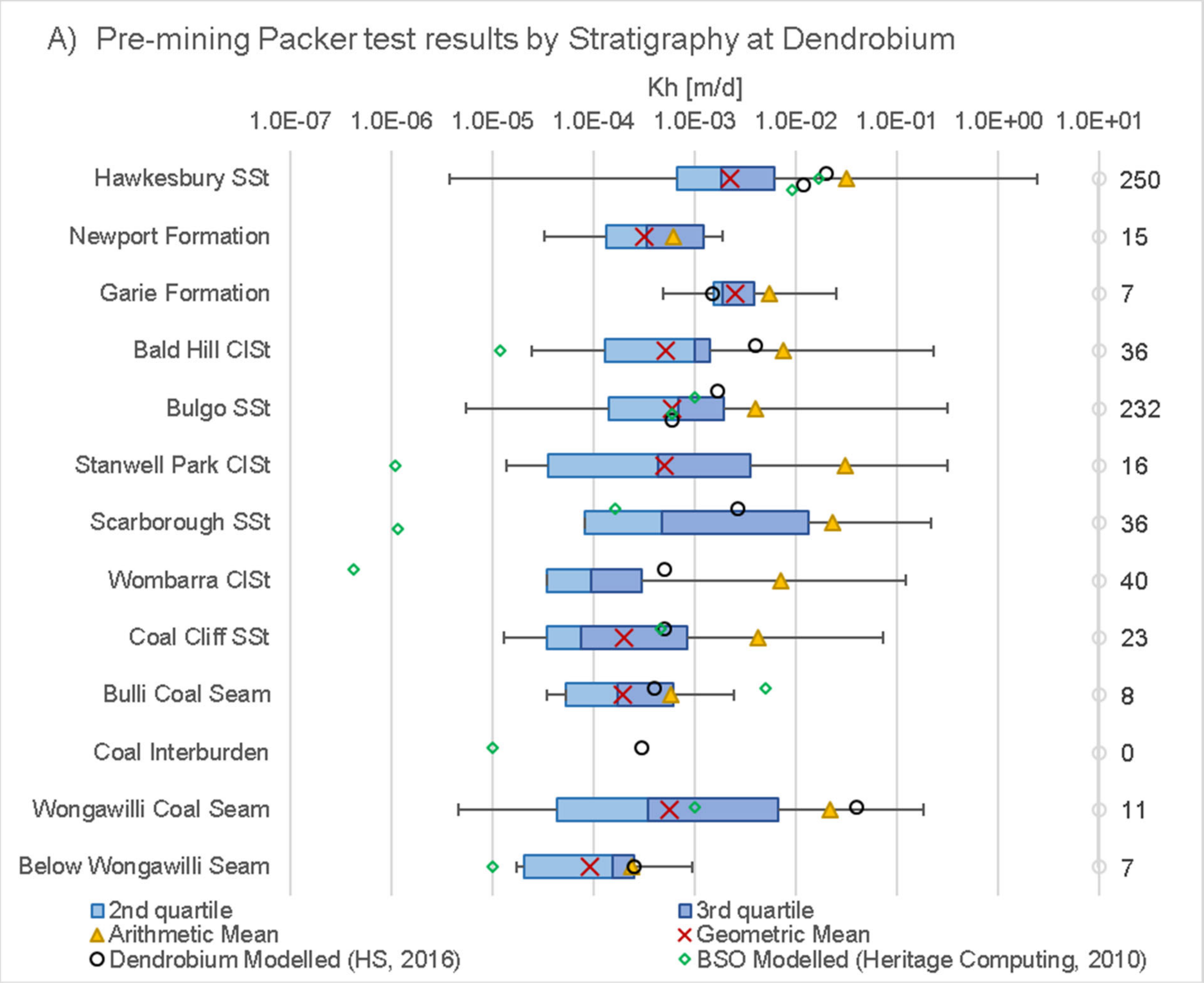
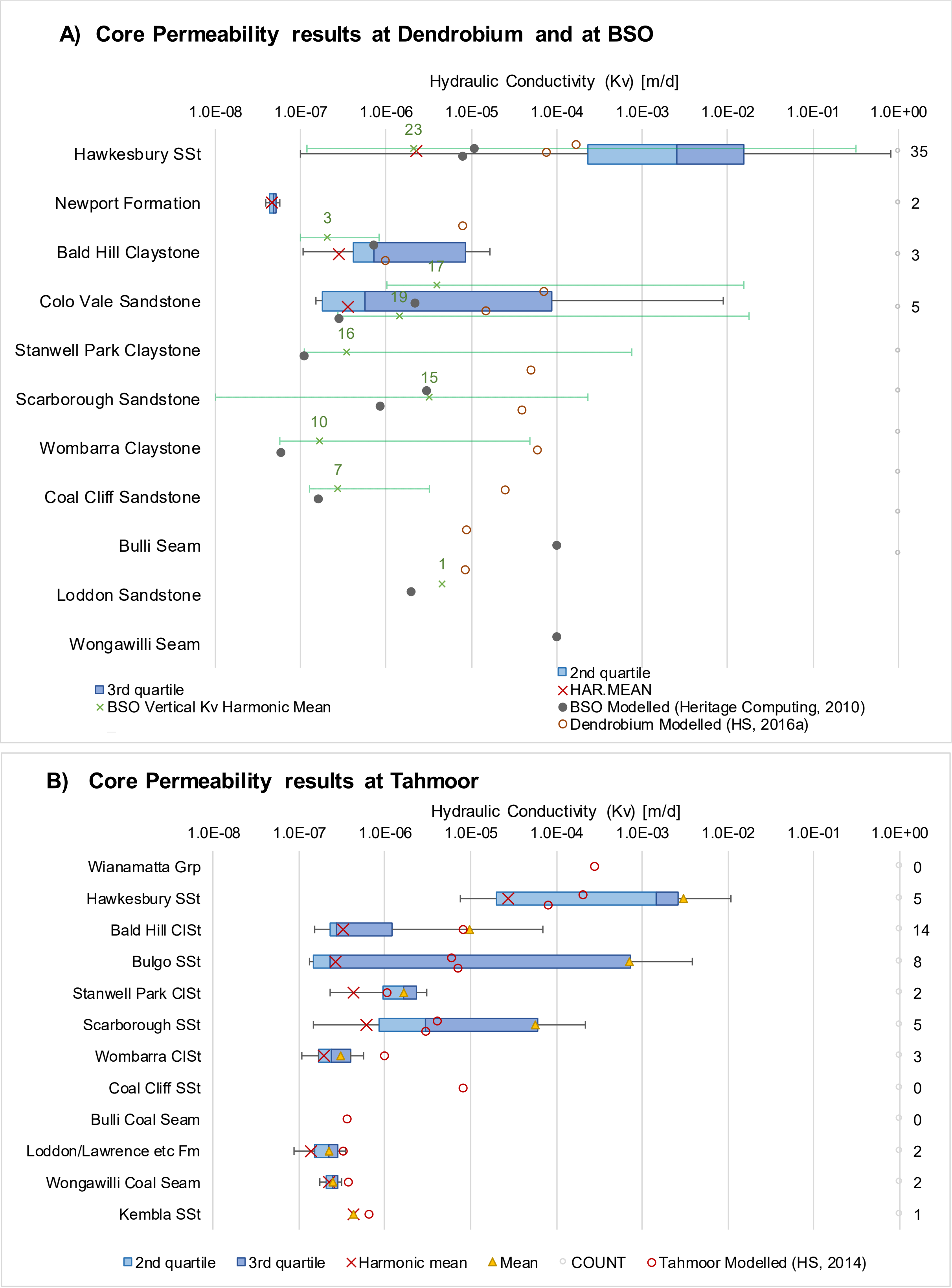
# APPENDIX B HORIZONTAL PERMEABILITY (PACKER TEST) SUMMARY





E:\DENDROBIUM\Tech\AquiferProperties\Packer\[Dendrobium_AquiferPropertiesDatabase_20171215.xlsx]Dend_CHARTS

**Figure B1 Summary of packer test (Kh) data at Dendrobium**

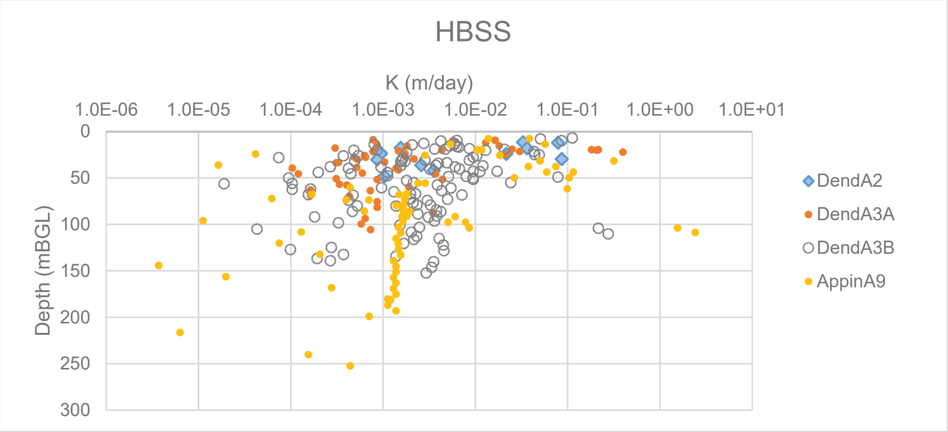


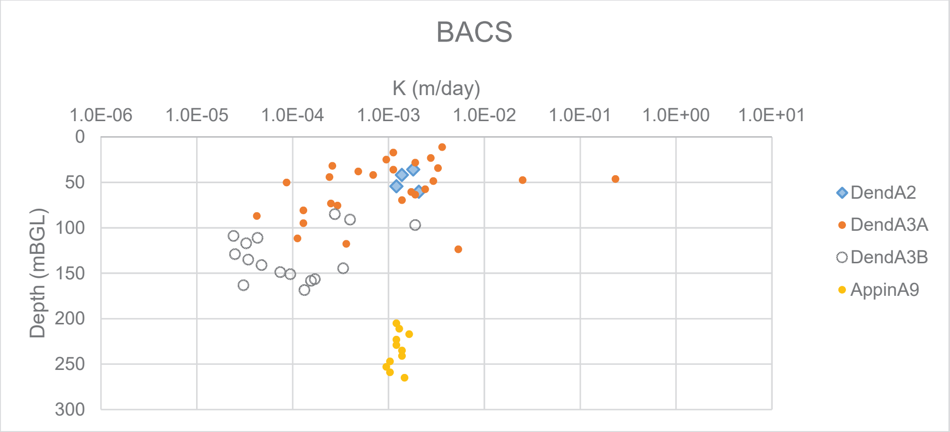
X:\HYDROSIM\DENDROBIUM\Tech\AquiferProperties\Packer\Dendrobium_AquiferPropertiesDatabase_20171215.xlsx

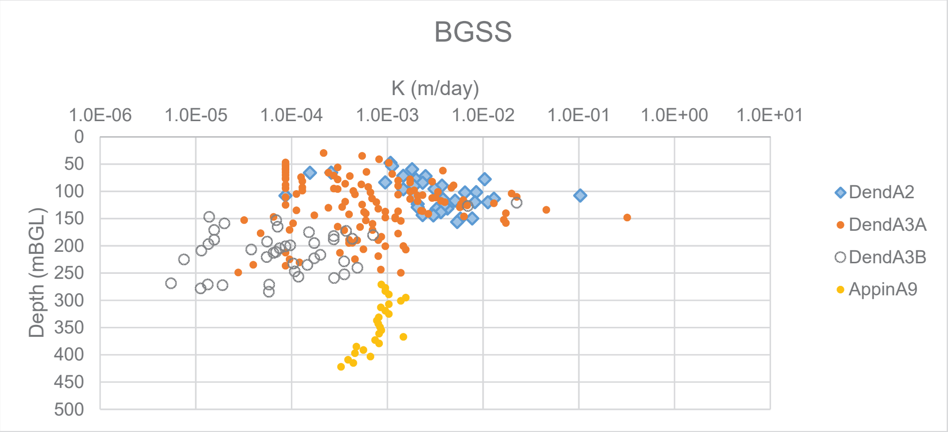
**Figure B2 Summary of core test (Kv) data at Dendrobium and Tahmoor**

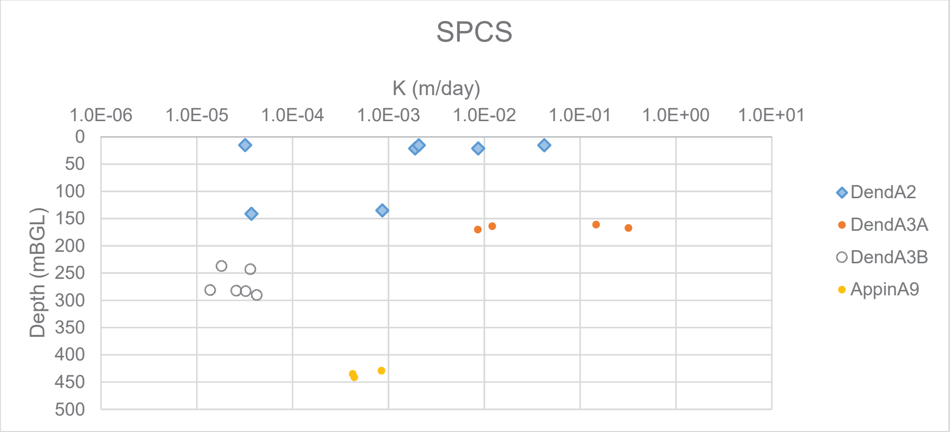
**Figure B3 Summary packer (Kh) by Mine Area** *(on following pages)*

## Packer test summary by Area

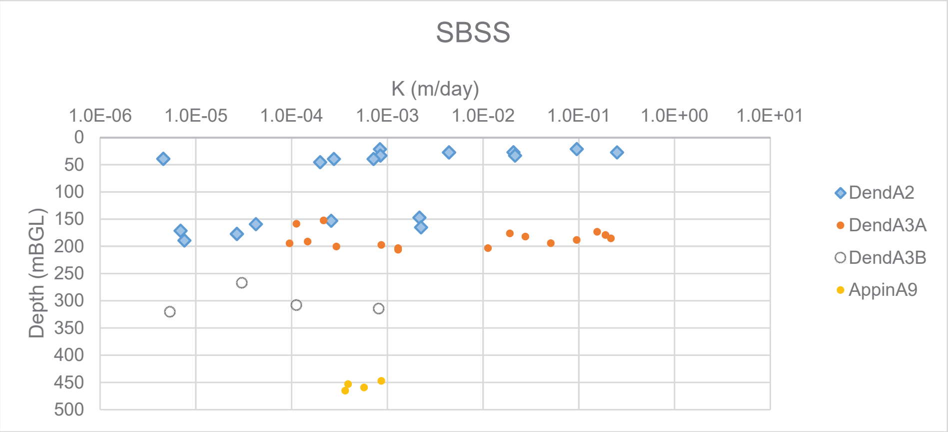


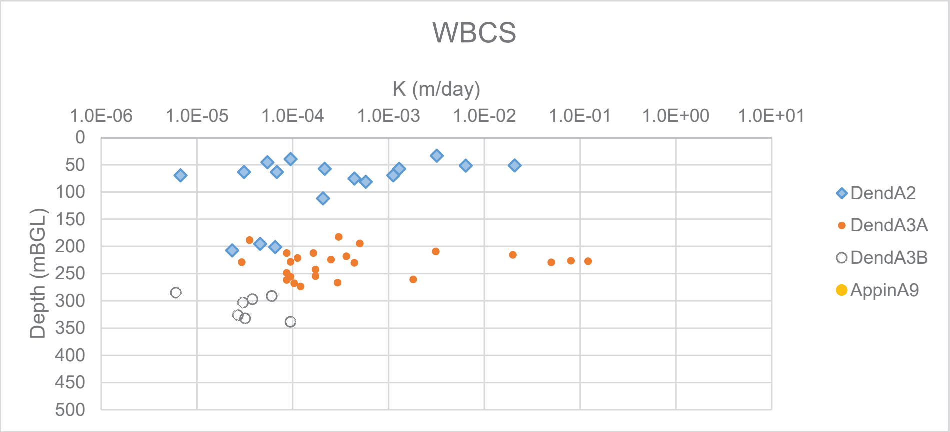


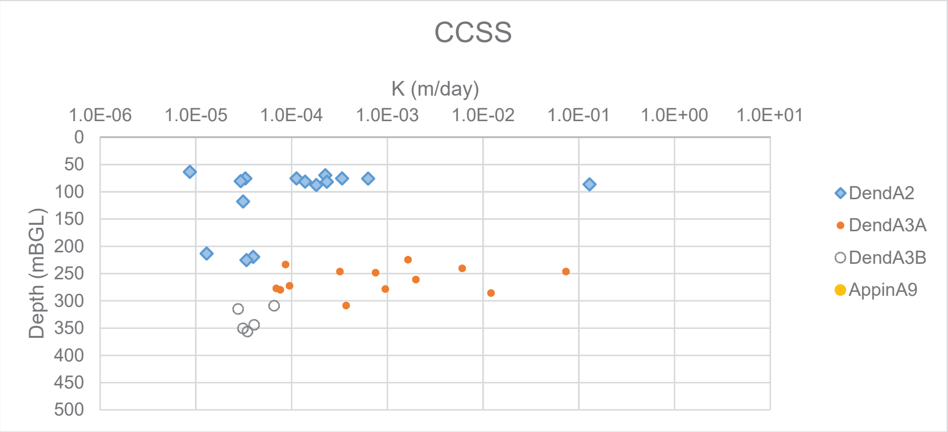


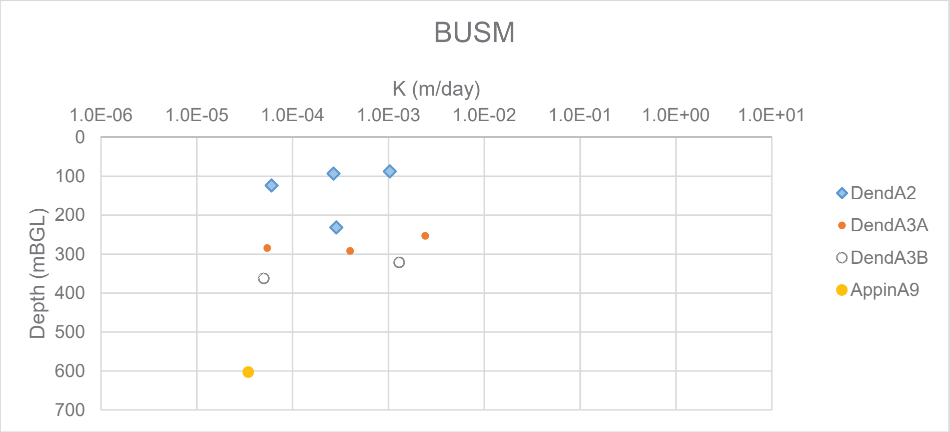


**Packer test summary by Area**

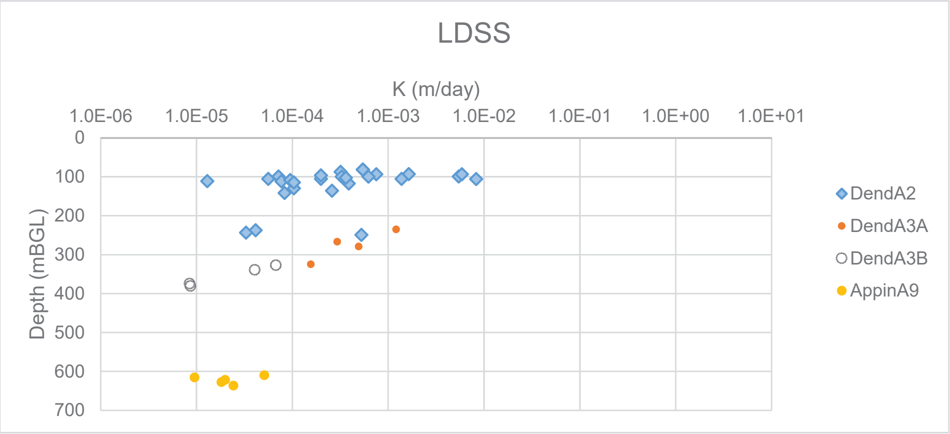


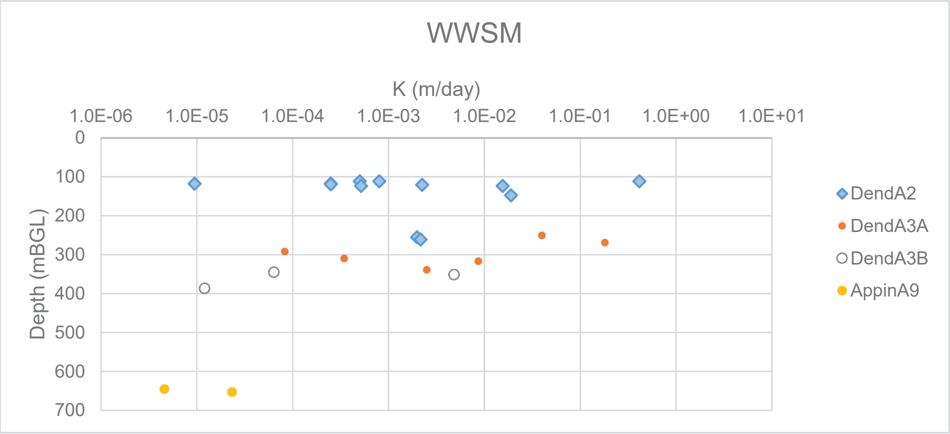




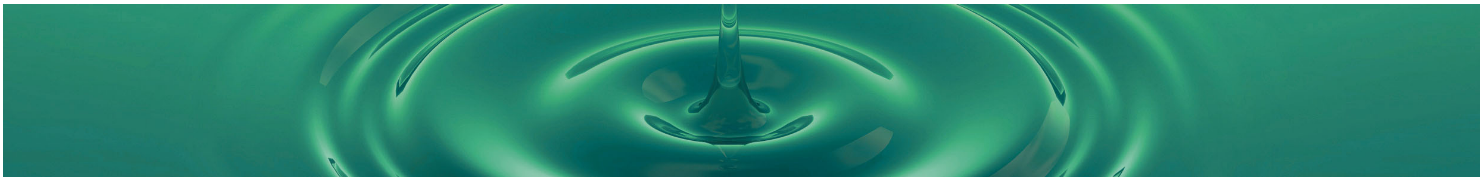


**Packer test summary by Area**



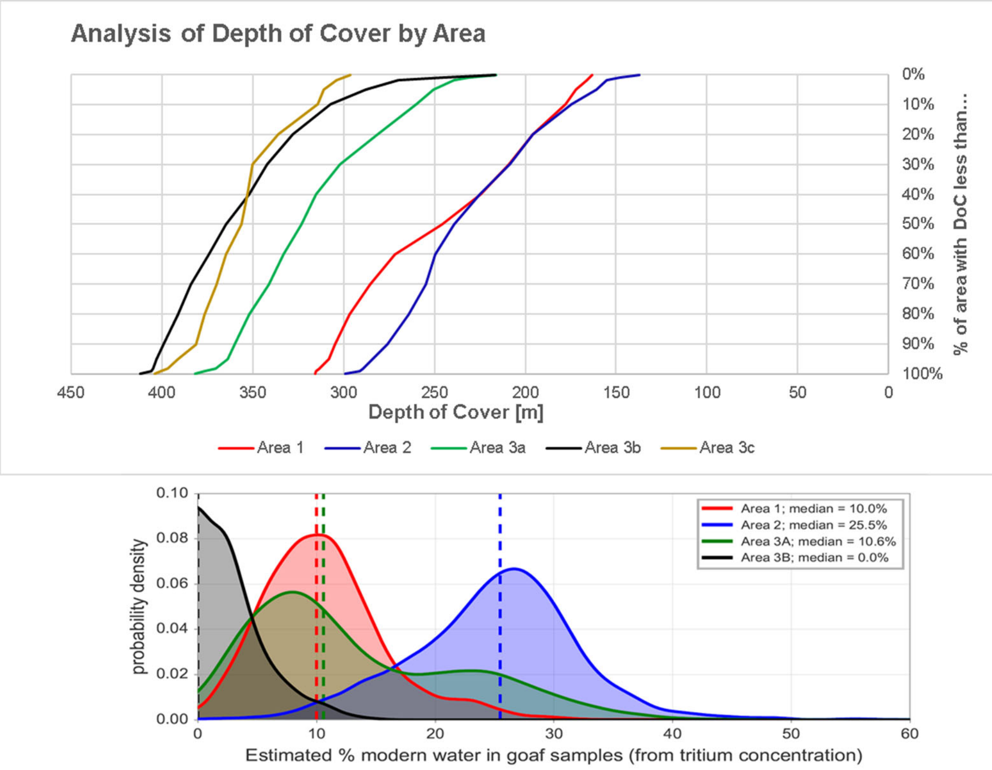


E:\DENDROBIUM\Tech\AquiferProperties\Packer\[Dendrobium_AquiferPropertiesDatabase_20171215.xlsx]Dend_CHARTS2



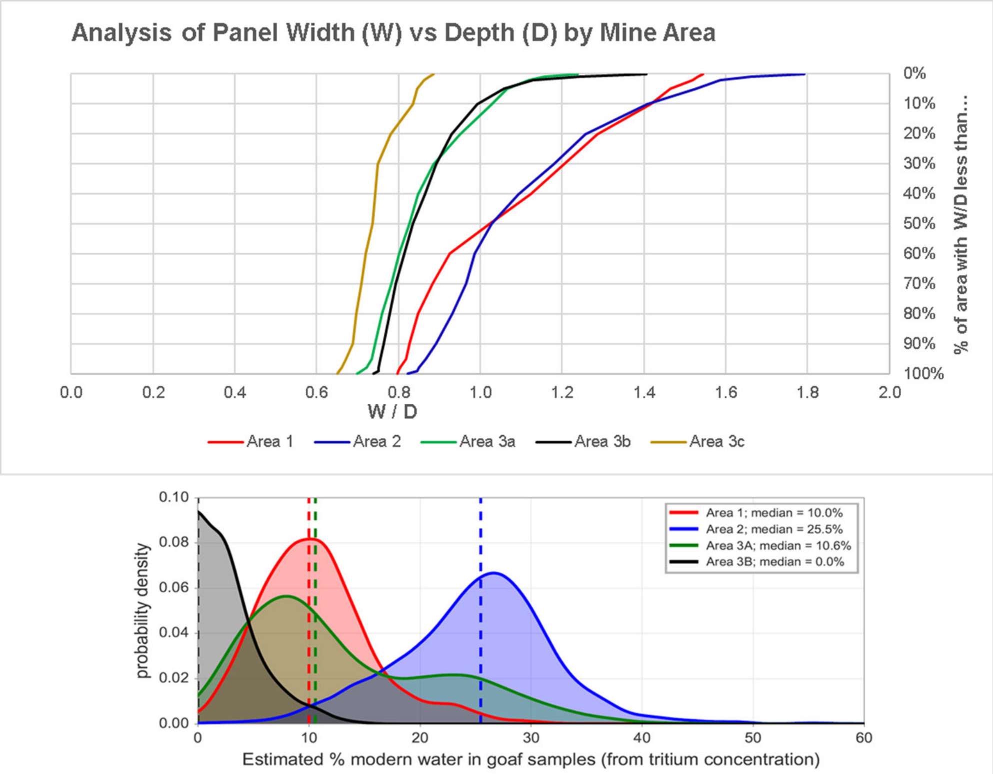
# APPENDIX C ASSESSMENT OF LONGWALL GEOMETRY AND SEAM-TO-SURFACE CONNECTIVITY

**Figure C1: Depth of Cover vs modern water contribution**



<u>Comment on correlation of Depth of Cover (DoC) to % modern water</u>: DoC suggests that Areas 1, 2 similar, and Area 3A contrasting to Area 2. Poor correlation suggests that DoC not the only consideration.

**Figure C2: Panel Width:Depth ratio vs modern water contribution**



<u>Comment on correlation of W/D to % modern water</u>: W/D suggests that Areas 1, 2 similar, Area 3A is similar, and Areas 2, 3A are contrasting. Lack of correlation suggests D/W not the only consideration.

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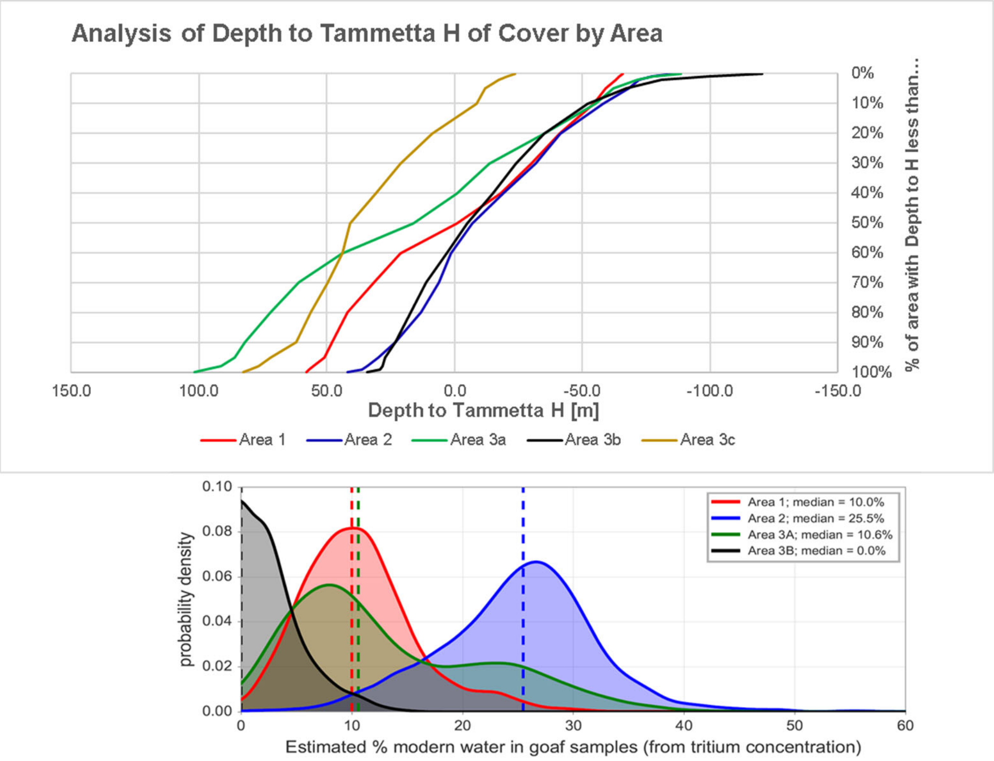
**Figure C3: Depth to Tammetta *H* vs modern water contribution**



Comment on correlation to % modern water: Distribution of H suggests that Area 3B should have more modern water than Area 3A, and 3B should have similar % to Area 2. Distribution of Depth to H by area has a poor correlation to the distribution of approx. % modern water.

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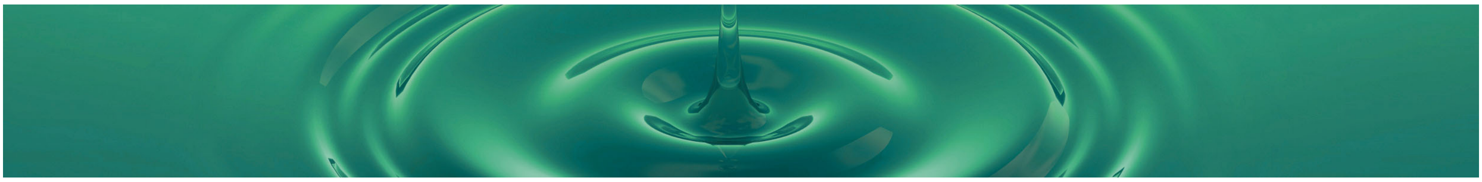
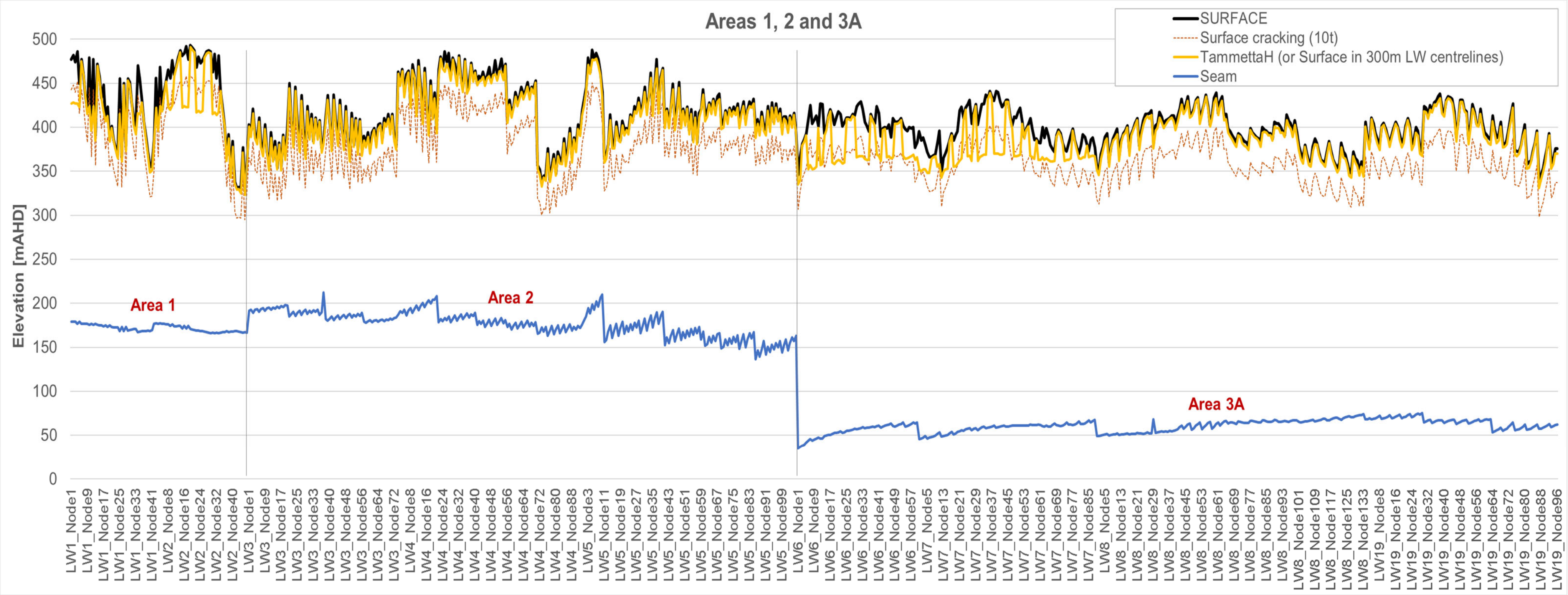


# APPENDIX D SIMULATED EXTENT OF CONNECTED FRACTURING AND SURFACE CRACKING


Areas 1, 2 and 3A
SURFACE
Surface cracking (10t)
TammettaH (or Surface in 300m LW centrelines)
Seam
Elevation [mAHD]
500
450
400
350
300
250
200
150
100
50
0
Area 1
Area 2
Area 3A
LW1_Node1
LW1_Node9
LW1_Node17
LW1_Node25
LW1_Node33
LW1_Node41
LW2_Node8
LW2_Node16
LW2_Node24
LW2_Node32
LW2_Node40
LW3_Node1
LW3_Node9
LW3_Node17
LW3_Node25
LW3_Node33
LW3_Node40
LW3_Node48
LW3_Node56
LW3_Node64
LW3_Node72
LW4_Node8
LW4_Node16
LW4_Node24
LW4_Node32
LW4_Node40
LW4_Node48
LW4_Node56
LW4_Node64
LW4_Node72
LW4_Node80
LW4_Node88
LW5_Node3
LW5_Node11
LW5_Node19
LW5_Node27
LW5_Node35
LW5_Node43
LW5_Node51
LW5_Node59
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LW5_Node83
LW5_Node91
LW5_Node99
LW6_Node1
LW6_Node9
LW6_Node17
LW6_Node25
LW6_Node33
LW6_Node41
LW6_Node49
LW6_Node57
LW7_Node5
LW7_Node13
LW7_Node21
LW7_Node29
LW7_Node37
LW7_Node45
LW7_Node53
LW7_Node61
LW7_Node69
LW7_Node77
LW7_Node85
LW8_Node5
LW8_Node13
LW8_Node21
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LW8_Node37
LW8_Node45
LW8_Node53
LW8_Node61
LW8_Node69
LW8_Node77
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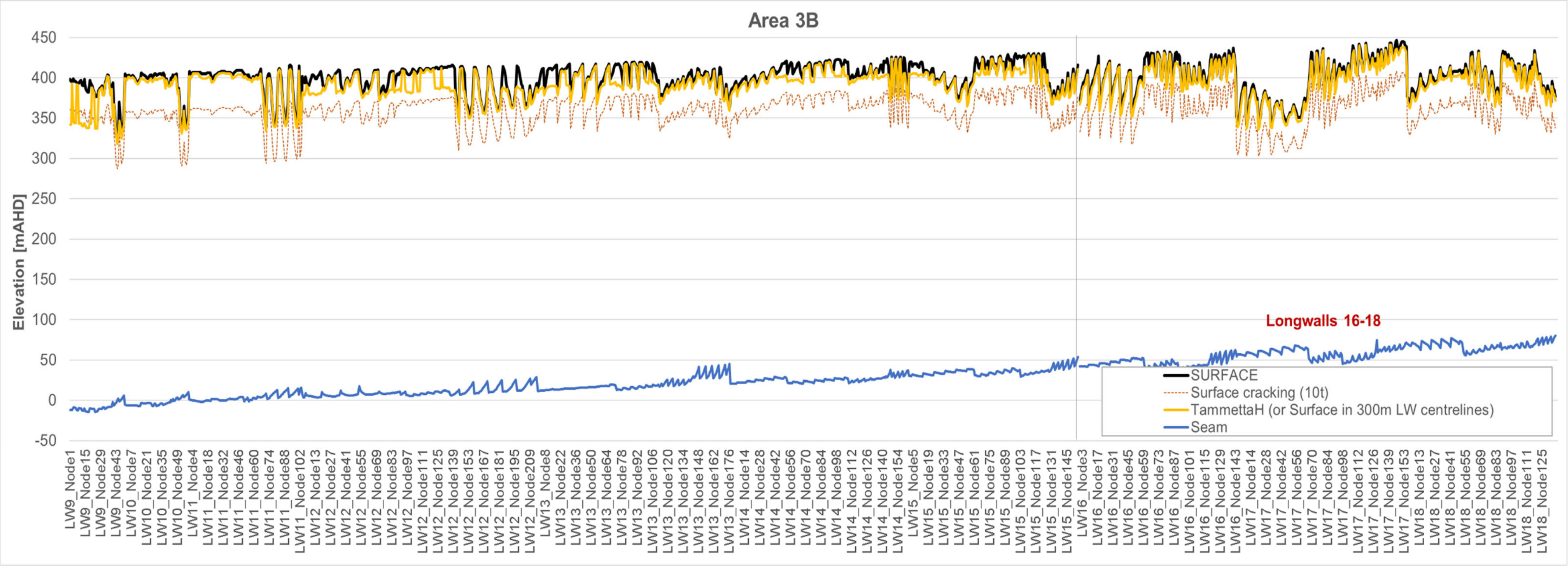
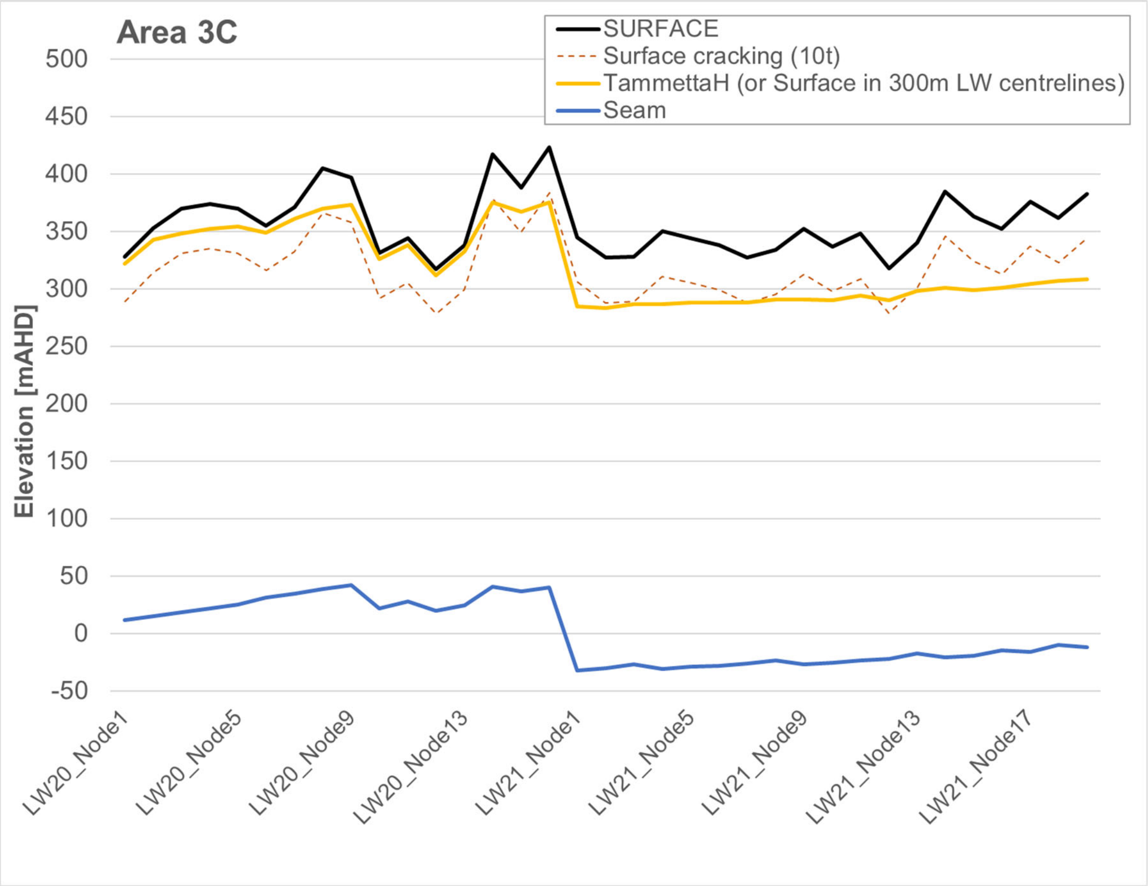
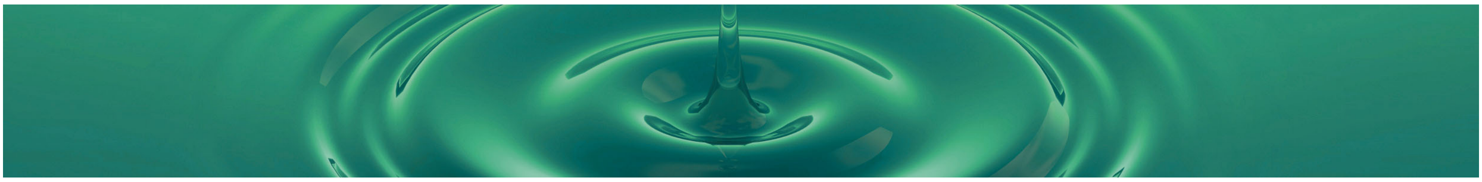
LW19_Node88
LW19_Node96



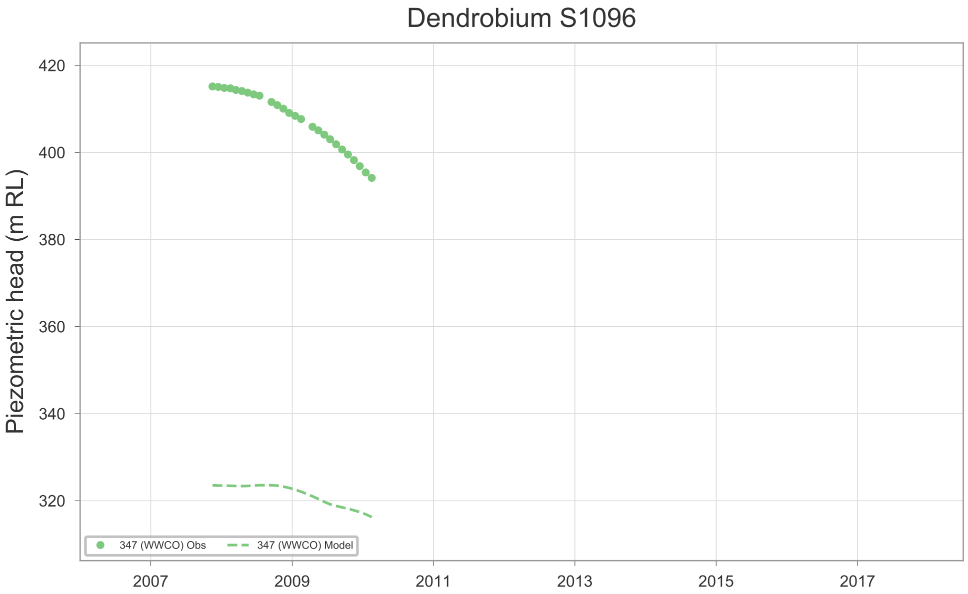
E:\DENDROBIUM\Model\GWModel\Construction\FracZone\[Comparison of HoF heights_v2.xlsx]Report

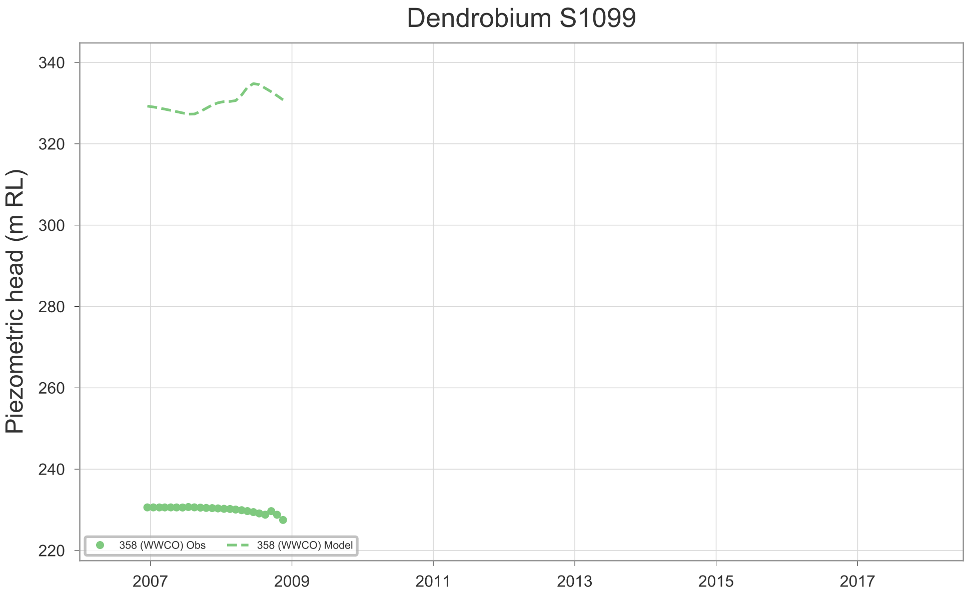


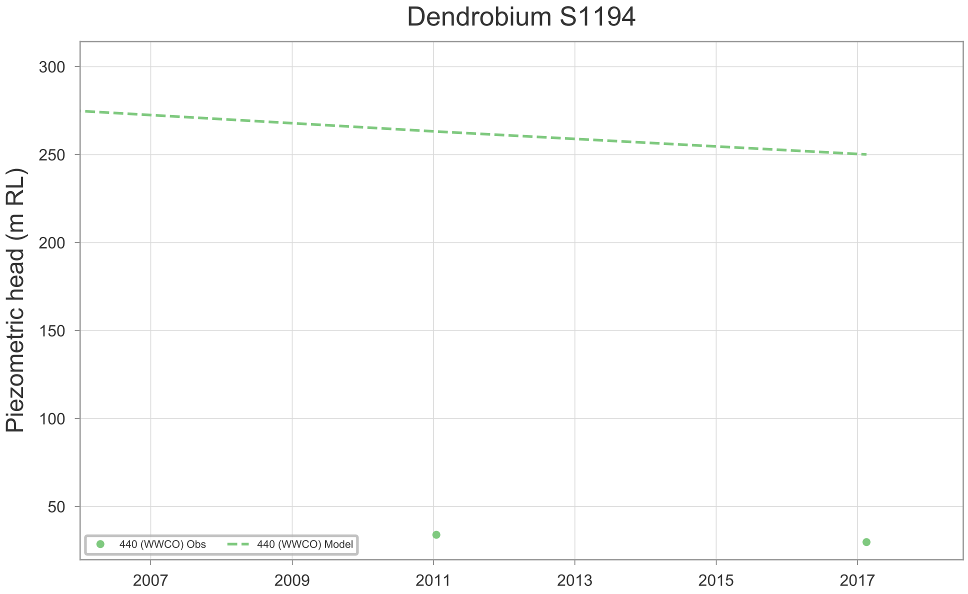
E:\DENDROBIUM\Model\GWModel\Construction\FracZone\[Comparison of HoF heights_v3_(LW20-21).xlsx]Report

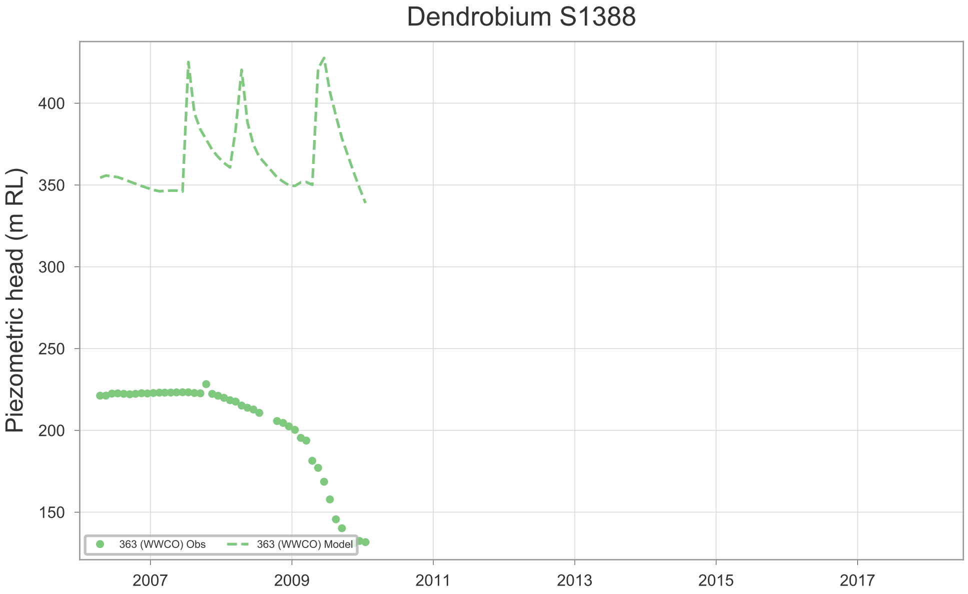


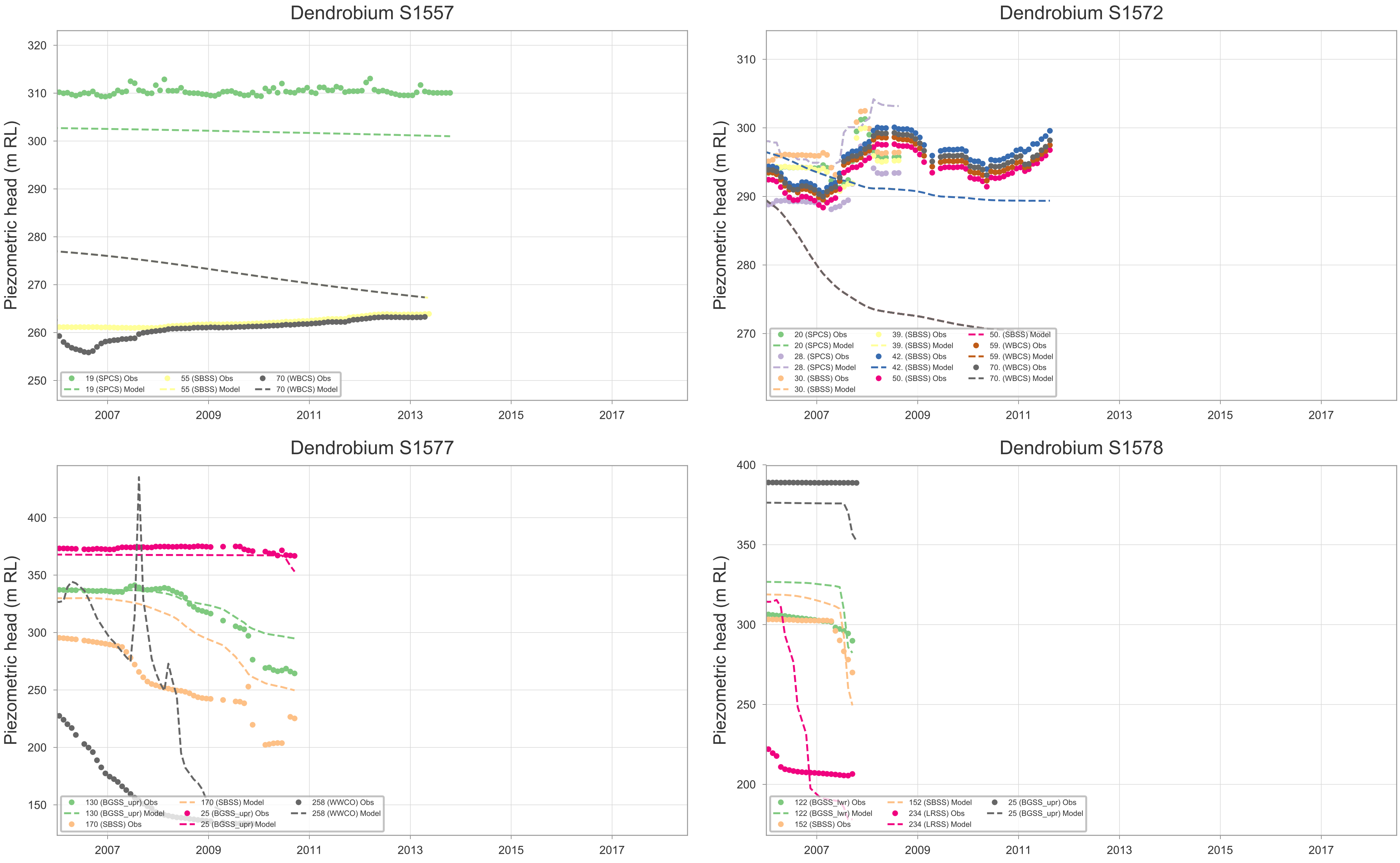
# APPENDIX E COMPARISON OF MODELLED AND OBSERVED GROUNDWATER LEVELS


Dendrobium S1096
Piezometric head (m RL)
420
400
380
360
340
320
2007
2009
2011
2013
2015
2017
347 (WWCO) Obs
347 (WWCO) Model

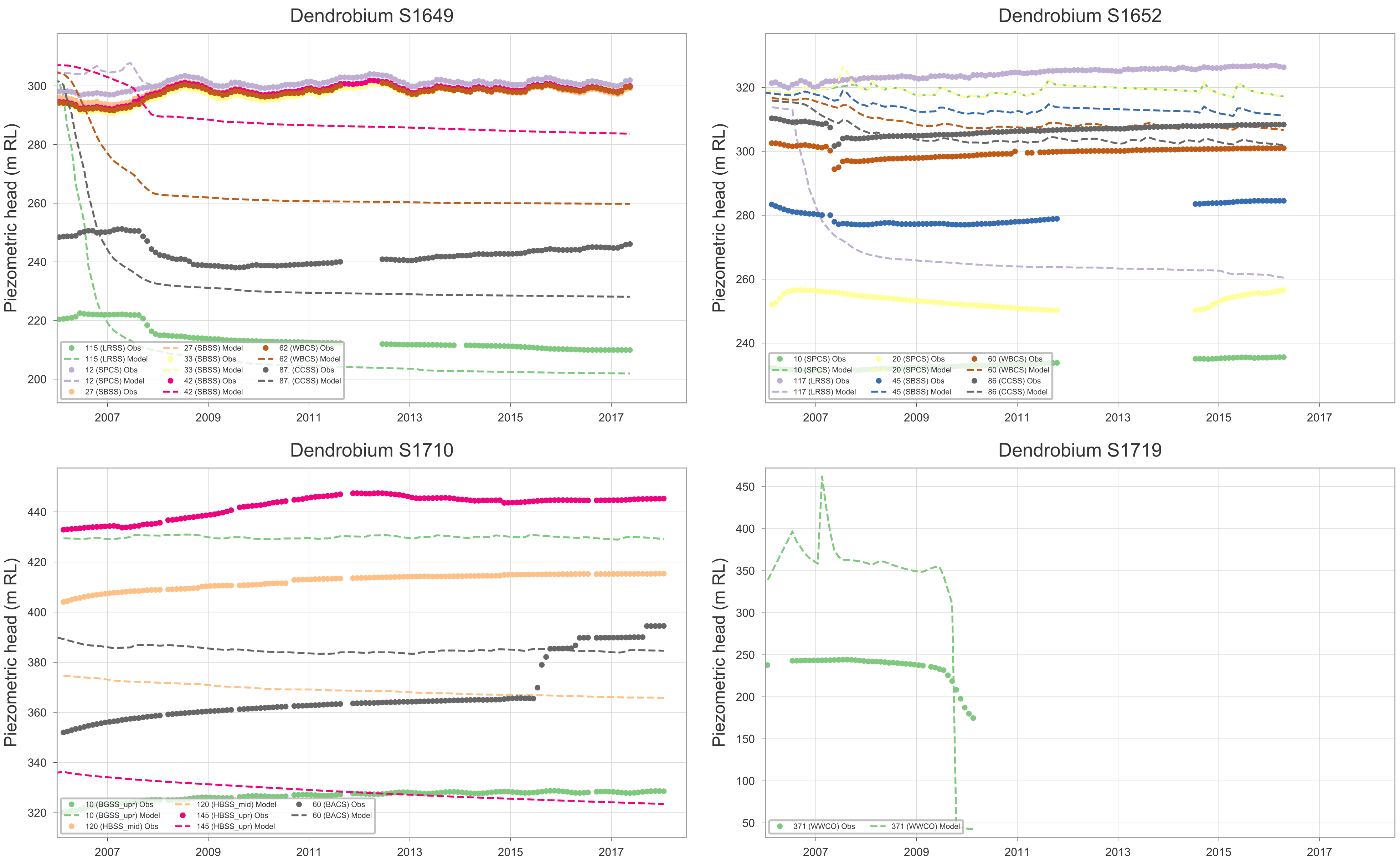

Dendrobium S1099
Piezometric head (m RL)
340
320
300
280
260
240
220
2007
2009
2011
2013
2015
2017
358 (WWCO) Obs
358 (WWCO) Model

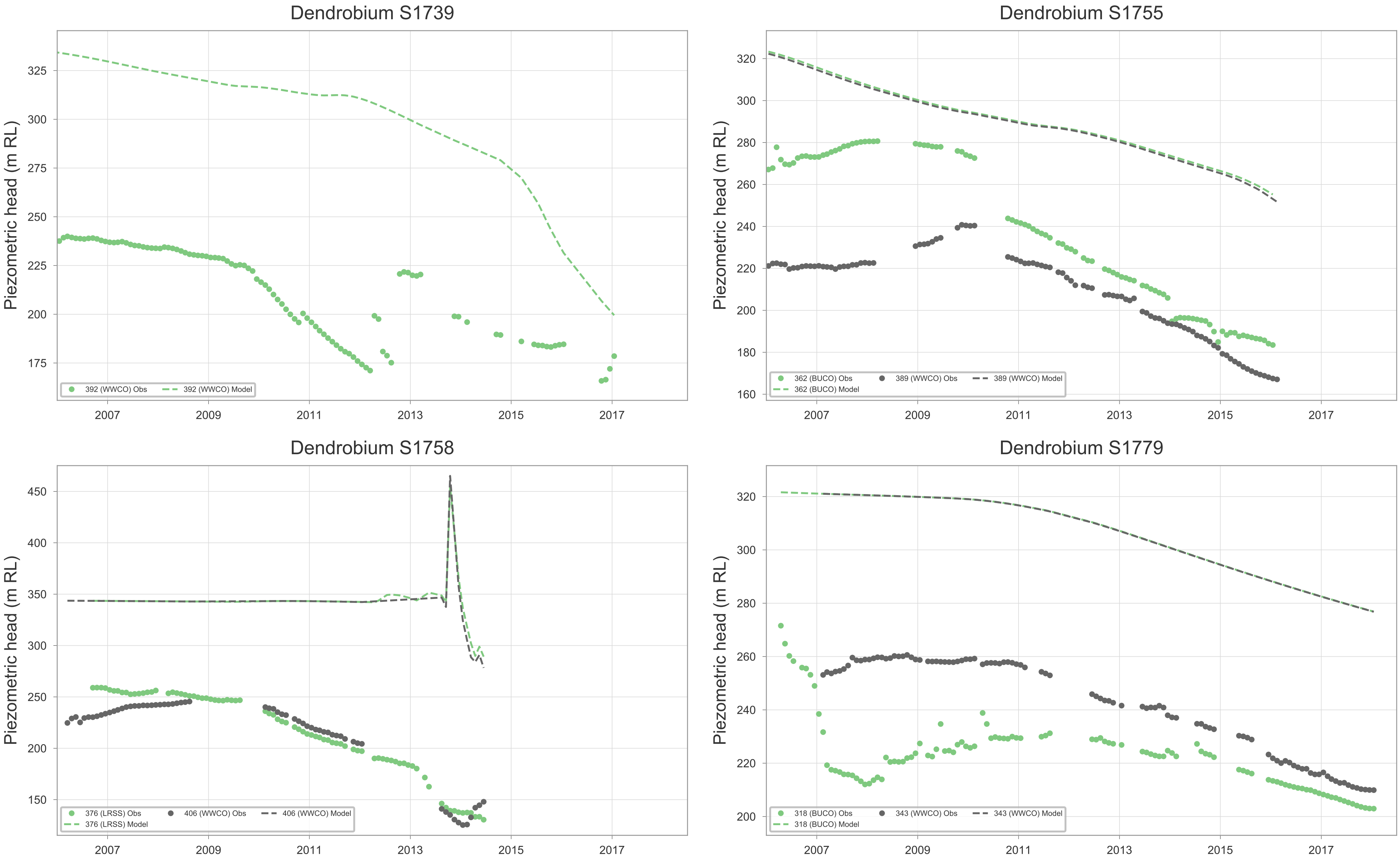

Dendrobium S1194
Piezometric head (m RL)
300
250
200
150
100
50
2007
2009
2011
2013
2015
2017
440 (WWCO) Obs
440 (WWCO) Model

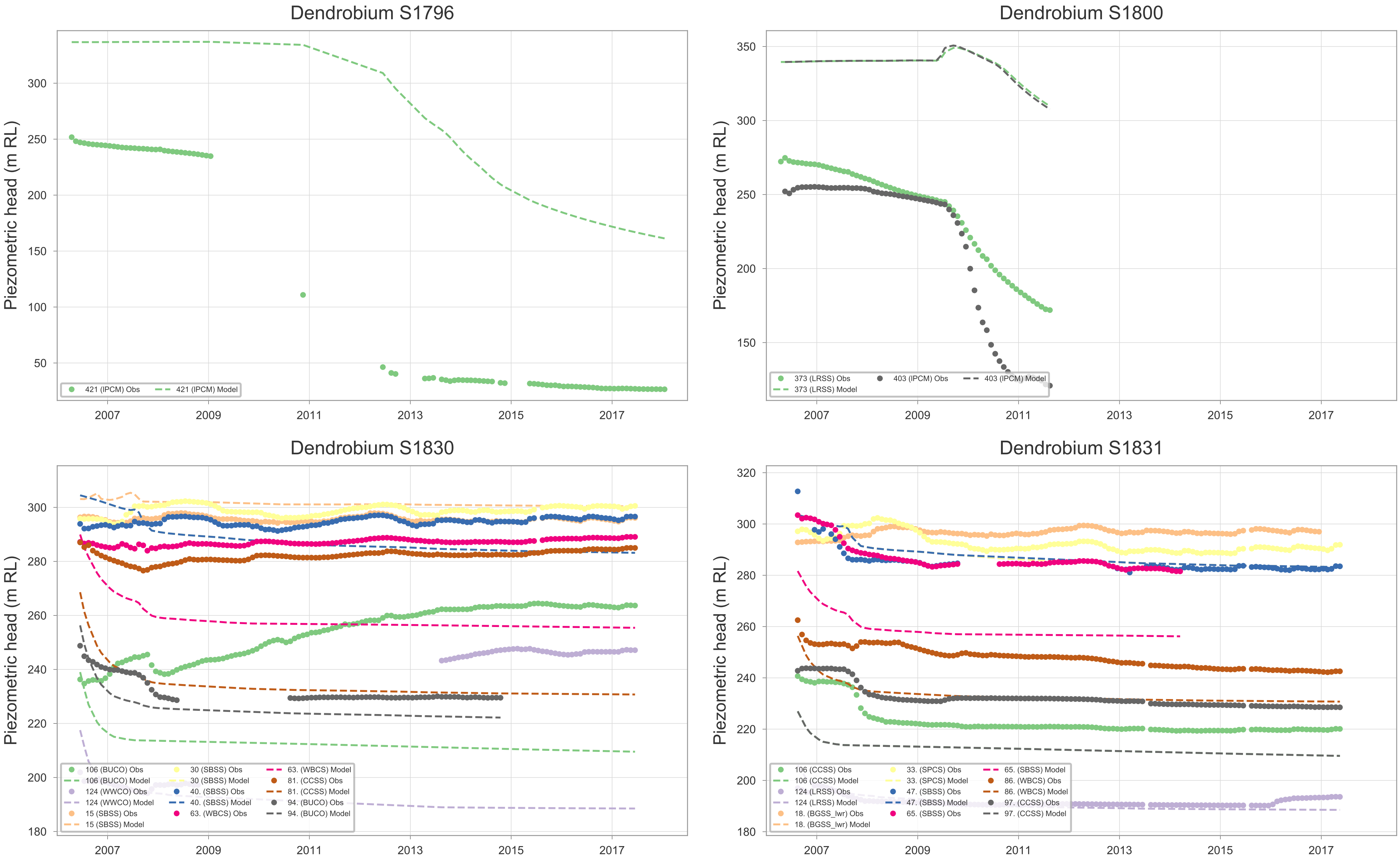

Dendrobium S1388
Piezometric head (m RL)
400
350
300
250
200
150
2007
2009
2011
2013
2015
2017
363 (WWCO) Obs
363 (WWCO) Model

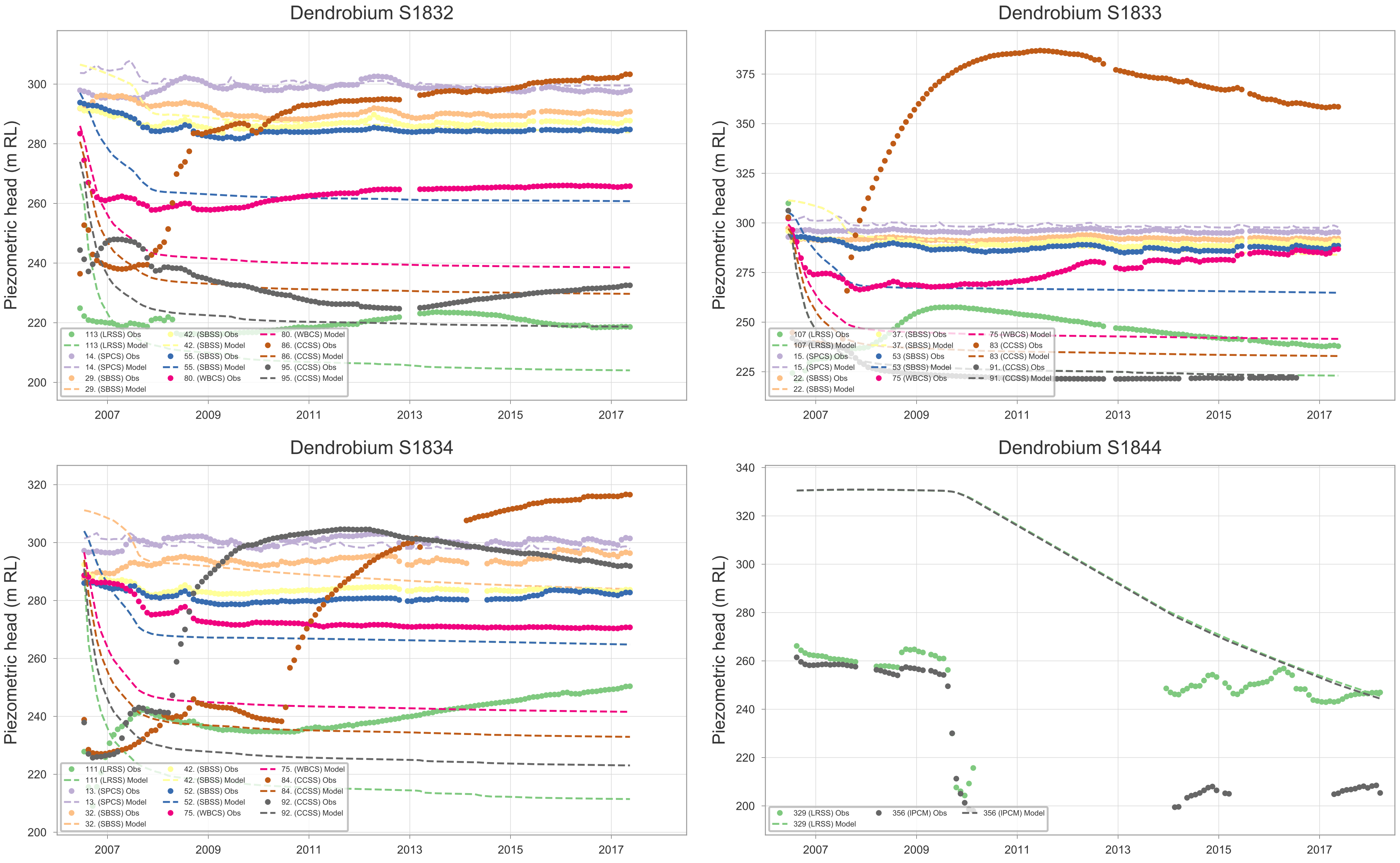


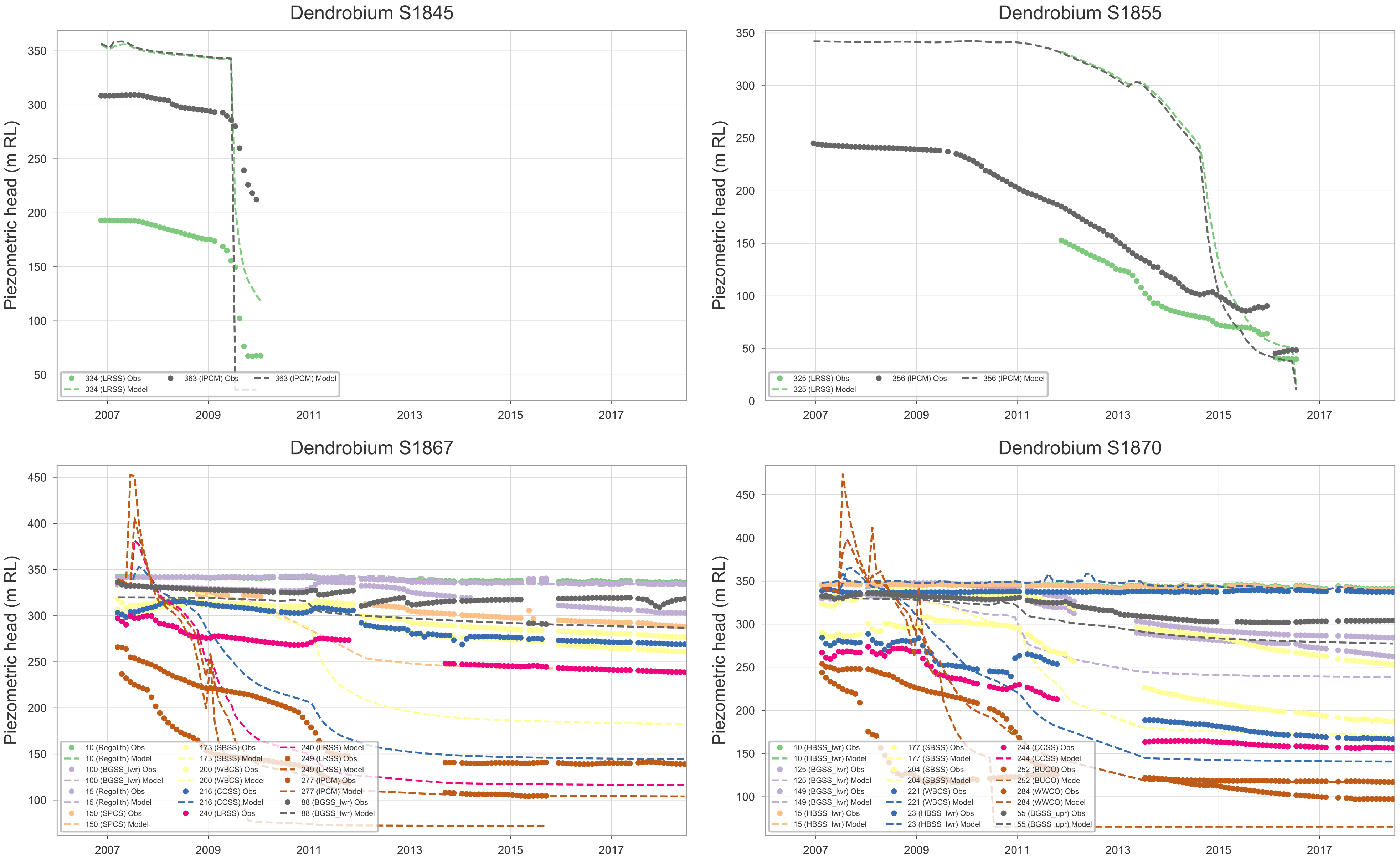
Dendrobium S1557
Piezometric head (m RL)
320
310
300
290
280
270
260
250
2007
2009
2011
2013
2015
2017
19 (SPCS) Obs
19 (SPCS) Model
55 (SBSS) Obs
55 (SBSS) Model
70 (WBCS) Obs
70 (WBCS) Model
Dendrobium S1572
Piezometric head (m RL)
310
300
290
280
270
2007
2009
2011
2013
2015
2017
20 (SPCS) Obs
20 (SPCS) Model
28. (SPCS) Obs
28. (SPCS) Model
30. (SBSS) Obs
30. (SBSS) Model
39. (SBSS) Obs
39. (SBSS) Model
42. (SBSS) Obs
42. (SBSS) Model
50. (SBSS) Obs
50. (SBSS) Model
59. (WBCS) Obs
59. (WBCS) Model
70. (WBCS) Obs
70. (WBCS) Model
Dendrobium S1577
Piezometric head (m RL)
400
350
300
250
200
150
2007
2009
2011
2013
2015
2017
130 (BGSS_upr) Obs
130 (BGSS_upr) Model
170 (SBSS) Obs
170 (SBSS) Model
25 (BGSS_upr) Obs
25 (BGSS_upr) Model
258 (WWCO) Obs
258 (WWCO) Model
Dendrobium S1578
Piezometric head (m RL)
400
350
300
250
200
2007
2009
2011
2013
2015
2017
122 (BGSS_lwr) Obs
122 (BGSS_lwr) Model
152 (SBSS) Obs
152 (SBSS) Model
234 (LRSS) Obs
234 (LRSS) Model
25 (BGSS_upr) Obs
25 (BGSS_upr) Model

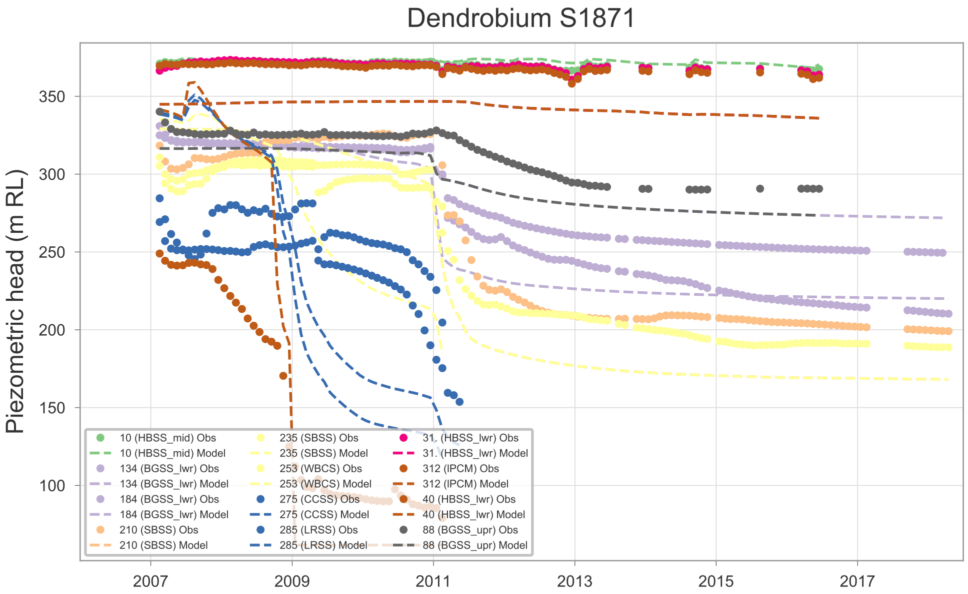

Dendrobium S1649
Piezometric head (m RL)
200
220
240
260
280
300
2007
2009
2011
2013
2015
2017
115 (LRSS) Obs
115 (LRSS) Model
12 (SPCS) Obs
12 (SPCS) Model
27 (SBSS) Obs
27 (SBSS) Model
33 (SBSS) Obs
33 (SBSS) Model
42 (SBSS) Obs
42 (SBSS) Model
62 (WBCS) Obs
62 (WBCS) Model
87. (CCSS) Obs
87. (CCSS) Model
Dendrobium S1652
Piezometric head (m RL)
240
260
280
300
320
2007
2009
2011
2013
2015
2017
10 (SPCS) Obs
10 (SPCS) Model
117 (LRSS) Obs
117 (LRSS) Model
20 (SPCS) Obs
20 (SPCS) Model
45 (SBSS) Obs
45 (SBSS) Model
60 (WBCS) Obs
60 (WBCS) Model
86 (CCSS) Obs
86 (CCSS) Model
Dendrobium S1710
Piezometric head (m RL)
320
340
360
380
400
420
440
2007
2009
2011
2013
2015
2017
10 (BGSS_upr) Obs
10 (BGSS_upr) Model
120 (HBSS_mid) Obs
120 (HBSS_mid) Model
145 (HBSS_upr) Obs
145 (HBSS_upr) Model
60 (BACS) Obs
60 (BACS) Model
Dendrobium S1719
Piezometric head (m RL)
50
100
150
200
250
300
350
400
450
2007
2009
2011
2013
2015
2017
371 (WWCO) Obs
371 (WWCO) Model

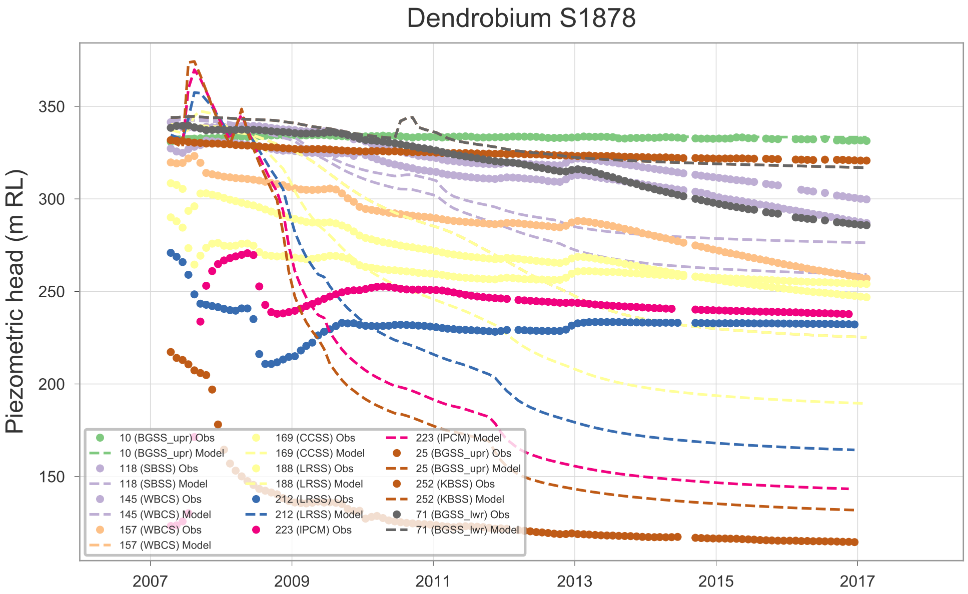

Dendrobium S1739
Piezometric head (m RL)
325
300
275
250
225
200
175
2007
2009
2011
2013
2015
2017
392 (WWCO) Obs
392 (WWCO) Model
Dendrobium S1755
Piezometric head (m RL)
320
300
280
260
240
220
200
180
160
2007
2009
2011
2013
2015
2017
362 (BUCO) Obs
362 (BUCO) Model
389 (WWCO) Obs
389 (WWCO) Model
Dendrobium S1758
Piezometric head (m RL)
450
400
350
300
250
200
150
2007
2009
2011
2013
2015
2017
376 (LRSS) Obs
376 (LRSS) Model
406 (WWCO) Obs
406 (WWCO) Model
Dendrobium S1779
Piezometric head (m RL)
320
300
280
260
240
220
200
2007
2009
2011
2013
2015
2017
318 (BUCO) Obs
318 (BUCO) Model
343 (WWCO) Obs
343 (WWCO) Model

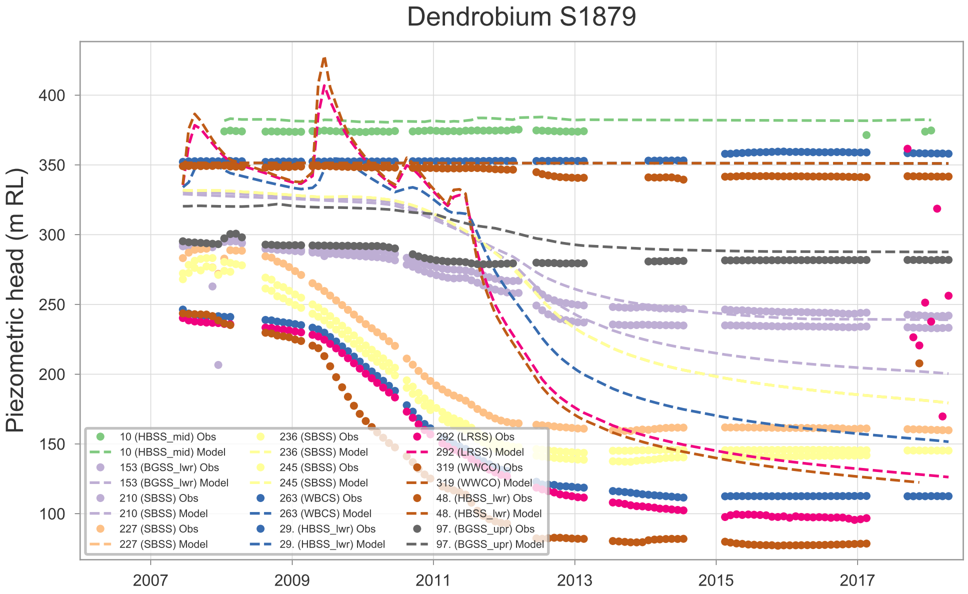

Dendrobium S1796
Piezometric head (m RL)
50
100
150
200
250
300
2007
2009
2011
2013
2015
2017
421 (IPCM) Obs
421 (IPCM) Model
Dendrobium S1800
Piezometric head (m RL)
150
200
250
300
350
2007
2009
2011
2013
2015
2017
373 (LRSS) Obs
373 (LRSS) Model
403 (IPCM) Obs
403 (IPCM) Model
Dendrobium S1830
Piezometric head (m RL)
180
200
220
240
260
280
300
2007
2009
2011
2013
2015
2017
106 (BUCO) Obs
106 (BUCO) Model
124 (WWCO) Obs
124 (WWCO) Model
15 (SBSS) Obs
15 (SBSS) Model
30 (SBSS) Obs
30 (SBSS) Model
40. (SBSS) Obs
40. (SBSS) Model
63. (WBCS) Obs
63. (WBCS) Model
81. (CCSS) Obs
81. (CCSS) Model
94. (BUCO) Obs
94. (BUCO) Model
Dendrobium S1831
Piezometric head (m RL)
180
200
220
240
260
280
300
320
2007
2009
2011
2013
2015
2017
106 (CCSS) Obs
106 (CCSS) Model
124 (LRSS) Obs
124 (LRSS) Model
18. (BGSS_lwr) Obs
18. (BGSS_lwr) Model
33. (SPCS) Obs
33. (SPCS) Model
47. (SBSS) Obs
47. (SBSS) Model
65. (SBSS) Obs
65. (SBSS) Model
86. (WBCS) Obs
86. (WBCS) Model
97. (CCSS) Obs
97. (CCSS) Model

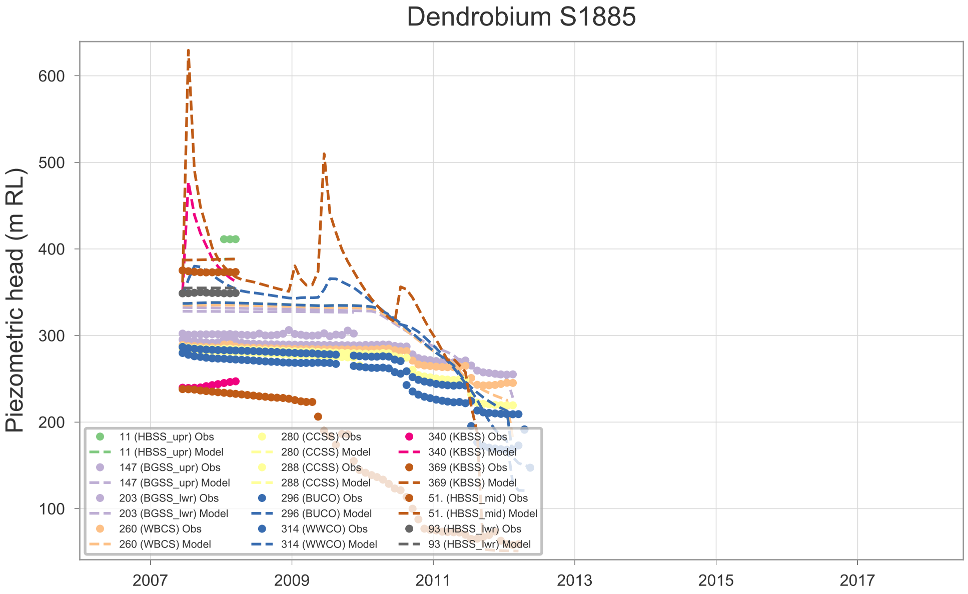

Dendrobium S1832
Piezometric head (m RL)
200
220
240
260
280
300
2007
2009
2011
2013
2015
2017
113 (LRSS) Obs
113 (LRSS) Model
14. (SPCS) Obs
14. (SPCS) Model
29. (SBSS) Obs
29. (SBSS) Model
42. (SBSS) Obs
42. (SBSS) Model
55. (SBSS) Obs
55. (SBSS) Model
80. (WBCS) Obs
80. (WBCS) Model
86. (CCSS) Obs
86. (CCSS) Model
95. (CCSS) Obs
95. (CCSS) Model
Dendrobium S1833
Piezometric head (m RL)
225
250
275
300
325
350
375
2007
2009
2011
2013
2015
2017
107 (LRSS) Obs
107 (LRSS) Model
15. (SPCS) Obs
15. (SPCS) Model
22. (SBSS) Obs
22. (SBSS) Model
37. (SBSS) Obs
37. (SBSS) Model
53 (SBSS) Obs
53 (SBSS) Model
75 (WBCS) Obs
75 (WBCS) Model
83 (CCSS) Obs
83 (CCSS) Model
91. (CCSS) Obs
91. (CCSS) Model
Dendrobium S1834
Piezometric head (m RL)
200
220
240
260
280
300
320
2007
2009
2011
2013
2015
2017
111 (LRSS) Obs
111 (LRSS) Model
13. (SPCS) Obs
13. (SPCS) Model
32. (SBSS) Obs
32. (SBSS) Model
42. (SBSS) Obs
42. (SBSS) Model
52. (SBSS) Obs
52. (SBSS) Model
75. (WBCS) Obs
75. (WBCS) Model
84. (CCSS) Obs
84. (CCSS) Model
92. (CCSS) Obs
92. (CCSS) Model
Dendrobium S1844
Piezometric head (m RL)
200
220
240
260
280
300
320
340
2007
2009
2011
2013
2015
2017
329 (LRSS) Obs
329 (LRSS) Model
356 (IPCM) Obs
356 (IPCM) Model

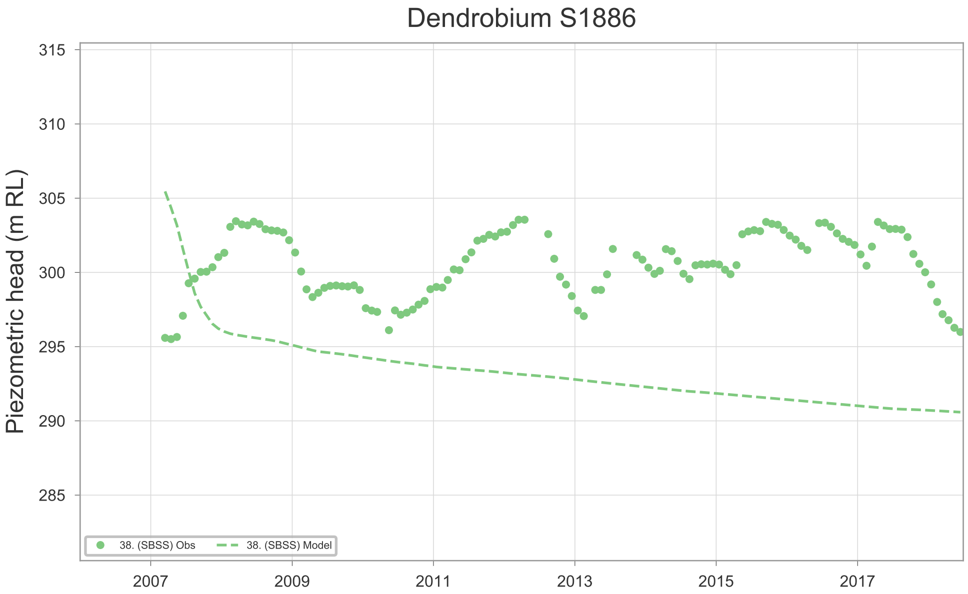

Dendrobium S1845
Piezometric head (m RL)
50
100
150
200
250
300
350
2007
2009
2011
2013
2015
2017
334 (LRSS) Obs
334 (LRSS) Model
363 (IPCM) Obs
363 (IPCM) Model
Dendrobium S1855
Piezometric head (m RL)
0
50
100
150
200
250
300
350
2007
2009
2011
2013
2015
2017
325 (LRSS) Obs
325 (LRSS) Model
356 (IPCM) Obs
356 (IPCM) Model
Dendrobium S1867
Piezometric head (m RL)
100
150
200
250
300
350
400
450
2007
2009
2011
2013
2015
2017
10 (Regolith) Obs
10 (Regolith) Model
100 (BGSS_lwr) Obs
100 (BGSS_lwr) Model
15 (Regolith) Obs
15 (Regolith) Model
150 (SPCS) Obs
150 (SPCS) Model
173 (SBSS) Obs
173 (SBSS) Model
200 (WBCS) Obs
200 (WBCS) Model
216 (CCSS) Obs
216 (CCSS) Model
240 (LRSS) Obs
240 (LRSS) Model
249 (LRSS) Obs
249 (LRSS) Model
277 (IPCM) Obs
277 (IPCM) Model
88 (BGSS_lwr) Obs
88 (BGSS_lwr) Model
Dendrobium S1870
Piezometric head (m RL)
100
150
200
250
300
350
400
450
2007
2009
2011
2013
2015
2017
10 (HBSS_lwr) Obs
10 (HBSS_lwr) Model
125 (BGSS_lwr) Obs
125 (BGSS_lwr) Model
149 (BGSS_lwr) Obs
149 (BGSS_lwr) Model
15 (HBSS_lwr) Obs
15 (HBSS_lwr) Model
177 (SBSS) Obs
177 (SBSS) Model
204 (SBSS) Obs
204 (SBSS) Model
221 (WBCS) Obs
221 (WBCS) Model
23 (HBSS_lwr) Obs
23 (HBSS_lwr) Model
244 (CCSS) Obs
244 (CCSS) Model
252 (BUCO) Obs
252 (BUCO) Model
284 (WWCO) Obs
284 (WWCO) Model
55 (BGSS_upr) Obs
55 (BGSS_upr) Model


Dendrobium S1871

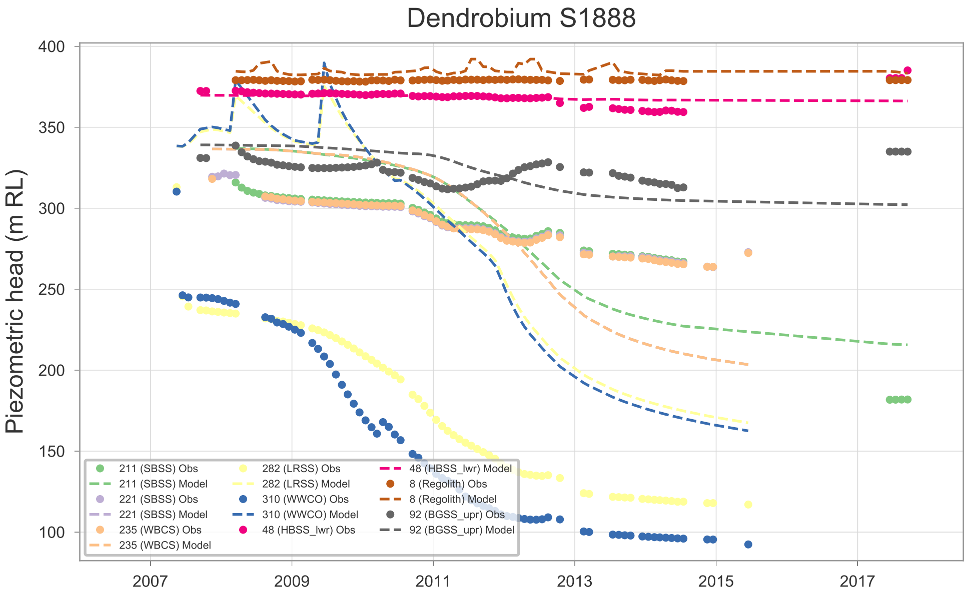

Dendrobium S1878


Dendrobium S1879

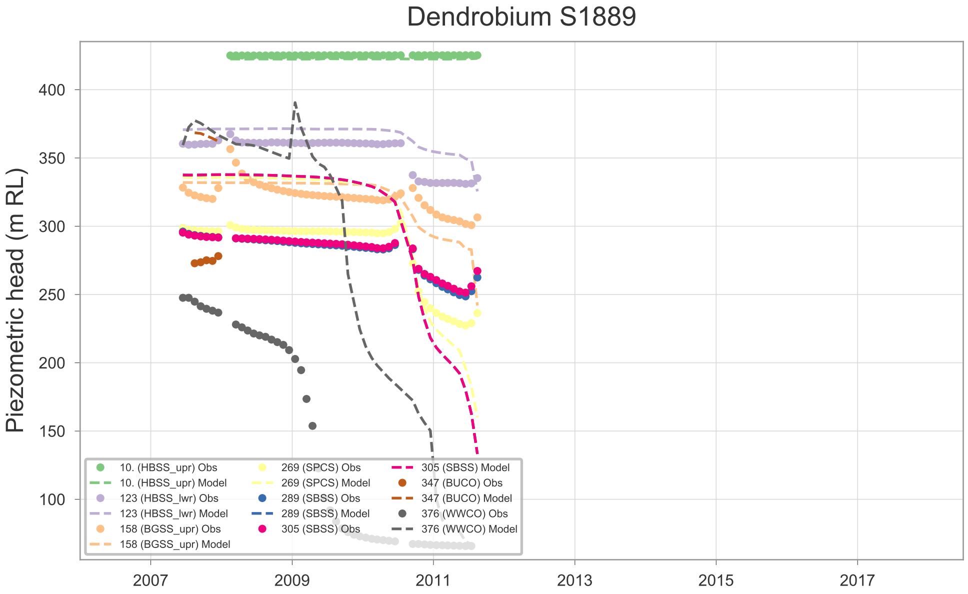

Dendrobium S1885



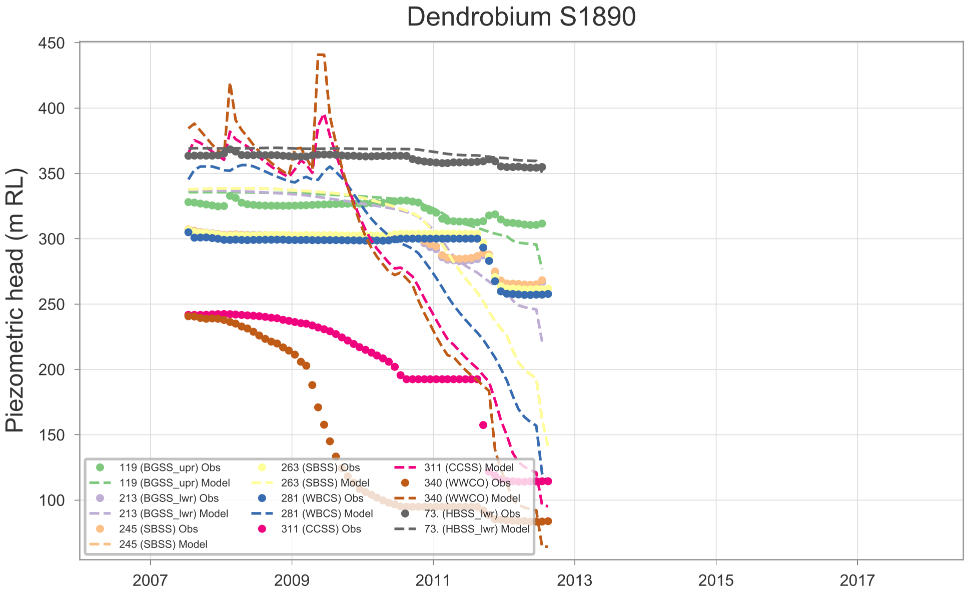
Dendrobium S1886
Piezometric head (m RL)
315
310
305
300
295
290
285
2007
2009
2011
2013
2015
2017
38. (SBSS) Obs
38. (SBSS) Model



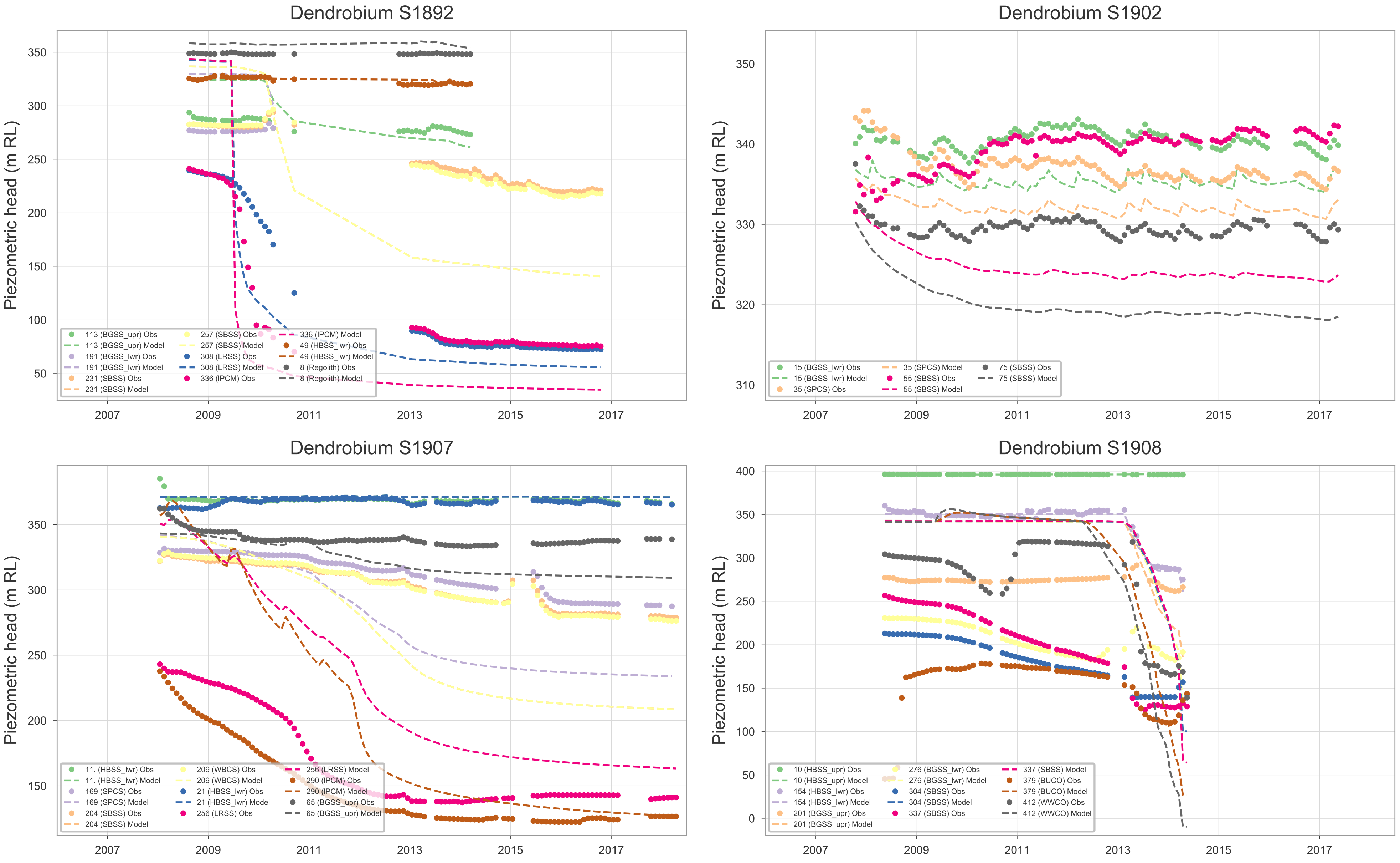
Dendrobium S1888
Piezometric head (m RL)
400
350
300
250
200
150
100
2007
2009
2011
2013
2015
2017
211 (SBSS) Obs
211 (SBSS) Model
221 (SBSS) Obs
221 (SBSS) Model
235 (WBCS) Obs
235 (WBCS) Model
282 (LRSS) Obs
282 (LRSS) Model
310 (WWCO) Obs
310 (WWCO) Model
48 (HBSS_lwr) Obs
48 (HBSS_lwr) Model
8 (Regolith) Obs
8 (Regolith) Model
92 (BGSS_upr) Obs
92 (BGSS_upr) Model

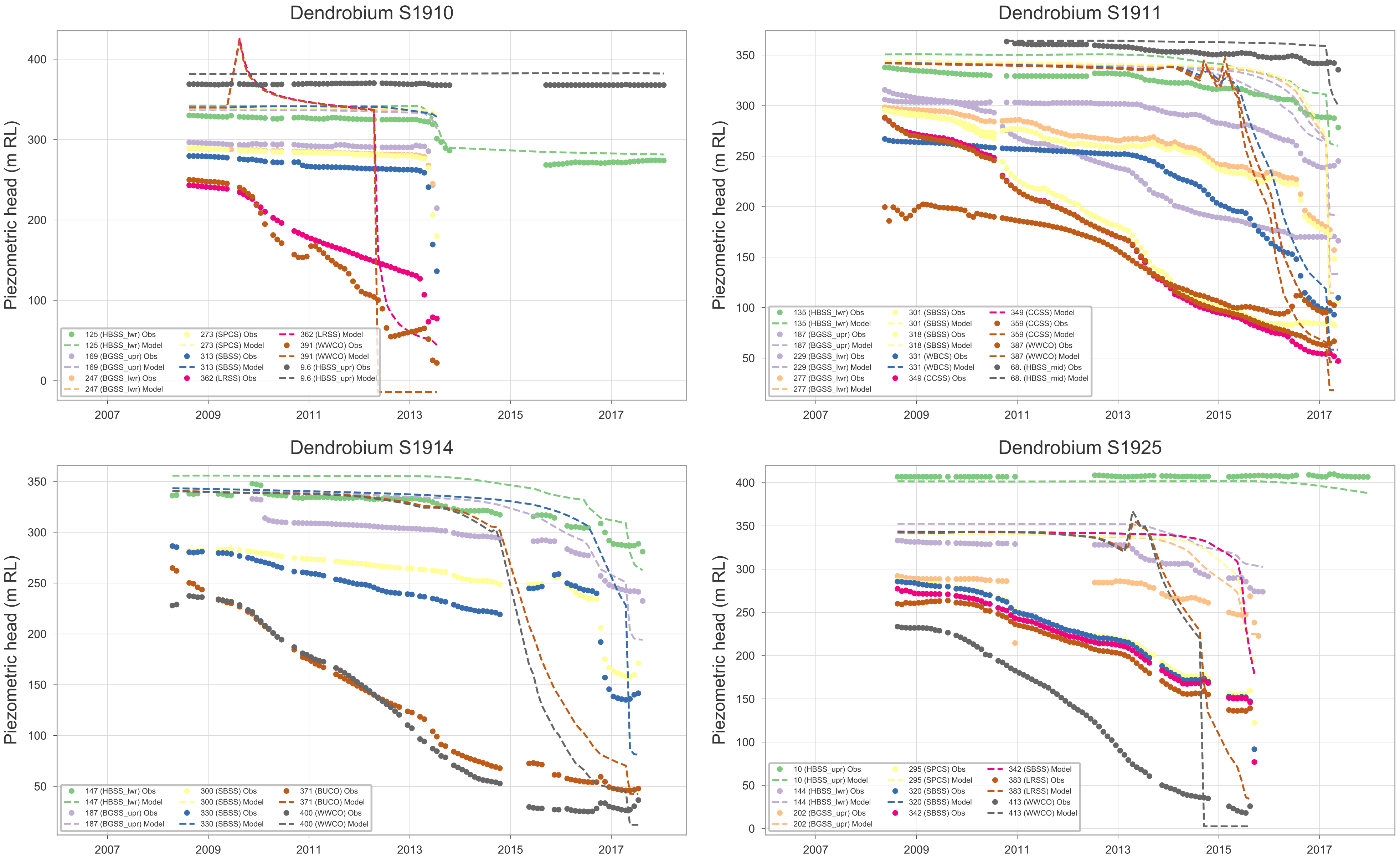


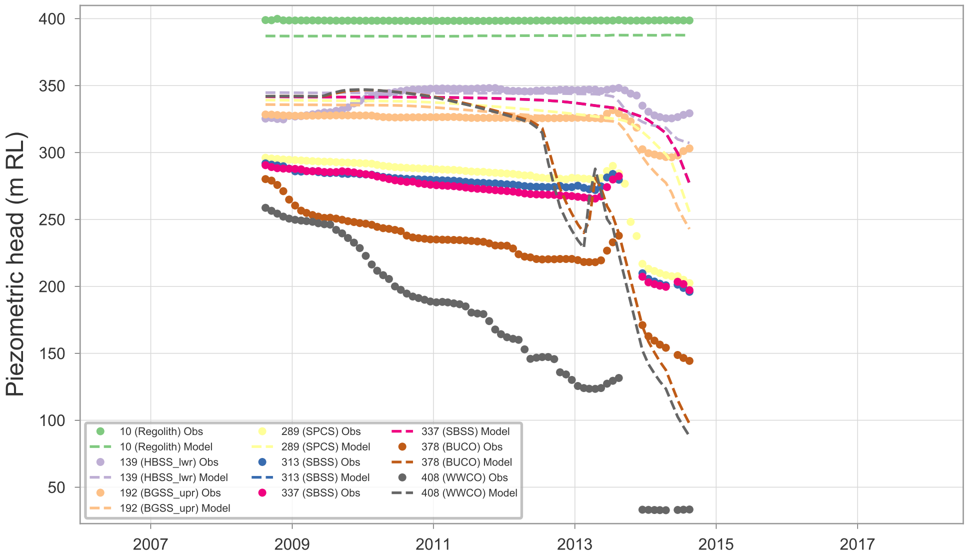
Dendrobium S1889
Piezometric head (m RL)
400
350
300
250
200
150
100
2007
2009
2011
2013
2015
2017
10. (HBSS_upr) Obs
10. (HBSS_upr) Model
123 (HBSS_lwr) Obs
123 (HBSS_lwr) Model
158 (BGSS_upr) Obs
158 (BGSS_upr) Model
269 (SPCS) Obs
269 (SPCS) Model
289 (SBSS) Obs
289 (SBSS) Model
305 (SBSS) Obs
305 (SBSS) Model
347 (BUCO) Obs
347 (BUCO) Model
376 (WWCO) Obs
376 (WWCO) Model



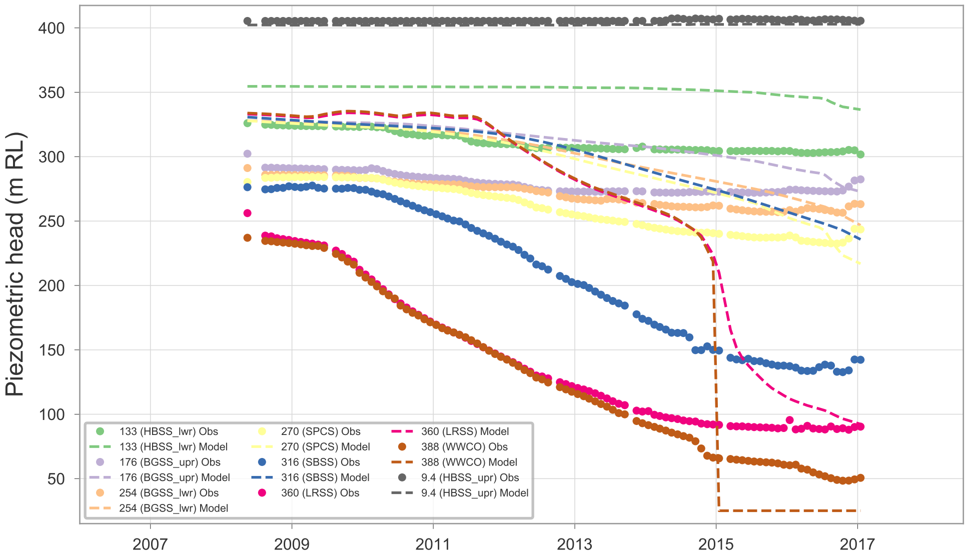
Dendrobium S1890
Piezometric head (m RL)
450
400
350
300
250
200
150
100
2007
2009
2011
2013
2015
2017
119 (BGSS_upr) Obs
119 (BGSS_upr) Model
213 (BGSS_lwr) Obs
213 (BGSS_lwr) Model
245 (SBSS) Obs
245 (SBSS) Model
263 (SBSS) Obs
263 (SBSS) Model
281 (WBCS) Obs
281 (WBCS) Model
311 (CCSS) Obs
311 (CCSS) Model
340 (WWCO) Obs
340 (WWCO) Model
73. (HBSS_lwr) Obs
73. (HBSS_lwr) Model


Dendrobium S1892
Piezometric head (m RL)
350
300
250
200
150
100
50
2007
2009
2011
2013
2015
2017
113 (BGSS_upr) Obs
113 (BGSS_upr) Model
191 (BGSS_lwr) Obs
191 (BGSS_lwr) Model
231 (SBSS) Obs
231 (SBSS) Model
257 (SBSS) Obs
257 (SBSS) Model
308 (LRSS) Obs
308 (LRSS) Model
336 (IPCM) Obs
336 (IPCM) Model
49 (HBSS_lwr) Obs
49 (HBSS_lwr) Model
8 (Regolith) Obs
8 (Regolith) Model
Dendrobium S1902
Piezometric head (m RL)
350
340
330
320
310
2007
2009
2011
2013
2015
2017
15 (BGSS_lwr) Obs
15 (BGSS_lwr) Model
35 (SPCS) Obs
35 (SPCS) Model
55 (SBSS) Obs
55 (SBSS) Model
75 (SBSS) Obs
75 (SBSS) Model
Dendrobium S1907
Piezometric head (m RL)
350
300
250
200
150
2007
2009
2011
2013
2015
2017
11. (HBSS_lwr) Obs
11. (HBSS_lwr) Model
169 (SPCS) Obs
169 (SPCS) Model
204 (SBSS) Obs
204 (SBSS) Model
209 (WBCS) Obs
209 (WBCS) Model
21 (HBSS_lwr) Obs
21 (HBSS_lwr) Model
256 (LRSS) Obs
256 (LRSS) Model
290 (IPCM) Obs
290 (IPCM) Model
65 (BGSS_upr) Obs
65 (BGSS_upr) Model
Dendrobium S1908
Piezometric head (m RL)
400
350
300
250
200
150
100
50
0
2007
2009
2011
2013
2015
2017
10 (HBSS_upr) Obs
10 (HBSS_upr) Model
154 (HBSS_lwr) Obs
154 (HBSS_lwr) Model
201 (BGSS_upr) Obs
201 (BGSS_upr) Model
276 (BGSS_lwr) Obs
276 (BGSS_lwr) Model
304 (SBSS) Obs
304 (SBSS) Model
337 (SBSS) Obs
337 (SBSS) Model
379 (BUCO) Obs
379 (BUCO) Model
412 (WWCO) Obs
412 (WWCO) Model

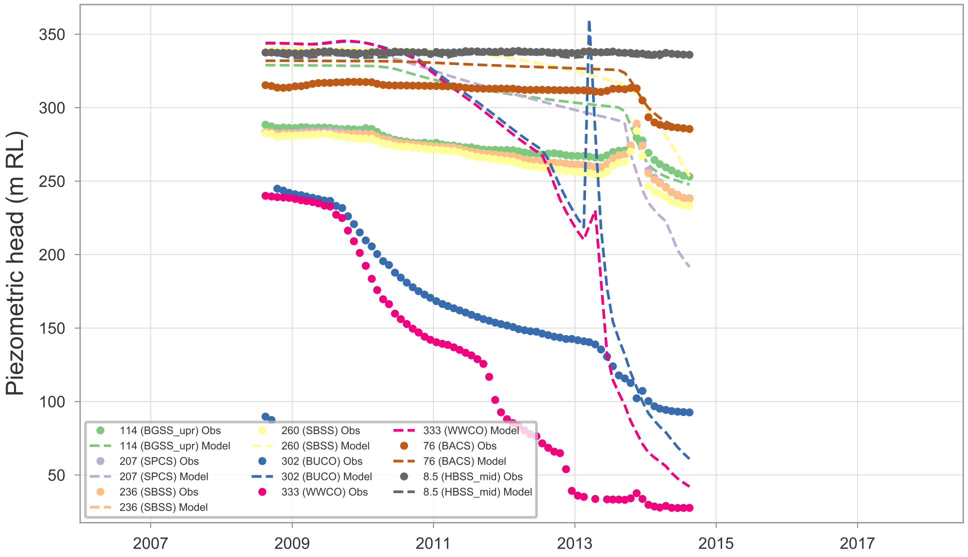

Dendrobium S1910
Piezometric head (m RL)
0
100
200
300
400
2007
2009
2011
2013
2015
2017
125 (HBSS_lwr) Obs
125 (HBSS_lwr) Model
169 (BGSS_upr) Obs
169 (BGSS_upr) Model
247 (BGSS_lwr) Obs
247 (BGSS_lwr) Model
273 (SPCS) Obs
273 (SPCS) Model
313 (SBSS) Obs
313 (SBSS) Model
362 (LRSS) Obs
362 (LRSS) Model
391 (WWCO) Obs
391 (WWCO) Model
9.6 (HBSS_upr) Obs
9.6 (HBSS_upr) Model
Dendrobium S1911
Piezometric head (m RL)
50
100
150
200
250
300
350
2007
2009
2011
2013
2015
2017
135 (HBSS_lwr) Obs
135 (HBSS_lwr) Model
187 (BGSS_upr) Obs
187 (BGSS_upr) Model
229 (BGSS_lwr) Obs
229 (BGSS_lwr) Model
277 (BGSS_lwr) Obs
277 (BGSS_lwr) Model
301 (SBSS) Obs
301 (SBSS) Model
318 (SBSS) Obs
318 (SBSS) Model
331 (WBCS) Obs
331 (WBCS) Model
349 (CCSS) Obs
349 (CCSS) Model
359 (CCSS) Obs
359 (CCSS) Model
387 (WWCO) Obs
387 (WWCO) Model
68. (HBSS_mid) Obs
68. (HBSS_mid) Model
Dendrobium S1914
Piezometric head (m RL)
50
100
150
200
250
300
350
2007
2009
2011
2013
2015
2017
147 (HBSS_lwr) Obs
147 (HBSS_lwr) Model
187 (BGSS_upr) Obs
187 (BGSS_upr) Model
300 (SBSS) Obs
300 (SBSS) Model
330 (SBSS) Obs
330 (SBSS) Model
371 (BUCO) Obs
371 (BUCO) Model
400 (WWCO) Obs
400 (WWCO) Model
Dendrobium S1925
Piezometric head (m RL)
0
50
100
150
200
250
300
350
400
2007
2009
2011
2013
2015
2017
10 (HBSS_upr) Obs
10 (HBSS_upr) Model
144 (HBSS_lwr) Obs
144 (HBSS_lwr) Model
202 (BGSS_upr) Obs
202 (BGSS_upr) Model
295 (SPCS) Obs
295 (SPCS) Model
320 (SBSS) Obs
320 (SBSS) Model
342 (SBSS) Obs
342 (SBSS) Model
383 (LRSS) Obs
383 (LRSS) Model
413 (WWCO) Obs
413 (WWCO) Model



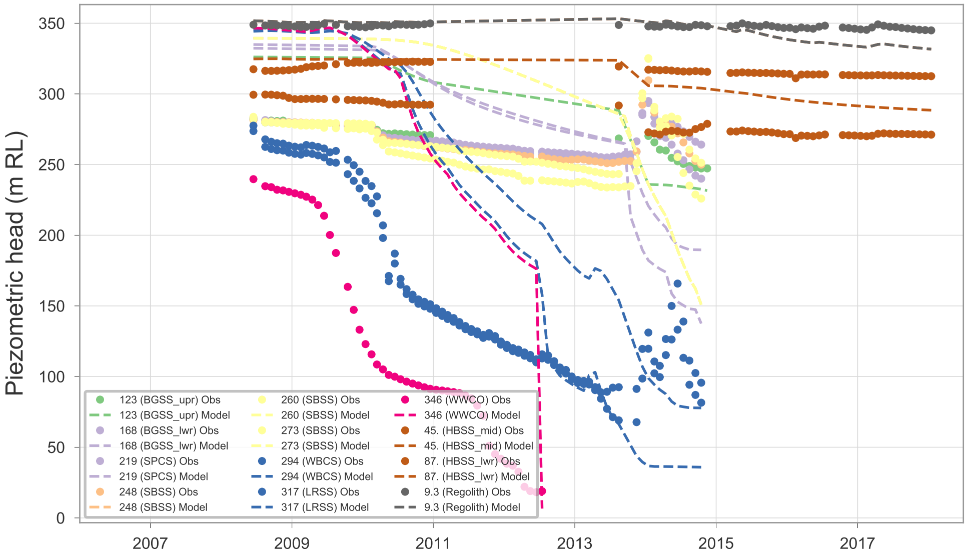
Dendrobium S1926



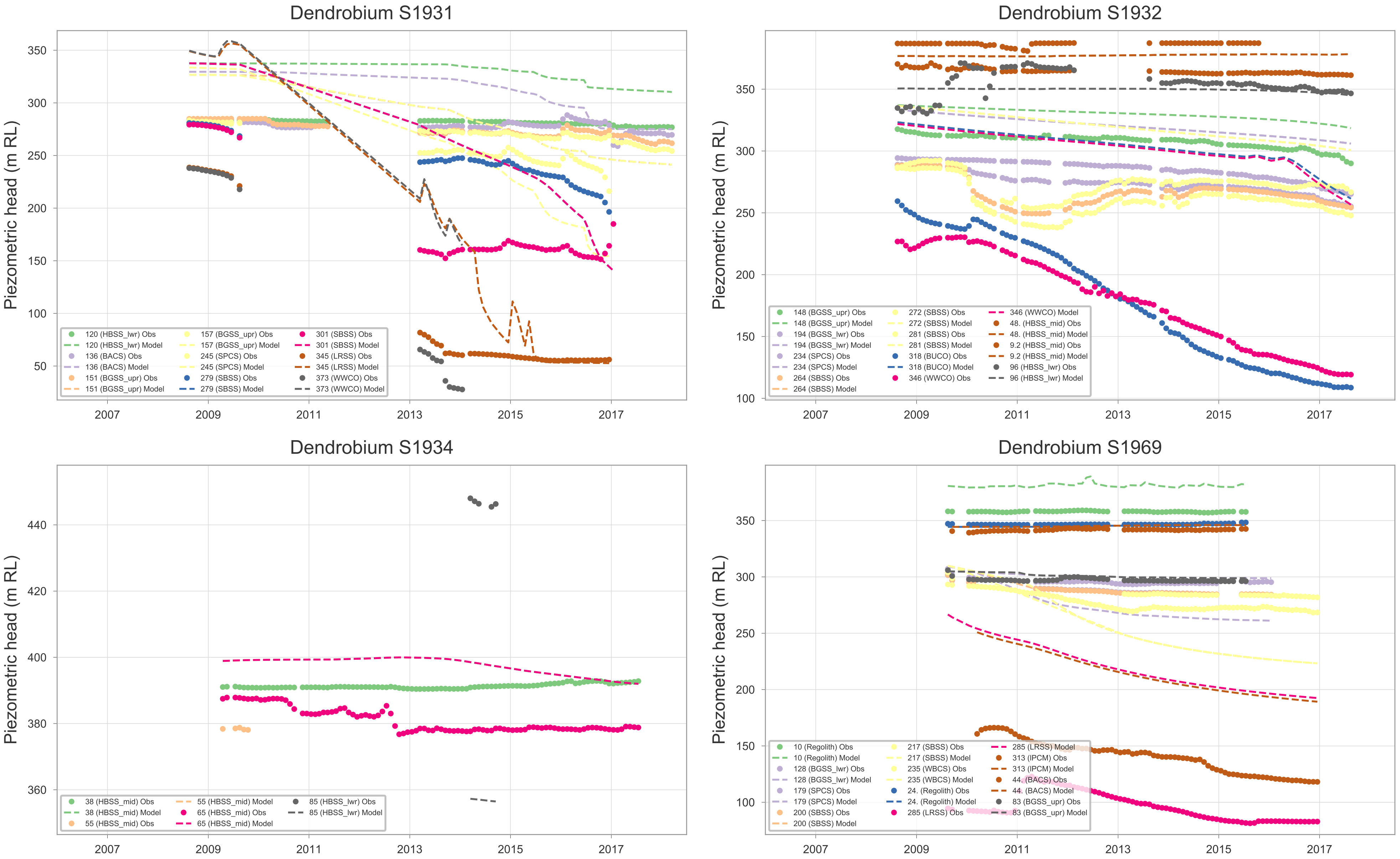
Dendrobium S1927

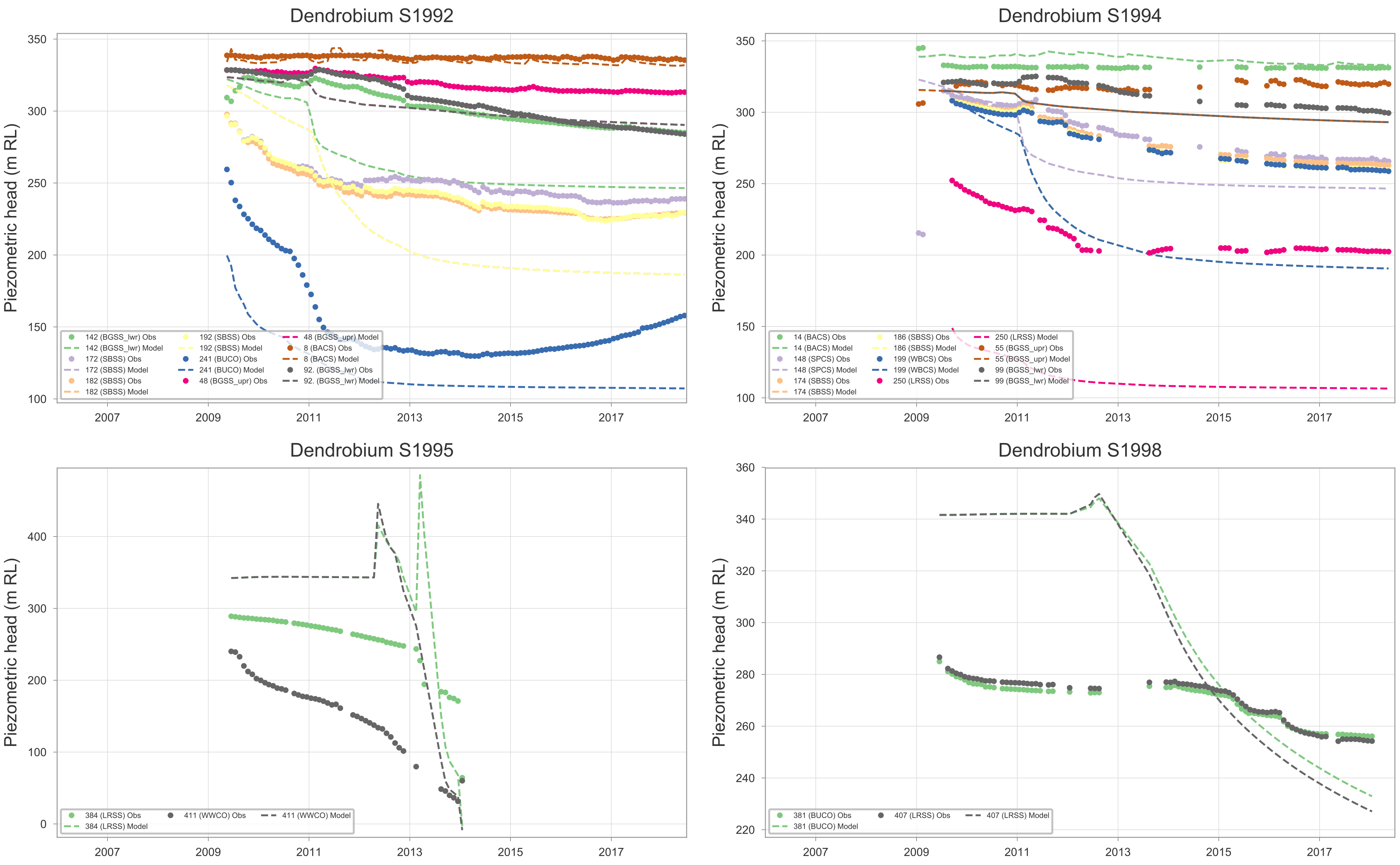


Dendrobium S1929

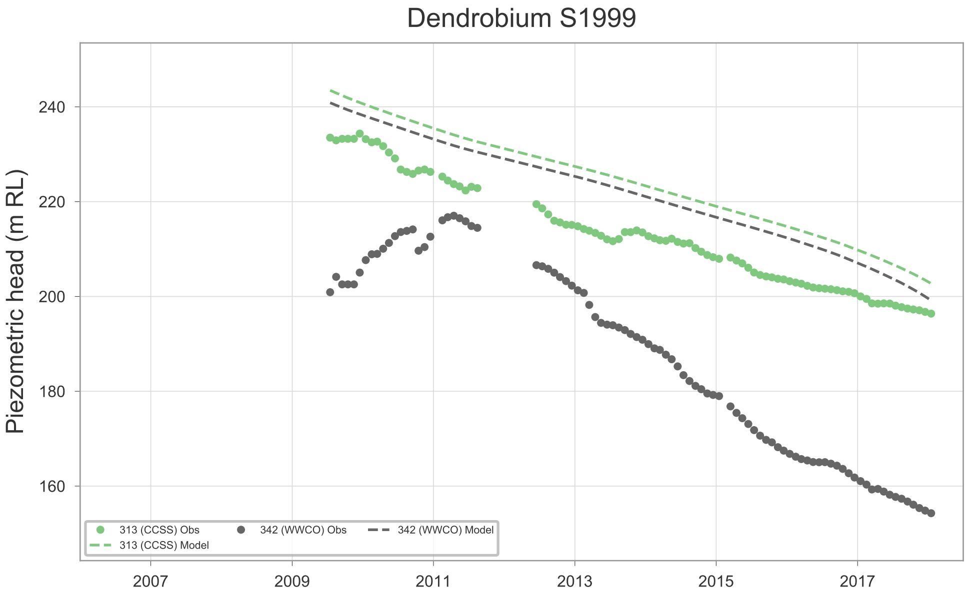


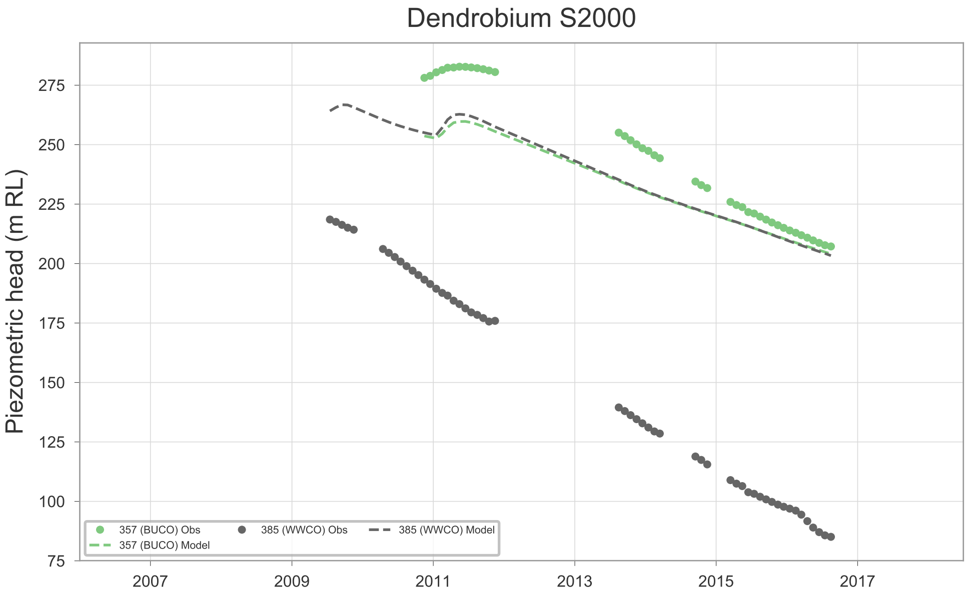
Dendrobium S1930

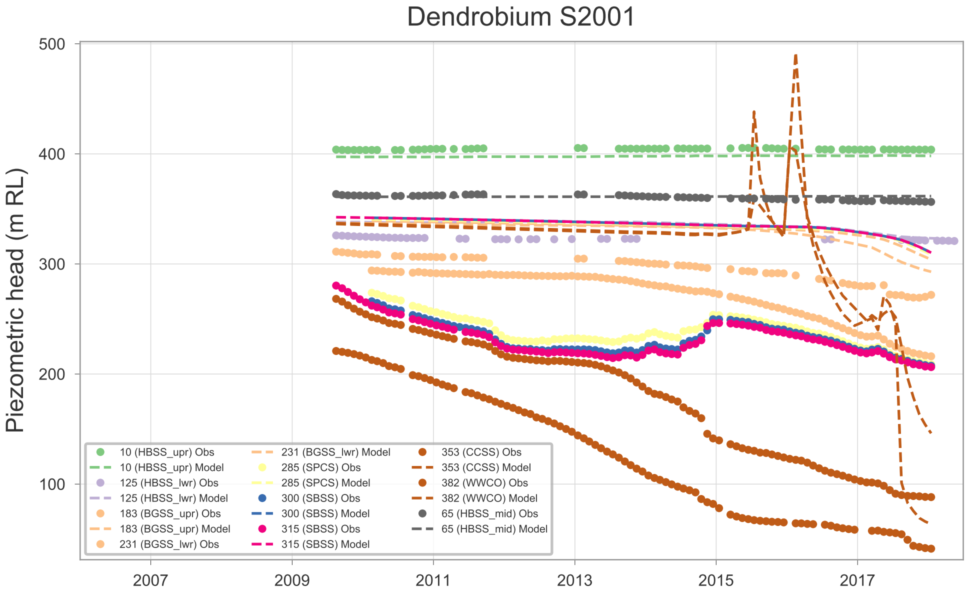

Dendrobium S1931
Piezometric head (m RL)
350
300
250
200
150
100
50
2007
2009
2011
2013
2015
2017
120 (HBSS_lwr) Obs
120 (HBSS_lwr) Model
136 (BACS) Obs
136 (BACS) Model
151 (BGSS_upr) Obs
151 (BGSS_upr) Model
157 (BGSS_upr) Obs
157 (BGSS_upr) Model
245 (SPCS) Obs
245 (SPCS) Model
279 (SBSS) Obs
279 (SBSS) Model
301 (SBSS) Obs
301 (SBSS) Model
345 (LRSS) Obs
345 (LRSS) Model
373 (WWCO) Obs
373 (WWCO) Model
Dendrobium S1932
Piezometric head (m RL)
350
300
250
200
150
100
2007
2009
2011
2013
2015
2017
148 (BGSS_upr) Obs
148 (BGSS_upr) Model
194 (BGSS_lwr) Obs
194 (BGSS_lwr) Model
234 (SPCS) Obs
234 (SPCS) Model
264 (SBSS) Obs
264 (SBSS) Model
272 (SBSS) Obs
272 (SBSS) Model
281 (SBSS) Obs
281 (SBSS) Model
318 (BUCO) Obs
318 (BUCO) Model
346 (WWCO) Obs
346 (WWCO) Model
48. (HBSS_mid) Obs
48. (HBSS_mid) Model
9.2 (HBSS_mid) Obs
9.2 (HBSS_mid) Model
96 (HBSS_lwr) Obs
96 (HBSS_lwr) Model
Dendrobium S1934
Piezometric head (m RL)
440
420
400
380
360
2007
2009
2011
2013
2015
2017
38 (HBSS_mid) Obs
38 (HBSS_mid) Model
55 (HBSS_mid) Obs
55 (HBSS_mid) Model
65 (HBSS_mid) Obs
65 (HBSS_mid) Model
85 (HBSS_lwr) Obs
85 (HBSS_lwr) Model
Dendrobium S1969
Piezometric head (m RL)
350
300
250
200
150
100
2007
2009
2011
2013
2015
2017
10 (Regolith) Obs
10 (Regolith) Model
128 (BGSS_lwr) Obs
128 (BGSS_lwr) Model
179 (SPCS) Obs
179 (SPCS) Model
200 (SBSS) Obs
200 (SBSS) Model
217 (SBSS) Obs
217 (SBSS) Model
235 (WBCS) Obs
235 (WBCS) Model
24. (Regolith) Obs
24. (Regolith) Model
285 (LRSS) Obs
285 (LRSS) Model
313 (IPCM) Obs
313 (IPCM) Model
44. (BACS) Obs
44. (BACS) Model
83 (BGSS_upr) Obs
83 (BGSS_upr) Model

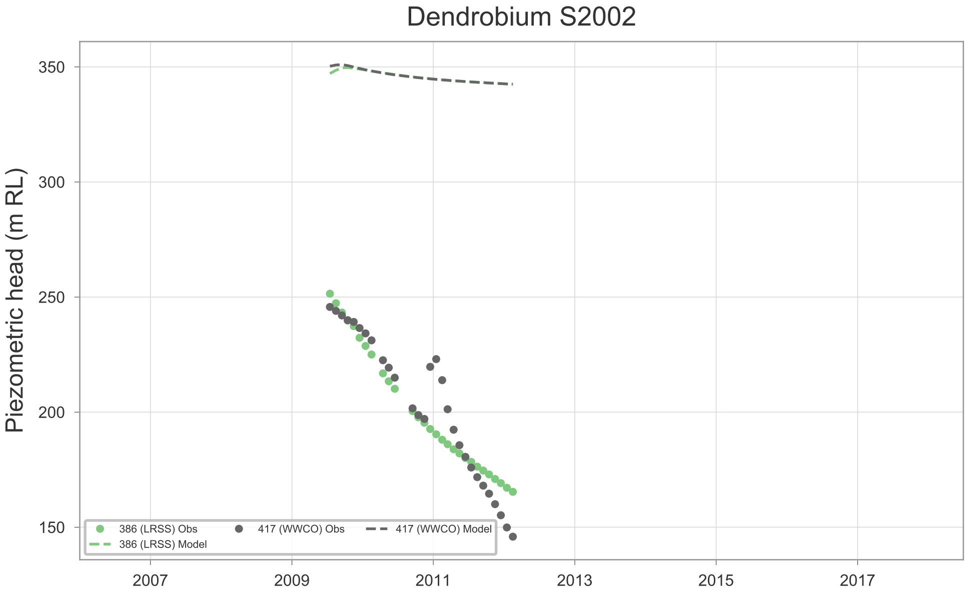


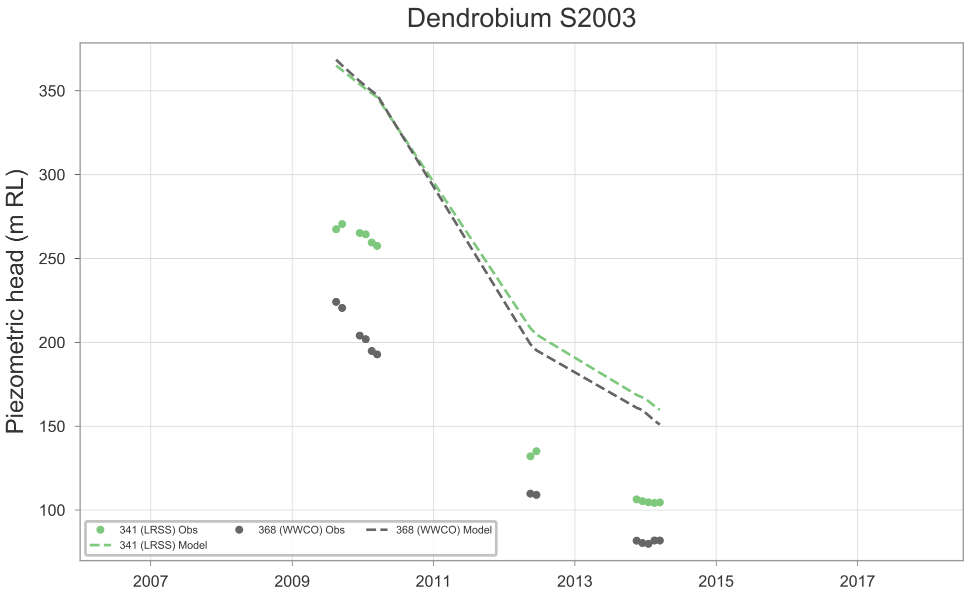
Dendrobium S1992
Piezometric head (m RL)
350
300
250
200
150
100
2007
2009
2011
2013
2015
2017
142 (BGSS_lwr) Obs
142 (BGSS_lwr) Model
172 (SBSS) Obs
172 (SBSS) Model
182 (SBSS) Obs
182 (SBSS) Model
192 (SBSS) Obs
192 (SBSS) Model
241 (BUCO) Obs
241 (BUCO) Model
48 (BGSS_upr) Obs
48 (BGSS_upr) Model
8 (BACS) Obs
8 (BACS) Model
92. (BGSS_lwr) Obs
92. (BGSS_lwr) Model
Dendrobium S1994
Piezometric head (m RL)
350
300
250
200
150
100
2007
2009
2011
2013
2015
2017
14 (BACS) Obs
14 (BACS) Model
148 (SPCS) Obs
148 (SPCS) Model
174 (SBSS) Obs
174 (SBSS) Model
186 (SBSS) Obs
186 (SBSS) Model
199 (WBCS) Obs
199 (WBCS) Model
250 (LRSS) Obs
250 (LRSS) Model
55 (BGSS_upr) Obs
55 (BGSS_upr) Model
99 (BGSS_lwr) Obs
99 (BGSS_lwr) Model
Dendrobium S1995
Piezometric head (m RL)
400
300
200
100
0
2007
2009
2011
2013
2015
2017
384 (LRSS) Obs
384 (LRSS) Model
411 (WWCO) Obs
411 (WWCO) Model
Dendrobium S1998
Piezometric head (m RL)
360
340
320
300
280
260
240
220
2007
2009
2011
2013
2015
2017
381 (BUCO) Obs
381 (BUCO) Model
407 (LRSS) Obs
407 (LRSS) Model

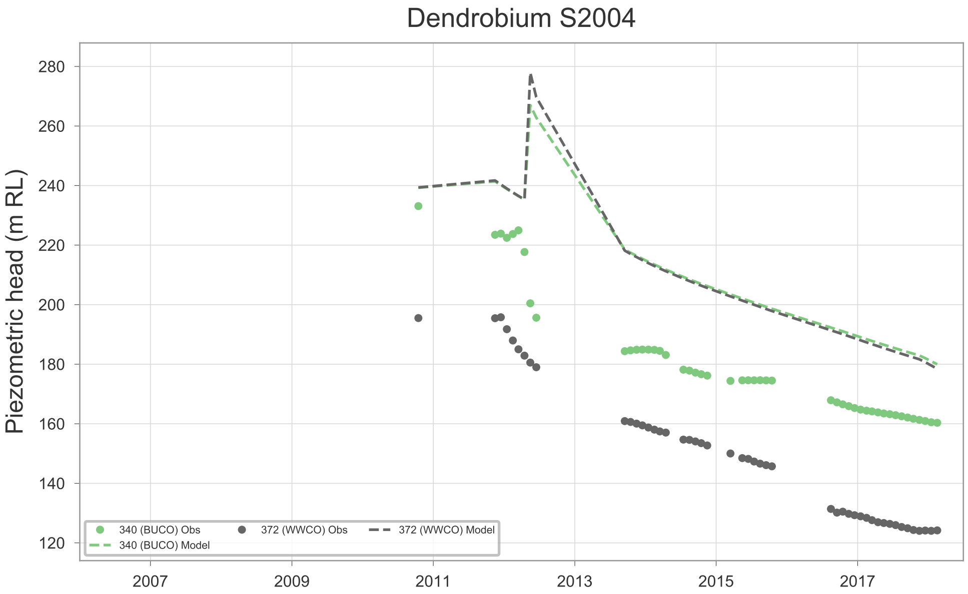

Dendrobium S1999
Piezometric head (m RL)
240
220
200
180
160
2007
2009
2011
2013
2015
2017
313 (CCSS) Obs
313 (CCSS) Model
342 (WWCO) Obs
342 (WWCO) Model

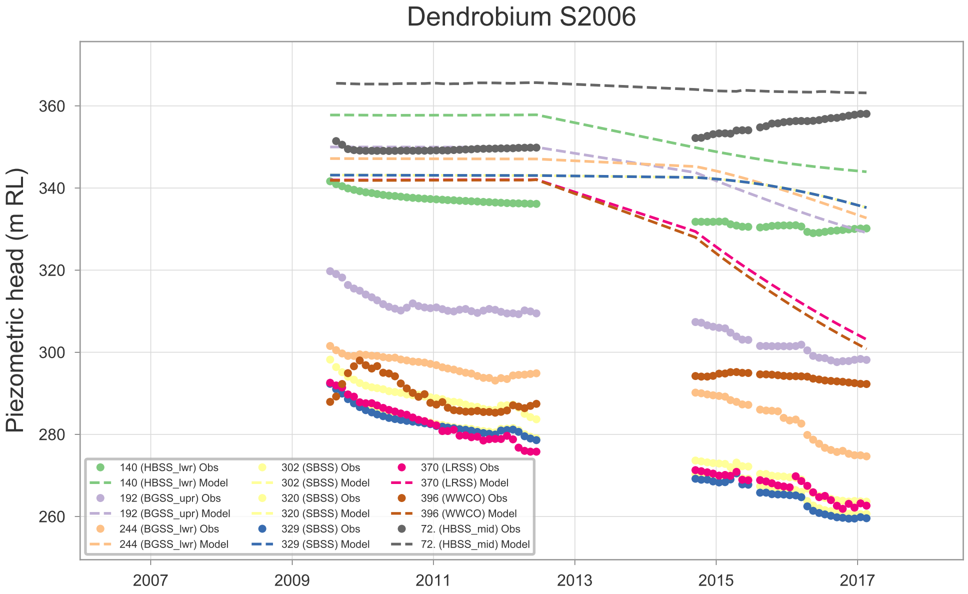

Dendrobium S2000
Piezometric head (m RL)
275
250
225
200
175
150
125
100
75
2007
2009
2011
2013
2015
2017
357 (BUCO) Obs
357 (BUCO) Model
385 (WWCO) Obs
385 (WWCO) Model

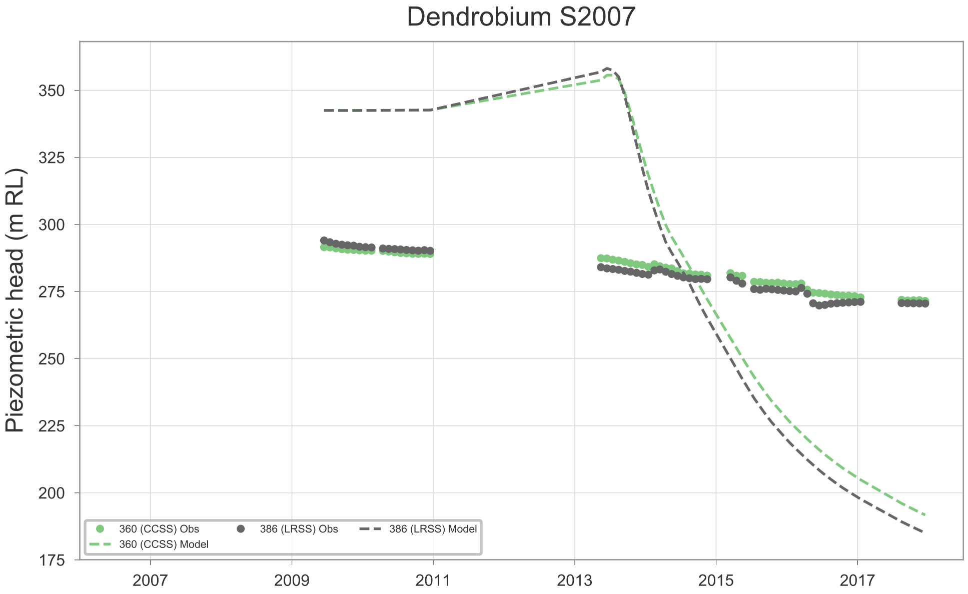

Dendrobium S2001
Piezometric head (m RL)
500
400
300
200
100
2007
2009
2011
2013
2015
2017
10 (HBSS_upr) Obs
10 (HBSS_upr) Model
125 (HBSS_lwr) Obs
125 (HBSS_lwr) Model
183 (BGSS_upr) Obs
183 (BGSS_upr) Model
231 (BGSS_lwr) Obs
231 (BGSS_lwr) Model
285 (SPCS) Obs
285 (SPCS) Model
300 (SBSS) Obs
300 (SBSS) Model
315 (SBSS) Obs
315 (SBSS) Model
353 (CCSS) Obs
353 (CCSS) Model
382 (WWCO) Obs
382 (WWCO) Model
65 (HBSS_mid) Obs
65 (HBSS_mid) Model

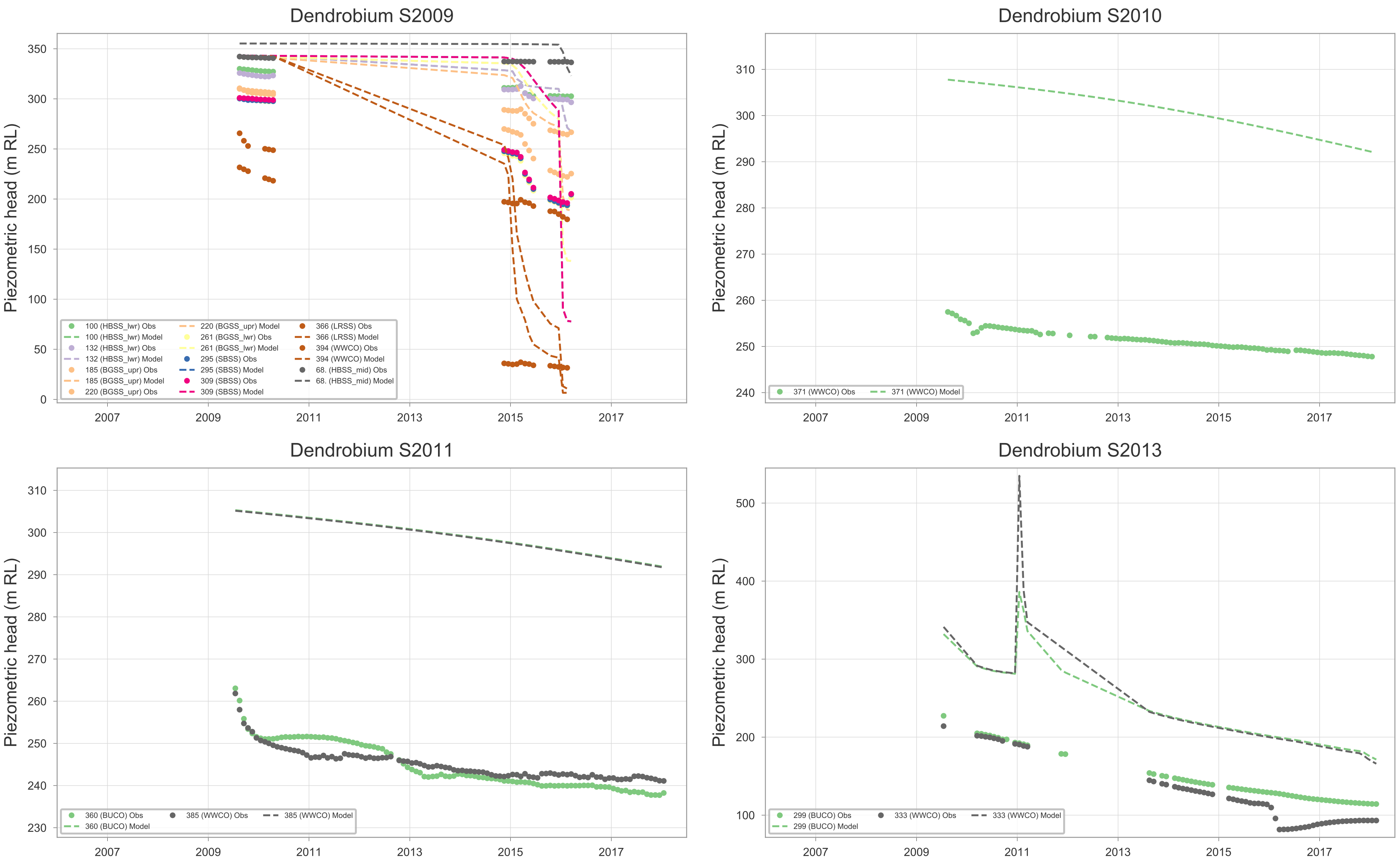

Dendrobium S2002
Piezometric head (m RL)
350
300
250
200
150
2007
2009
2011
2013
2015
2017
386 (LRSS) Obs
386 (LRSS) Model
417 (WWCO) Obs
417 (WWCO) Model

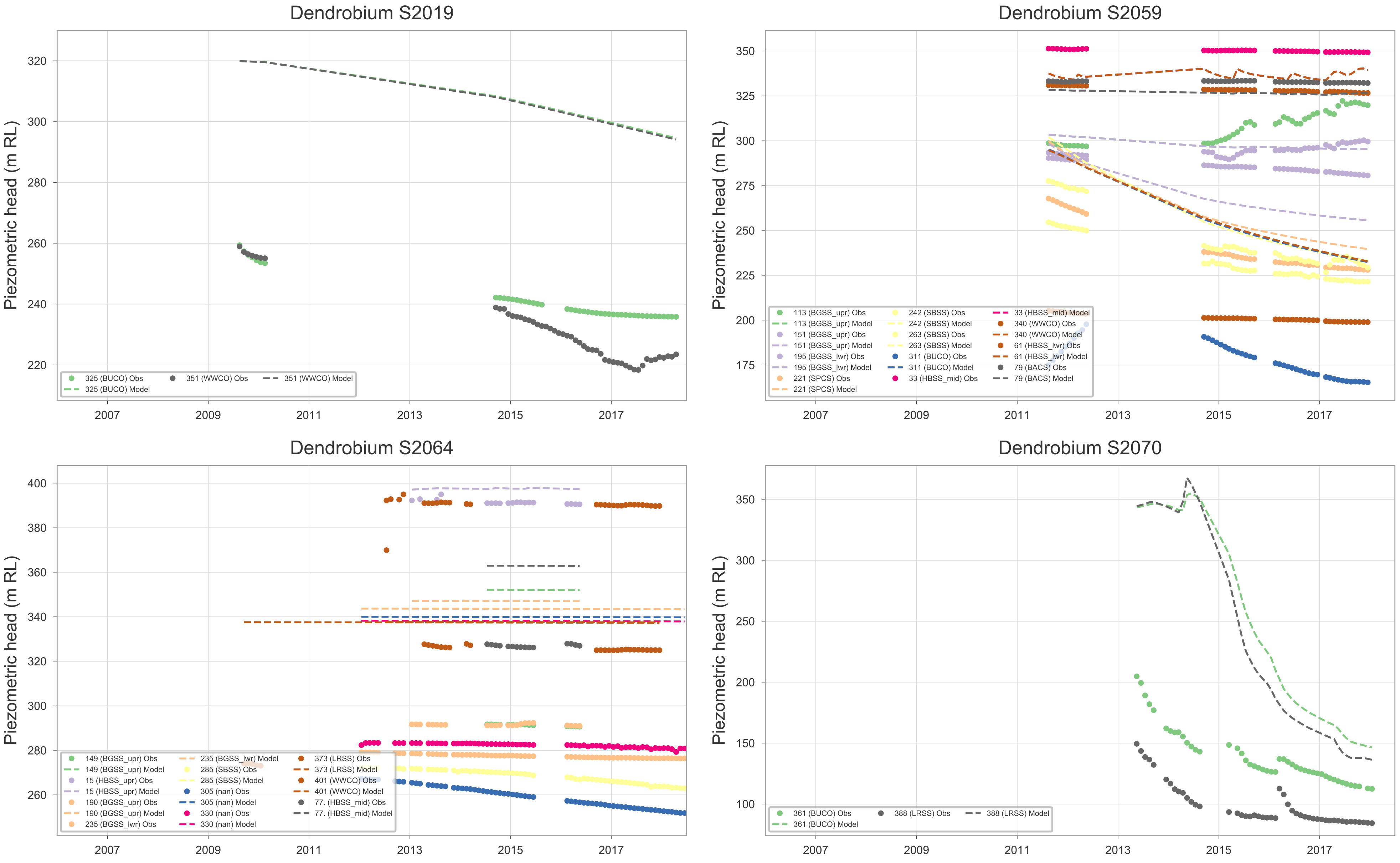

Dendrobium S2003
Piezometric head (m RL)
350
300
250
200
150
100
2007
2009
2011
2013
2015
2017
341 (LRSS) Obs
341 (LRSS) Model
368 (WWCO) Obs
368 (WWCO) Model

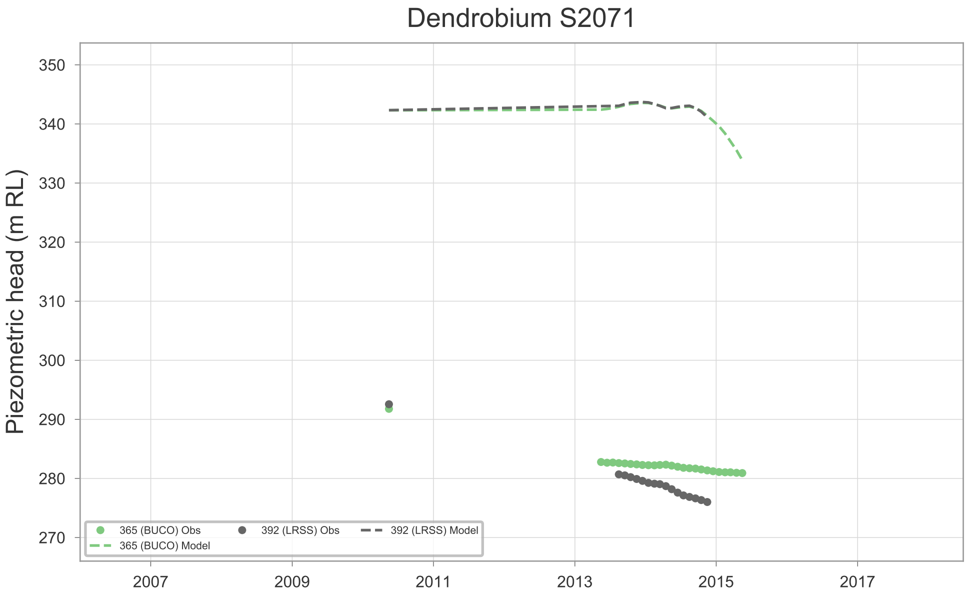

Dendrobium S2004
Piezometric head (m RL)
280
260
240
220
200
180
160
140
120
2007
2009
2011
2013
2015
2017
340 (BUCO) Obs
340 (BUCO) Model
372 (WWCO) Obs
372 (WWCO) Model


Dendrobium S2006
Piezometric head (m RL)
360
340
320
300
280
260
2007
2009
2011
2013
2015
2017
140 (HBSS_lwr) Obs
140 (HBSS_lwr) Model
192 (BGSS_upr) Obs
192 (BGSS_upr) Model
244 (BGSS_lwr) Obs
244 (BGSS_lwr) Model
302 (SBSS) Obs
302 (SBSS) Model
320 (SBSS) Obs
320 (SBSS) Model
329 (SBSS) Obs
329 (SBSS) Model
370 (LRSS) Obs
370 (LRSS) Model
396 (WWCO) Obs
396 (WWCO) Model
72. (HBSS_mid) Obs
72. (HBSS_mid) Model

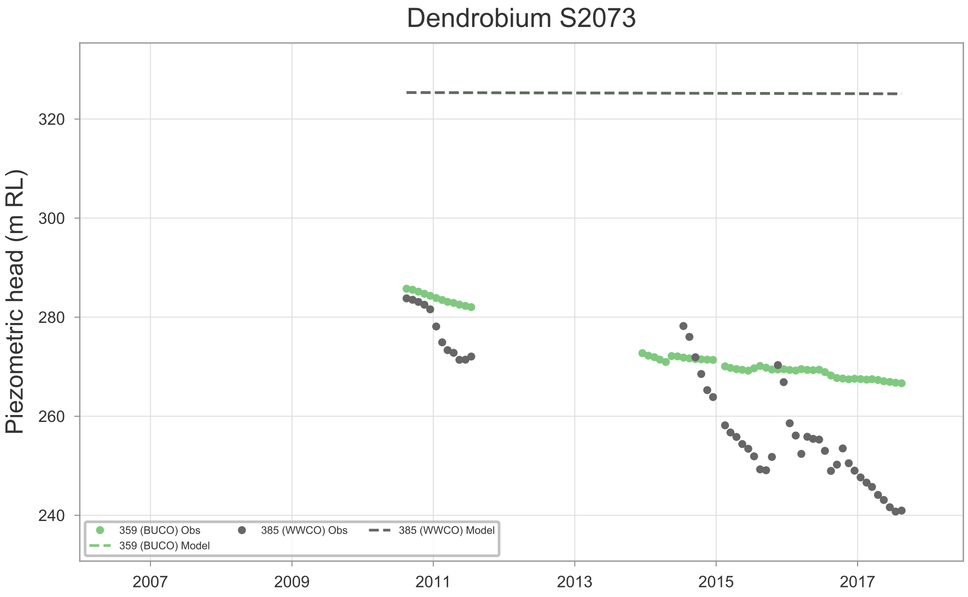

Dendrobium S2007
Piezometric head (m RL)
350
325
300
275
250
225
200
175
2007
2009
2011
2013
2015
2017
360 (CCSS) Obs
360 (CCSS) Model
386 (LRSS) Obs
386 (LRSS) Model


Dendrobium S2009
Piezometric head (m RL)
350
300
250
200
150
100
50
0
2007
2009
2011
2013
2015
2017
100 (HBSS_lwr) Obs
100 (HBSS_lwr) Model
132 (HBSS_lwr) Obs
132 (HBSS_lwr) Model
185 (BGSS_upr) Obs
185 (BGSS_upr) Model
220 (BGSS_upr) Obs
220 (BGSS_upr) Model
261 (BGSS_lwr) Obs
261 (BGSS_lwr) Model
295 (SBSS) Obs
295 (SBSS) Model
309 (SBSS) Obs
309 (SBSS) Model
366 (LRSS) Obs
366 (LRSS) Model
394 (WWCO) Obs
394 (WWCO) Model
68. (HBSS_mid) Obs
68. (HBSS_mid) Model
Dendrobium S2010
Piezometric head (m RL)
310
300
290
280
270
260
250
240
2007
2009
2011
2013
2015
2017
371 (WWCO) Obs
371 (WWCO) Model
Dendrobium S2011
Piezometric head (m RL)
310
300
290
280
270
260
250
240
230
2007
2009
2011
2013
2015
2017
360 (BUCO) Obs
360 (BUCO) Model
385 (WWCO) Obs
385 (WWCO) Model
Dendrobium S2013
Piezometric head (m RL)
500
400
300
200
100
2007
2009
2011
2013
2015
2017
299 (BUCO) Obs
299 (BUCO) Model
333 (WWCO) Obs
333 (WWCO) Model

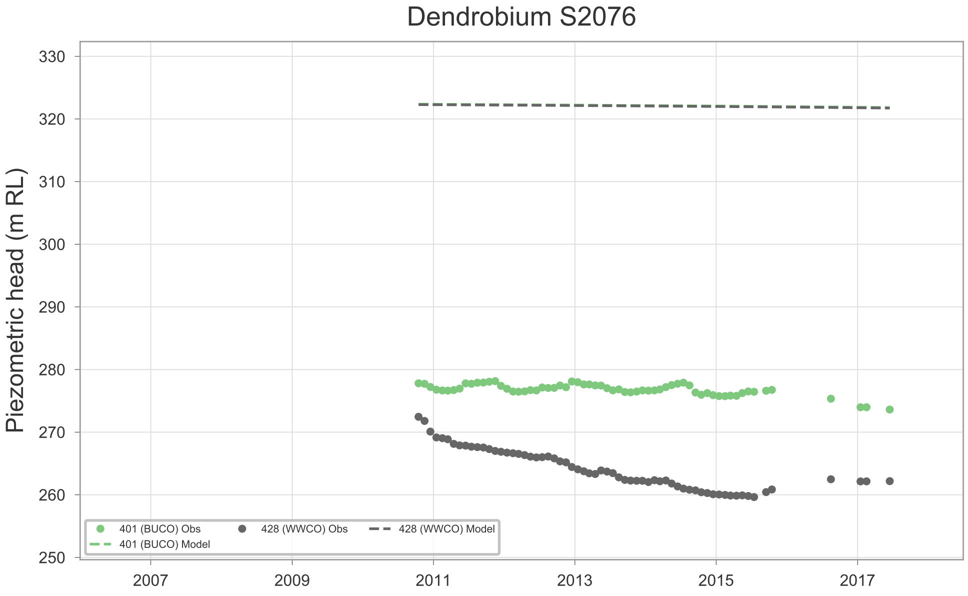

Dendrobium S2019
Piezometric head (m RL)
320
300
280
260
240
220
2007
2009
2011
2013
2015
2017
325 (BUCO) Obs
325 (BUCO) Model
351 (WWCO) Obs
351 (WWCO) Model
Dendrobium S2059
Piezometric head (m RL)
350
325
300
275
250
225
200
175
2007
2009
2011
2013
2015
2017
113 (BGSS_upr) Obs
113 (BGSS_upr) Model
151 (BGSS_upr) Obs
151 (BGSS_upr) Model
195 (BGSS_lwr) Obs
195 (BGSS_lwr) Model
221 (SPCS) Obs
221 (SPCS) Model
242 (SBSS) Obs
242 (SBSS) Model
263 (SBSS) Obs
263 (SBSS) Model
311 (BUCO) Obs
311 (BUCO) Model
33 (HBSS_mid) Obs
33 (HBSS_mid) Model
340 (WWCO) Obs
340 (WWCO) Model
61 (HBSS_lwr) Obs
61 (HBSS_lwr) Model
79 (BACS) Obs
79 (BACS) Model
Dendrobium S2064
Piezometric head (m RL)
400
380
360
340
320
300
280
260
2007
2009
2011
2013
2015
2017
149 (BGSS_upr) Obs
149 (BGSS_upr) Model
15 (HBSS_upr) Obs
15 (HBSS_upr) Model
190 (BGSS_upr) Obs
190 (BGSS_upr) Model
235 (BGSS_lwr) Obs
235 (BGSS_lwr) Model
285 (SBSS) Obs
285 (SBSS) Model
305 (nan) Obs
305 (nan) Model
330 (nan) Obs
330 (nan) Model
373 (LRSS) Obs
373 (LRSS) Model
401 (WWCO) Obs
401 (WWCO) Model
77. (HBSS_mid) Obs
77. (HBSS_mid) Model
Dendrobium S2070
Piezometric head (m RL)
350
300
250
200
150
100
2007
2009
2011
2013
2015
2017
361 (BUCO) Obs
361 (BUCO) Model
388 (LRSS) Obs
388 (LRSS) Model



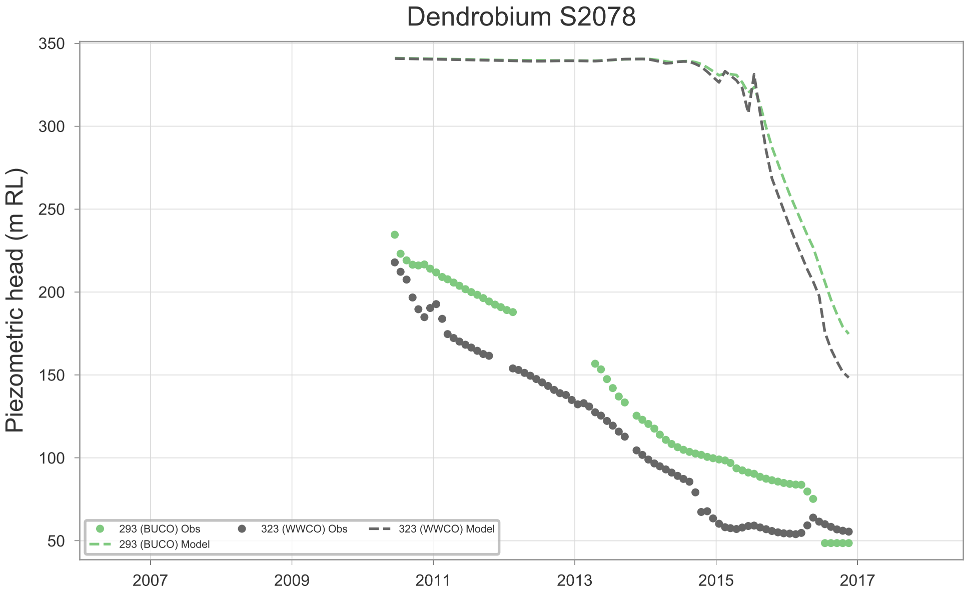
Dendrobium S2071



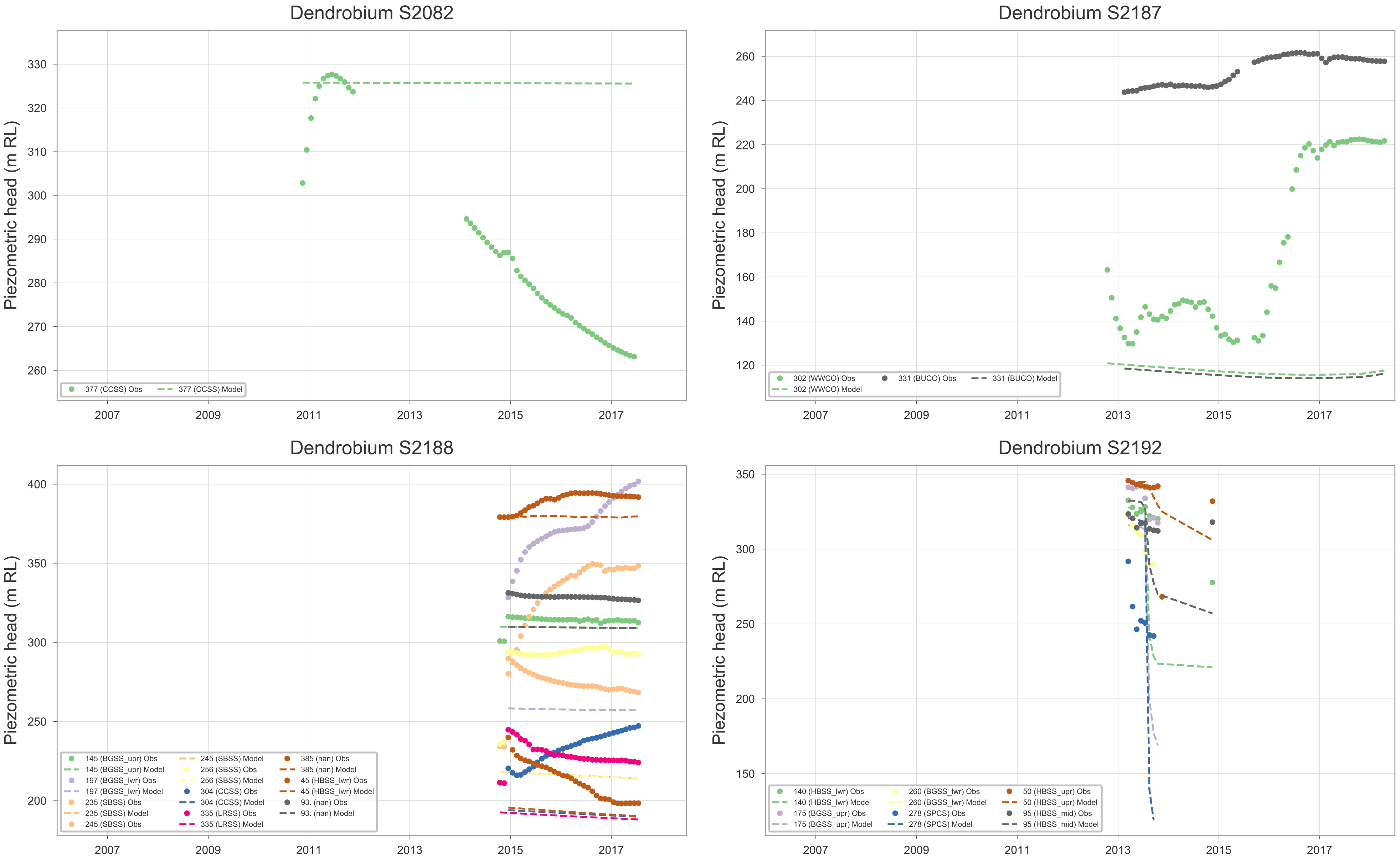
Dendrobium S2073

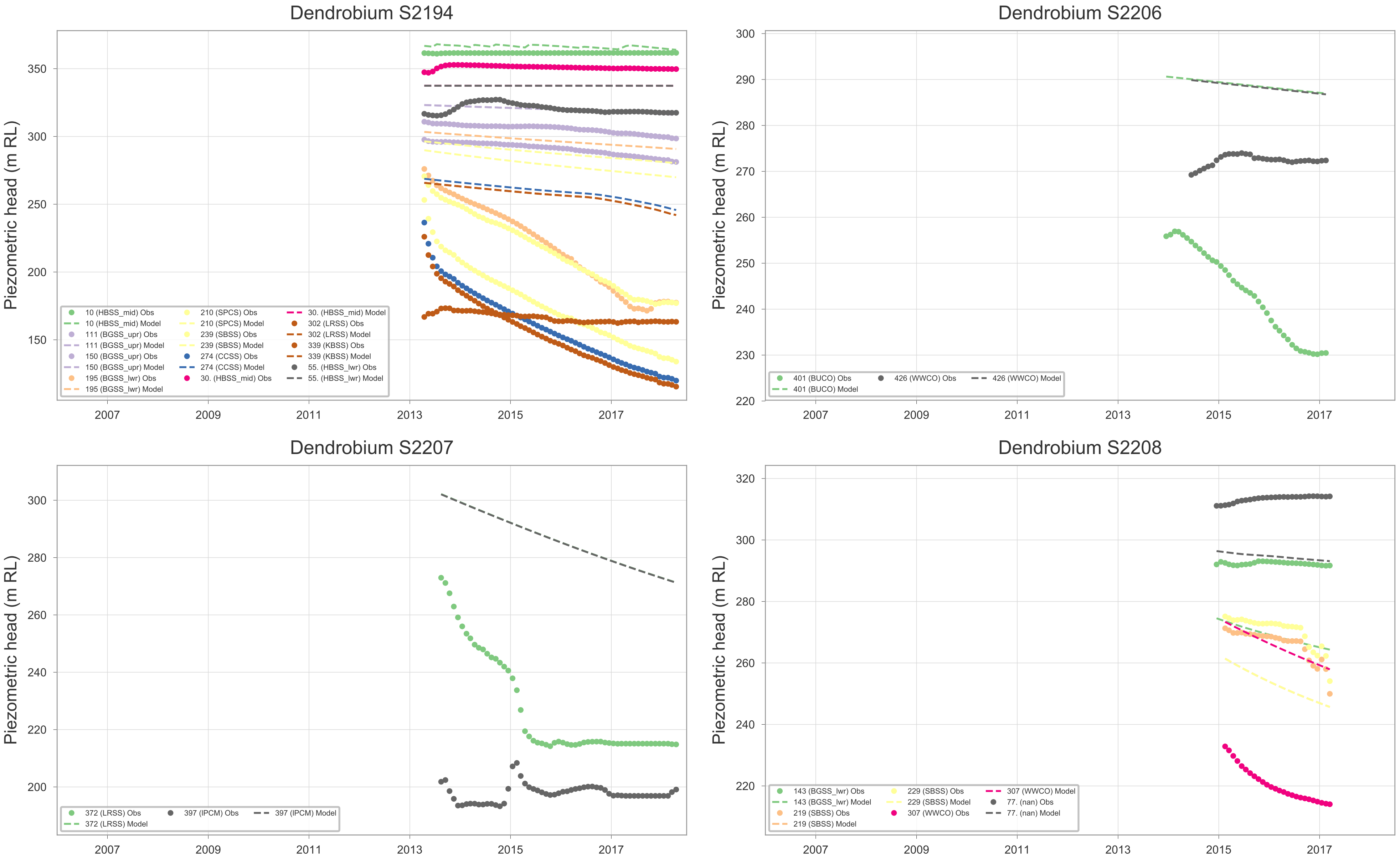


Dendrobium S2076

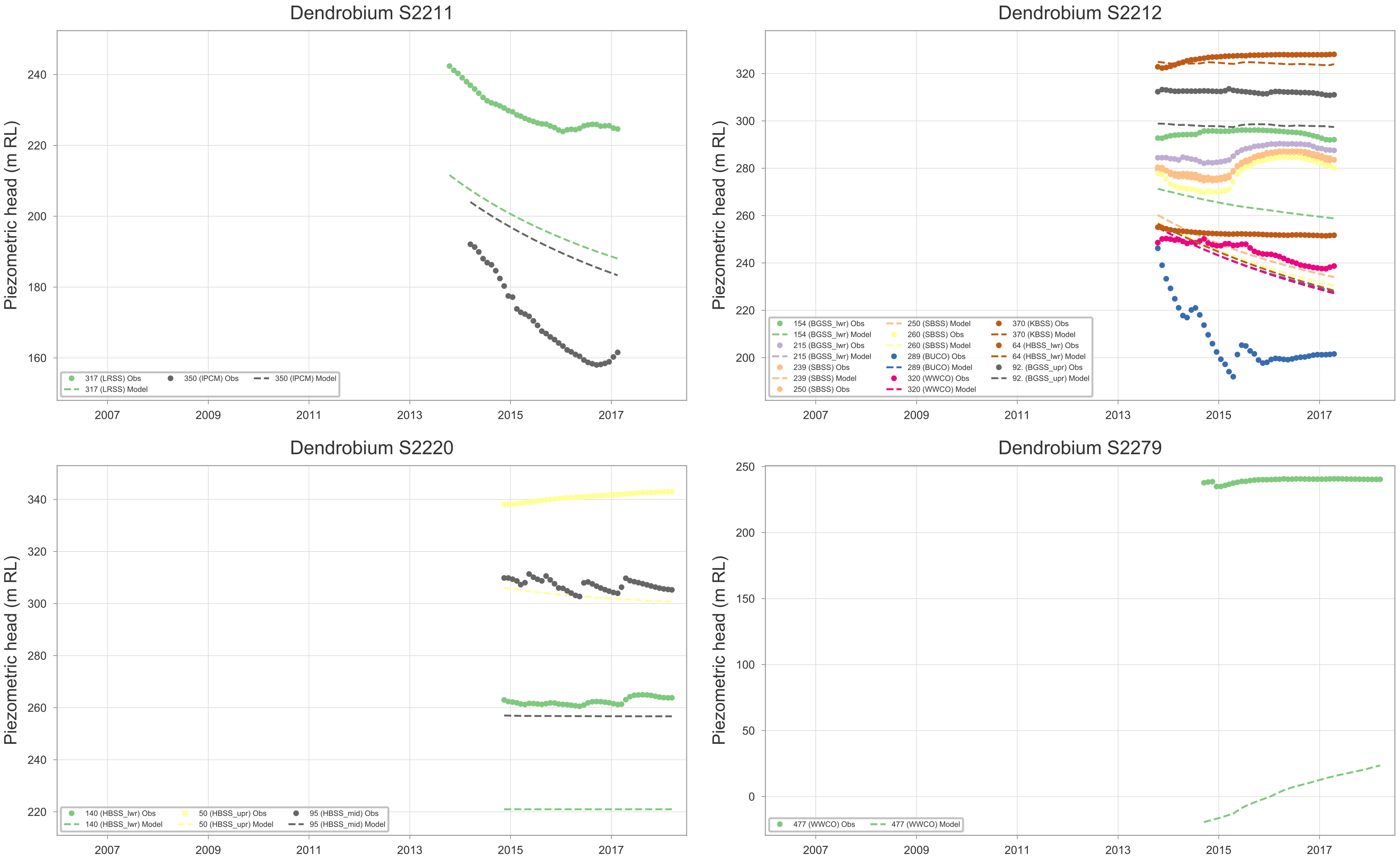


Dendrobium S2078


Dendrobium S2082
Piezometric head (m RL)
330
320
310
300
290
280
270
260
2007
2009
2011
2013
2015
2017
377 (CCSS) Obs
377 (CCSS) Model
Dendrobium S2187
Piezometric head (m RL)
260
240
220
200
180
160
140
120
2007
2009
2011
2013
2015
2017
302 (WWCO) Obs
302 (WWCO) Model
331 (BUCO) Obs
331 (BUCO) Model
Dendrobium S2188
Piezometric head (m RL)
400
350
300
250
200
2007
2009
2011
2013
2015
2017
145 (BGSS_upr) Obs
145 (BGSS_upr) Model
197 (BGSS_lwr) Obs
197 (BGSS_lwr) Model
235 (SBSS) Obs
235 (SBSS) Model
245 (SBSS) Obs
245 (SBSS) Model
256 (SBSS) Obs
256 (SBSS) Model
304 (CCSS) Obs
304 (CCSS) Model
335 (LRSS) Obs
335 (LRSS) Model
385 (nan) Obs
385 (nan) Model
45 (HBSS_lwr) Obs
45 (HBSS_lwr) Model
93. (nan) Obs
93. (nan) Model
Dendrobium S2192
Piezometric head (m RL)
350
300
250
200
150
2007
2009
2011
2013
2015
2017
140 (HBSS_lwr) Obs
140 (HBSS_lwr) Model
175 (BGSS_upr) Obs
175 (BGSS_upr) Model
260 (BGSS_lwr) Obs
260 (BGSS_lwr) Model
278 (SPCS) Obs
278 (SPCS) Model
50 (HBSS_upr) Obs
50 (HBSS_upr) Model
95 (HBSS_mid) Obs
95 (HBSS_mid) Model



Dendrobium S2194
Piezometric head (m RL)
350
300
250
200
150
2007
2009
2011
2013
2015
2017
10 (HBSS_mid) Obs
10 (HBSS_mid) Model
111 (BGSS_upr) Obs
111 (BGSS_upr) Model
150 (BGSS_upr) Obs
150 (BGSS_upr) Model
195 (BGSS_lwr) Obs
195 (BGSS_lwr) Model
210 (SPCS) Obs
210 (SPCS) Model
239 (SBSS) Obs
239 (SBSS) Model
274 (CCSS) Obs
274 (CCSS) Model
30. (HBSS_mid) Obs
30. (HBSS_mid) Model
302 (LRSS) Obs
302 (LRSS) Model
339 (KBSS) Obs
339 (KBSS) Model
55. (HBSS_lwr) Obs
55. (HBSS_lwr) Model
Dendrobium S2206
Piezometric head (m RL)
300
290
280
270
260
250
240
230
220
2007
2009
2011
2013
2015
2017
401 (BUCO) Obs
401 (BUCO) Model
426 (WWCO) Obs
426 (WWCO) Model
Dendrobium S2207
Piezometric head (m RL)
300
280
260
240
220
200
2007
2009
2011
2013
2015
2017
372 (LRSS) Obs
372 (LRSS) Model
397 (IPCM) Obs
397 (IPCM) Model
Dendrobium S2208
Piezometric head (m RL)
320
300
280
260
240
220
2007
2009
2011
2013
2015
2017
143 (BGSS_lwr) Obs
143 (BGSS_lwr) Model
219 (SBSS) Obs
219 (SBSS) Model
229 (SBSS) Obs
229 (SBSS) Model
307 (WWCO) Obs
307 (WWCO) Model
77. (nan) Obs
77. (nan) Model

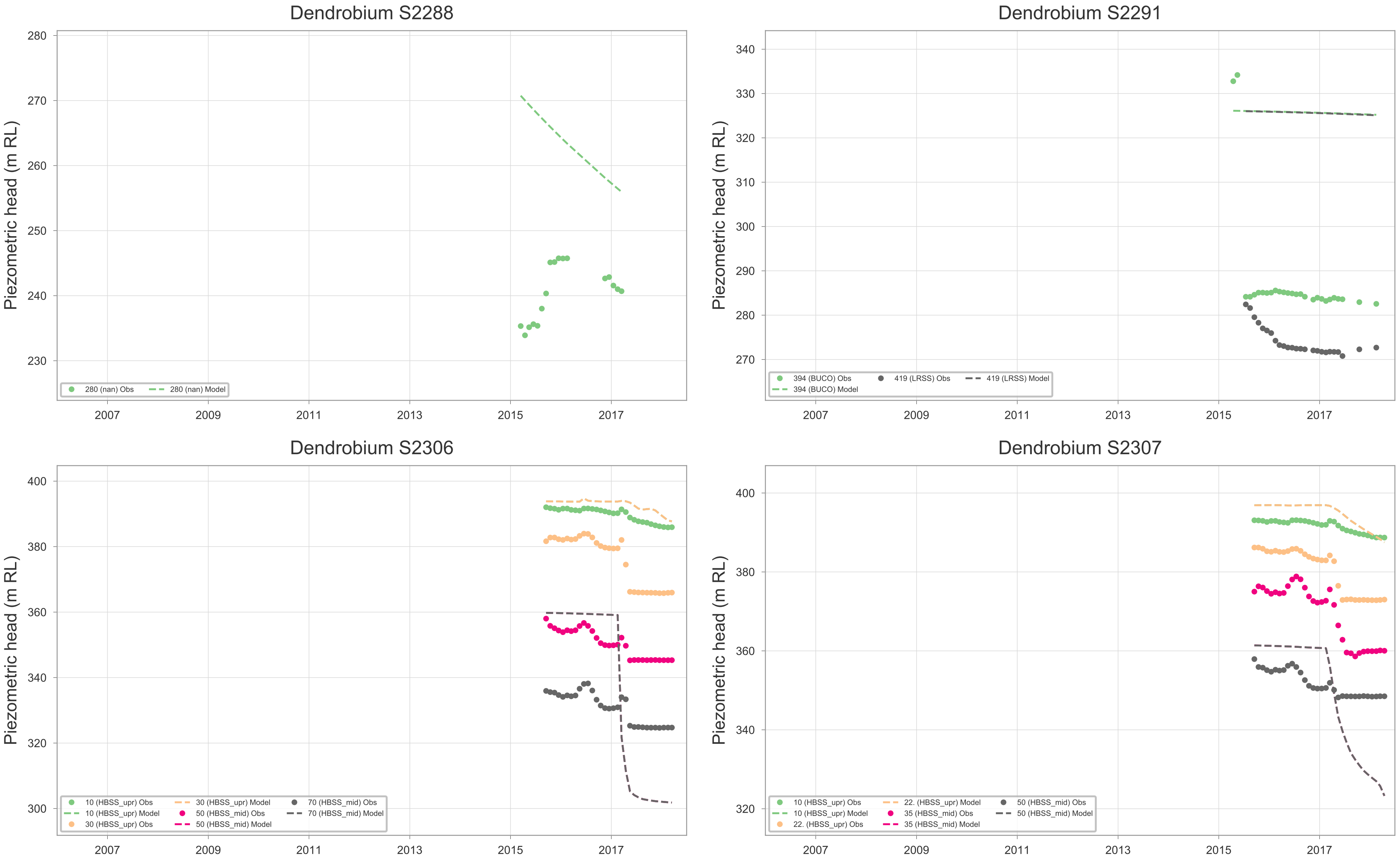


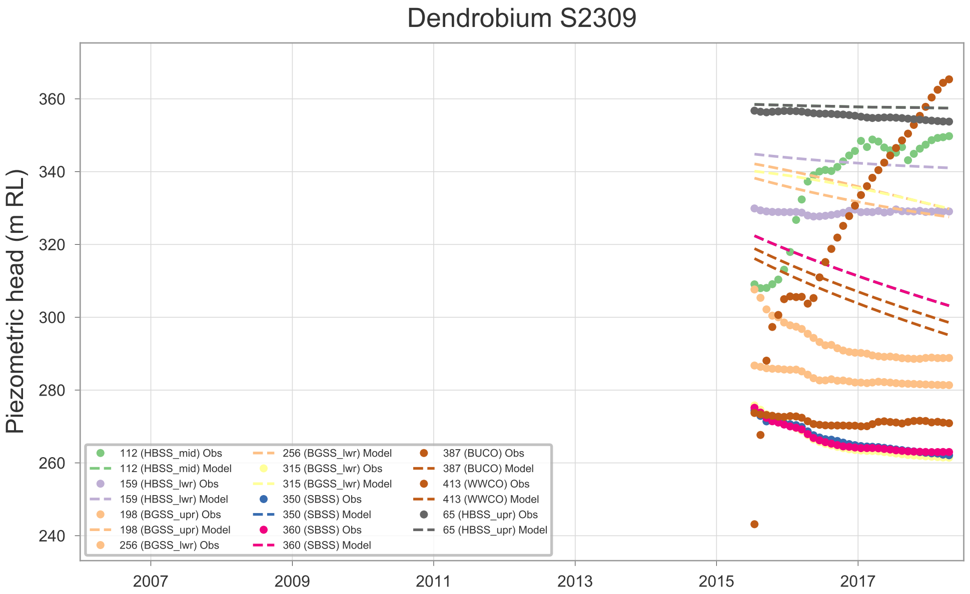
Dendrobium S2211

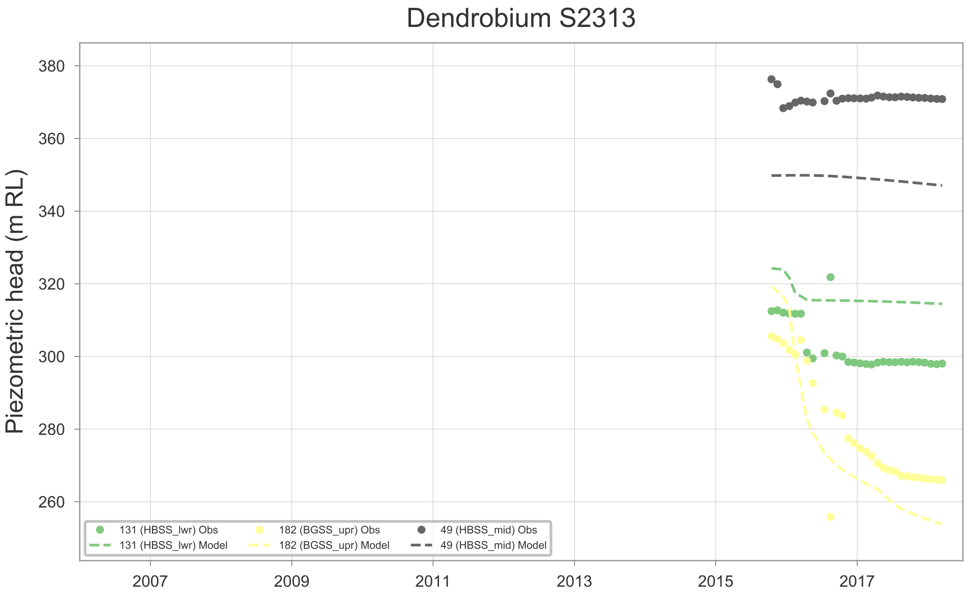
Dendrobium S2212

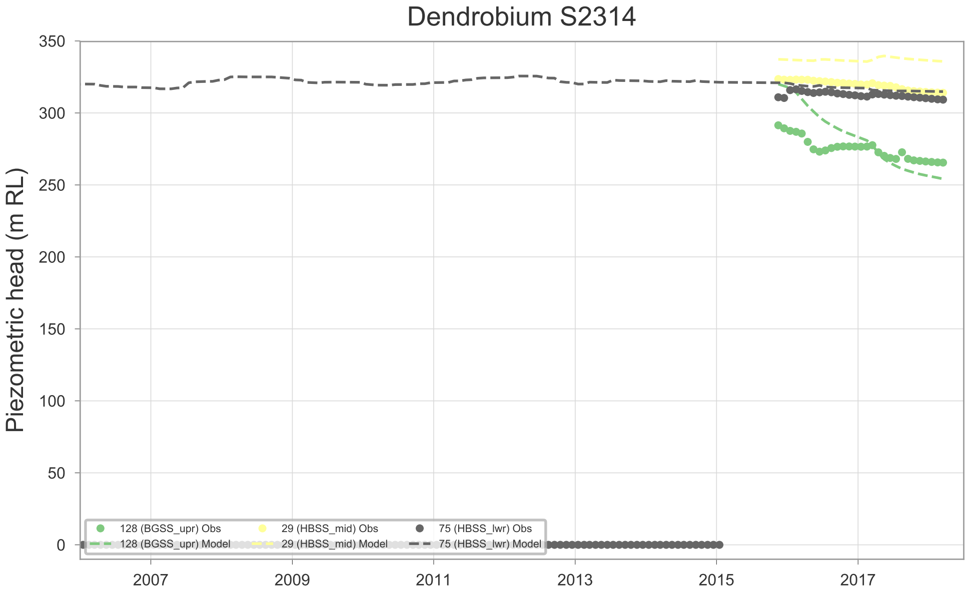
Dendrobium S2220

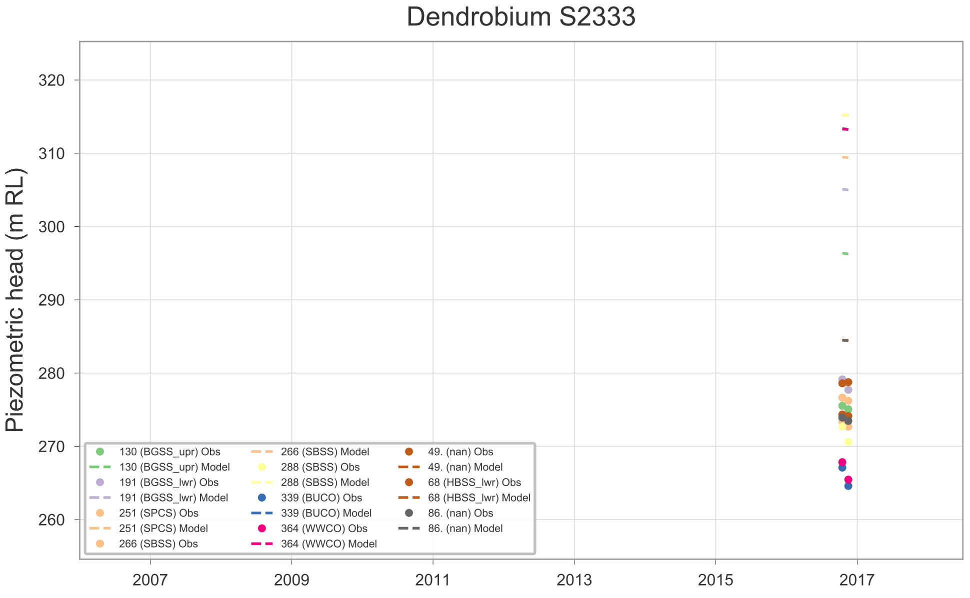
Dendrobium S2279


Dendrobium S2288
Piezometric head (m RL)
280
270
260
250
240
230
2007
2009
2011
2013
2015
2017
280 (nan) Obs
280 (nan) Model
Dendrobium S2291
Piezometric head (m RL)
340
330
320
310
300
290
280
270
2007
2009
2011
2013
2015
2017
394 (BUCO) Obs
394 (BUCO) Model
419 (LRSS) Obs
419 (LRSS) Model
Dendrobium S2306
Piezometric head (m RL)
400
380
360
340
320
300
2007
2009
2011
2013
2015
2017
10 (HBSS_upr) Obs
10 (HBSS_upr) Model
30 (HBSS_upr) Obs
30 (HBSS_upr) Model
50 (HBSS_mid) Obs
50 (HBSS_mid) Model
70 (HBSS_mid) Obs
70 (HBSS_mid) Model
Dendrobium S2307
Piezometric head (m RL)
400
380
360
340
320
2007
2009
2011
2013
2015
2017
10 (HBSS_upr) Obs
10 (HBSS_upr) Model
22. (HBSS_upr) Obs
22. (HBSS_upr) Model
35 (HBSS_mid) Obs
35 (HBSS_mid) Model
50 (HBSS_mid) Obs
50 (HBSS_mid) Model

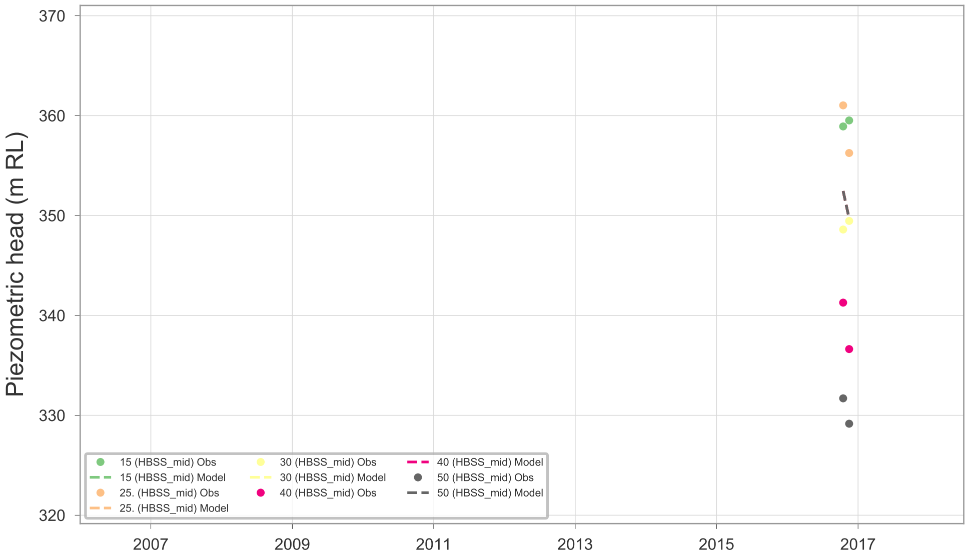

Dendrobium S2309
Piezometric head (m RL)
360
340
320
300
280
260
240
2007
2009
2011
2013
2015
2017
112 (HBSS_mid) Obs
112 (HBSS_mid) Model
159 (HBSS_lwr) Obs
159 (HBSS_lwr) Model
198 (BGSS_upr) Obs
198 (BGSS_upr) Model
256 (BGSS_lwr) Obs
256 (BGSS_lwr) Model
315 (BGSS_lwr) Obs
315 (BGSS_lwr) Model
350 (SBSS) Obs
350 (SBSS) Model
360 (SBSS) Obs
360 (SBSS) Model
387 (BUCO) Obs
387 (BUCO) Model
413 (WWCO) Obs
413 (WWCO) Model
65 (HBSS_upr) Obs
65 (HBSS_upr) Model


Dendrobium S2313
Piezometric head (m RL)
380
360
340
320
300
280
260
2007
2009
2011
2013
2015
2017
131 (HBSS_lwr) Obs
131 (HBSS_lwr) Model
182 (BGSS_upr) Obs
182 (BGSS_upr) Model
49 (HBSS_mid) Obs
49 (HBSS_mid) Model

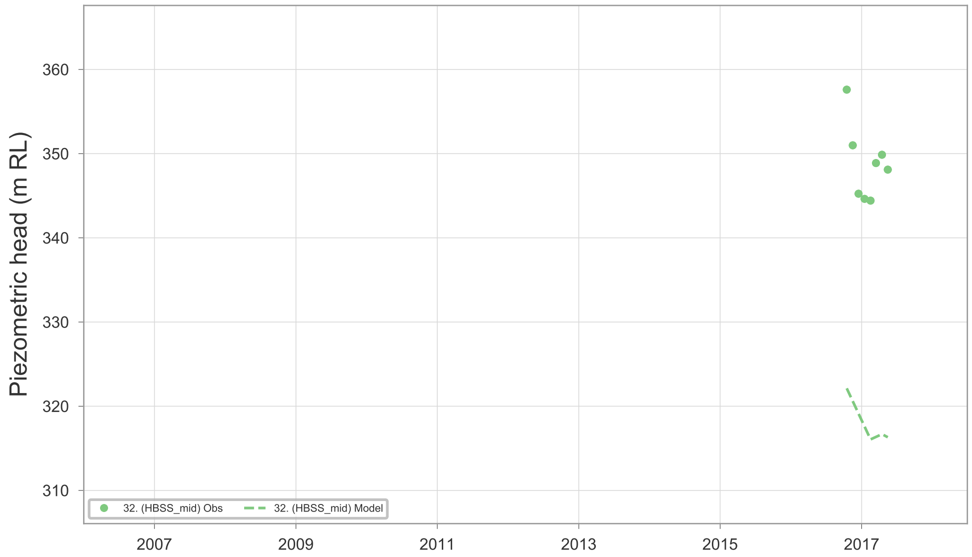

Dendrobium S2314
Piezometric head (m RL)
350
300
250
200
150
100
50
0
2007
2009
2011
2013
2015
2017
128 (BGSS_upr) Obs
128 (BGSS_upr) Model
29 (HBSS_mid) Obs
29 (HBSS_mid) Model
75 (HBSS_lwr) Obs
75 (HBSS_lwr) Model


Dendrobium S2333
Piezometric head (m RL)
320
310
300
290
280
270
260
2007
2009
2011
2013
2015
2017
130 (BGSS_upr) Obs
130 (BGSS_upr) Model
191 (BGSS_lwr) Obs
191 (BGSS_lwr) Model
251 (SPCS) Obs
251 (SPCS) Model
266 (SBSS) Obs
266 (SBSS) Model
288 (SBSS) Obs
288 (SBSS) Model
339 (BUCO) Obs
339 (BUCO) Model
364 (WWCO) Obs
364 (WWCO) Model
49. (nan) Obs
49. (nan) Model
68 (HBSS_lwr) Obs
68 (HBSS_lwr) Model
86. (nan) Obs
86. (nan) Model

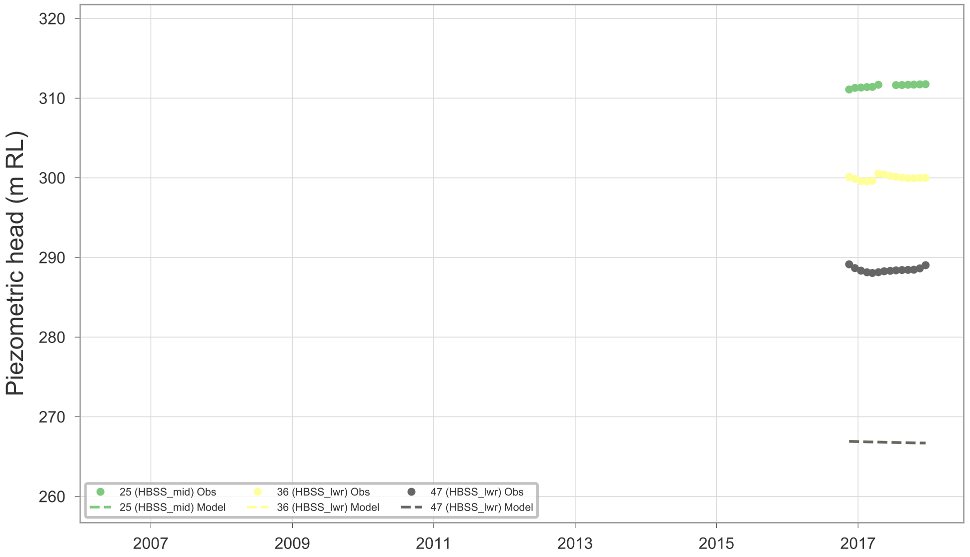
Dendrobium S2335



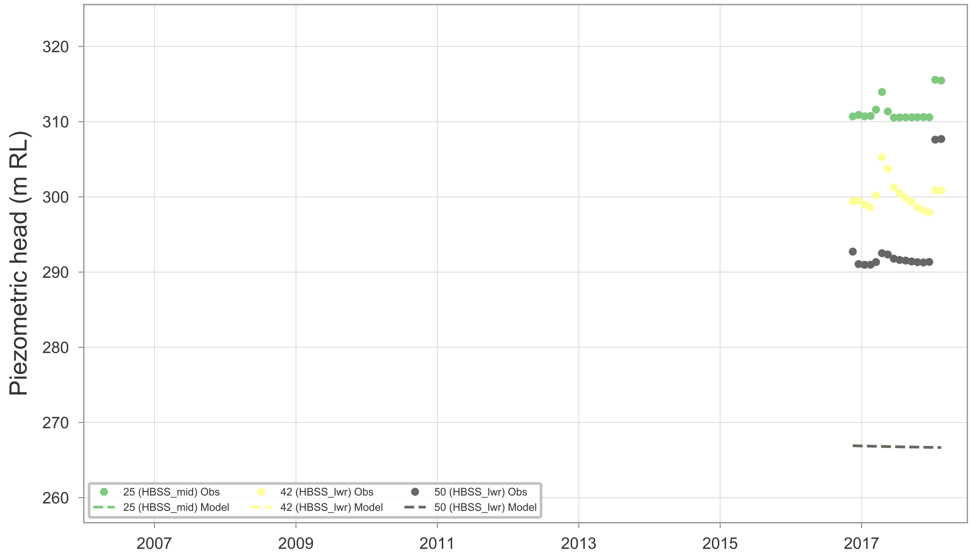
Dendrobium S2336

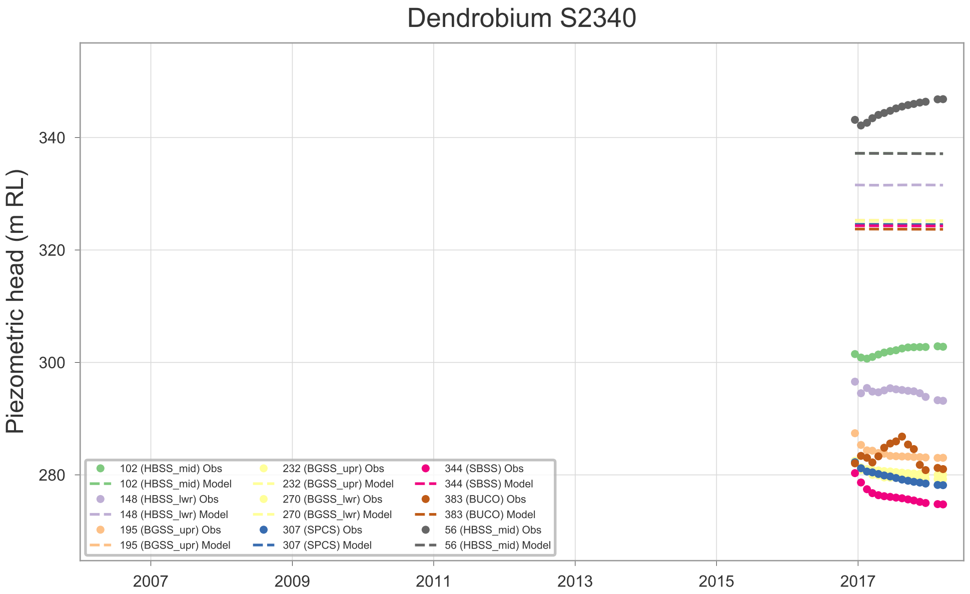


Dendrobium S2337

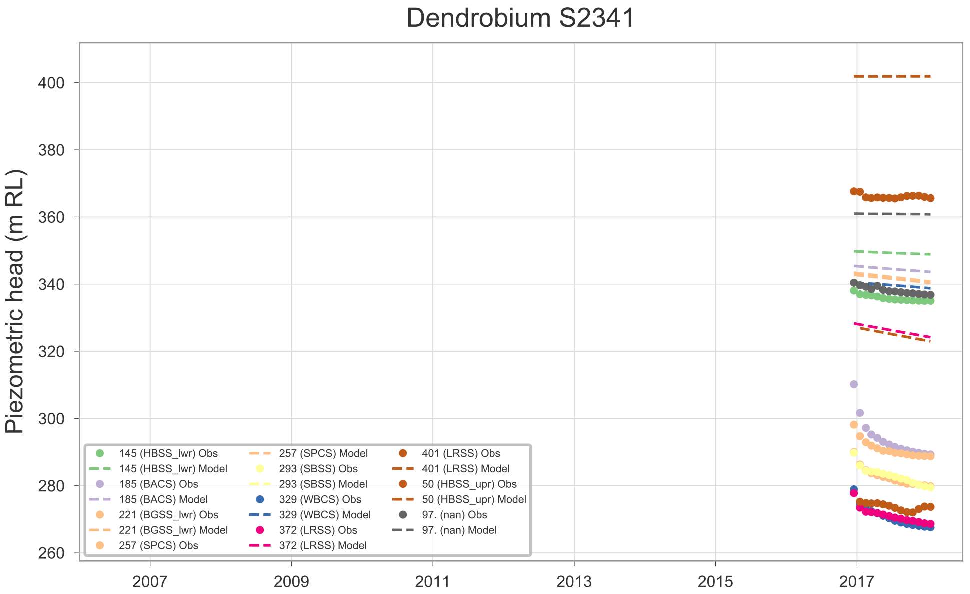


Dendrobium S2338

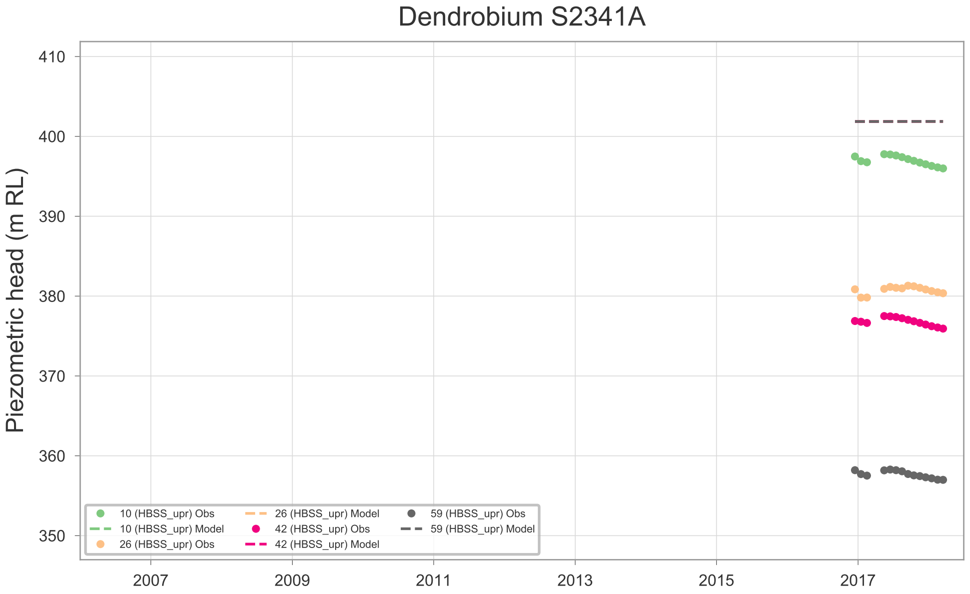




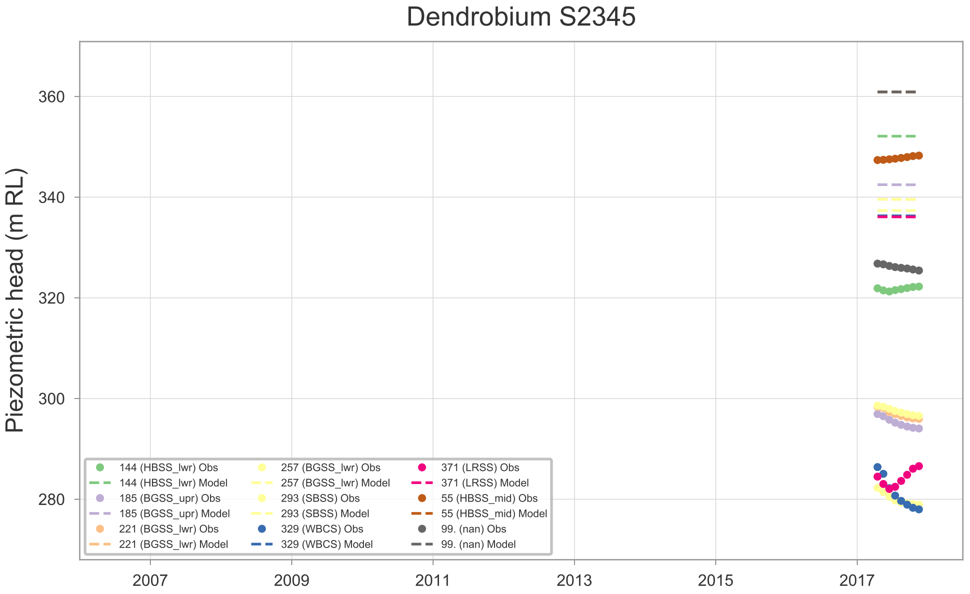
Dendrobium S2340



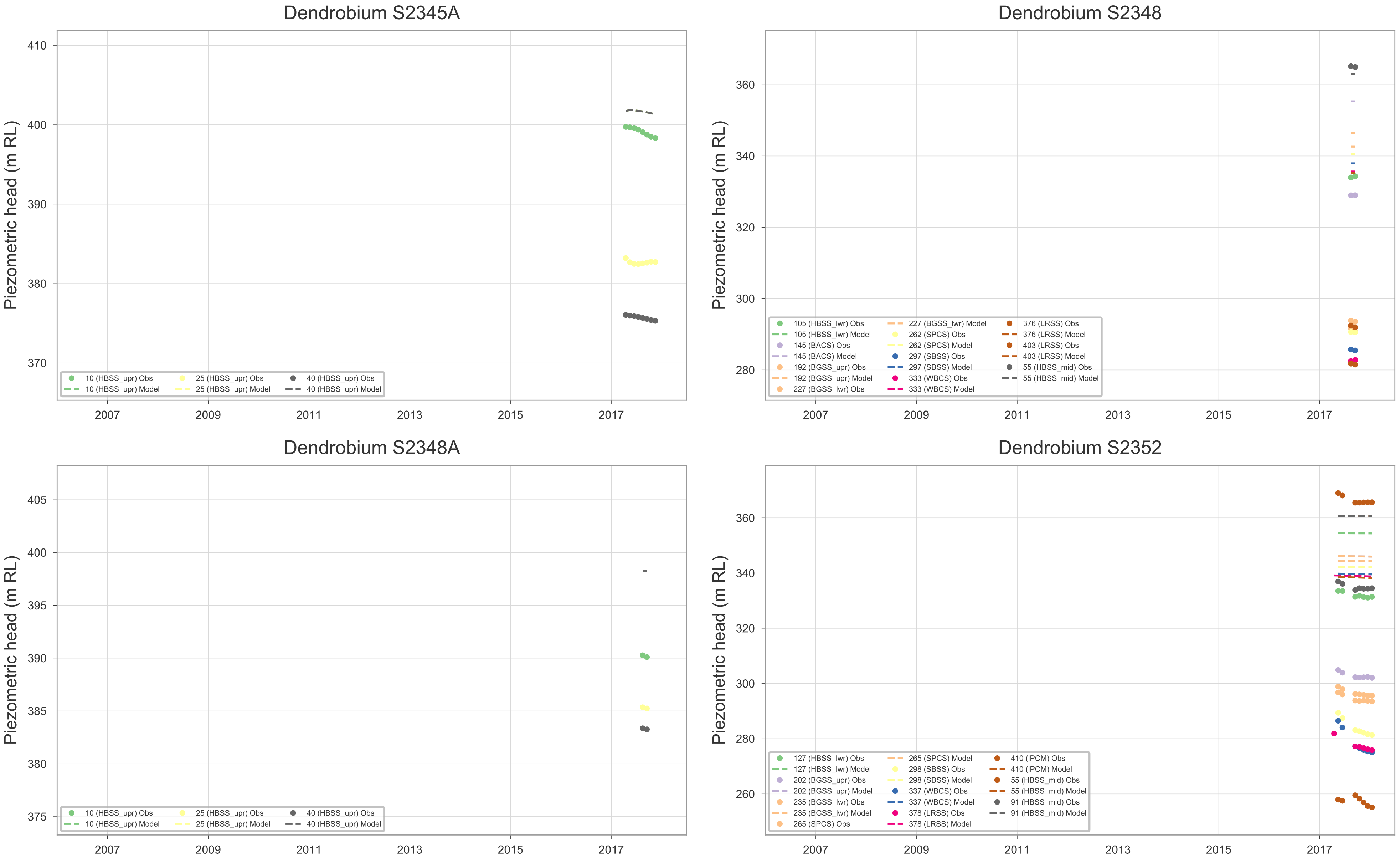
Dendrobium S2341



Dendrobium S2341A



Dendrobium S2345

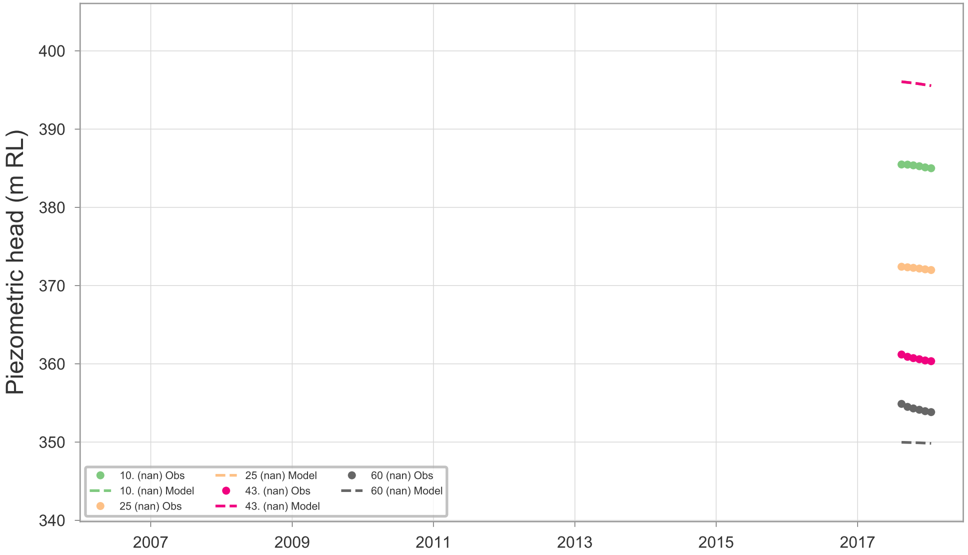


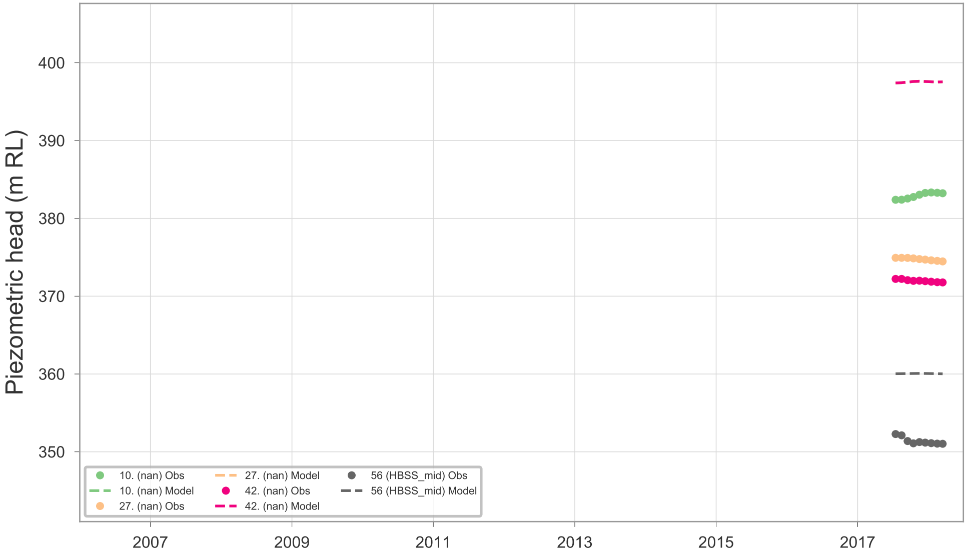
Dendrobium S2345A

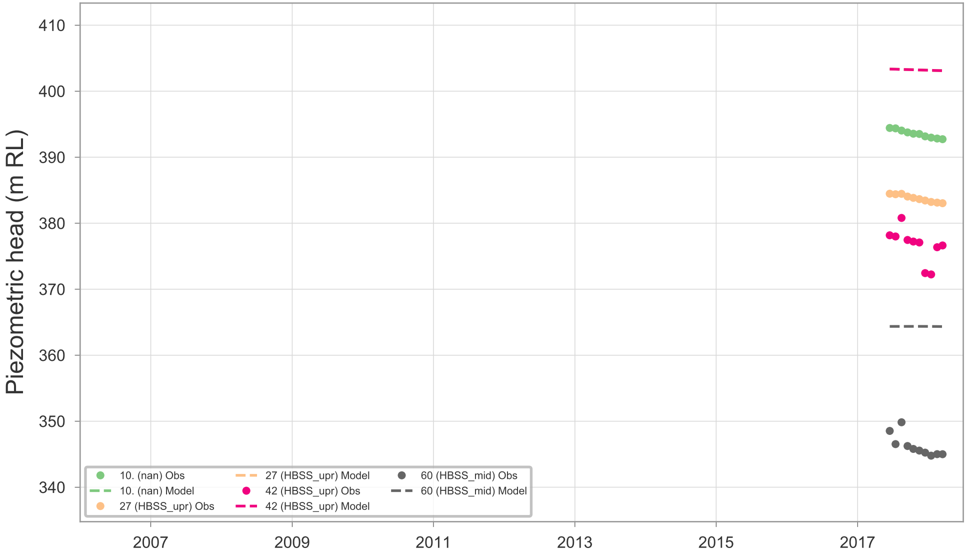
Dendrobium S2348

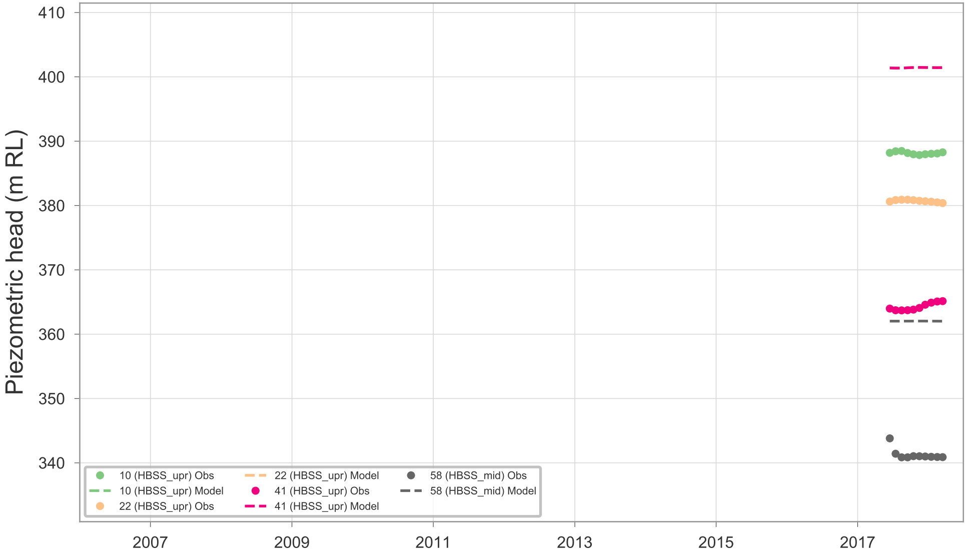
Dendrobium S2348A

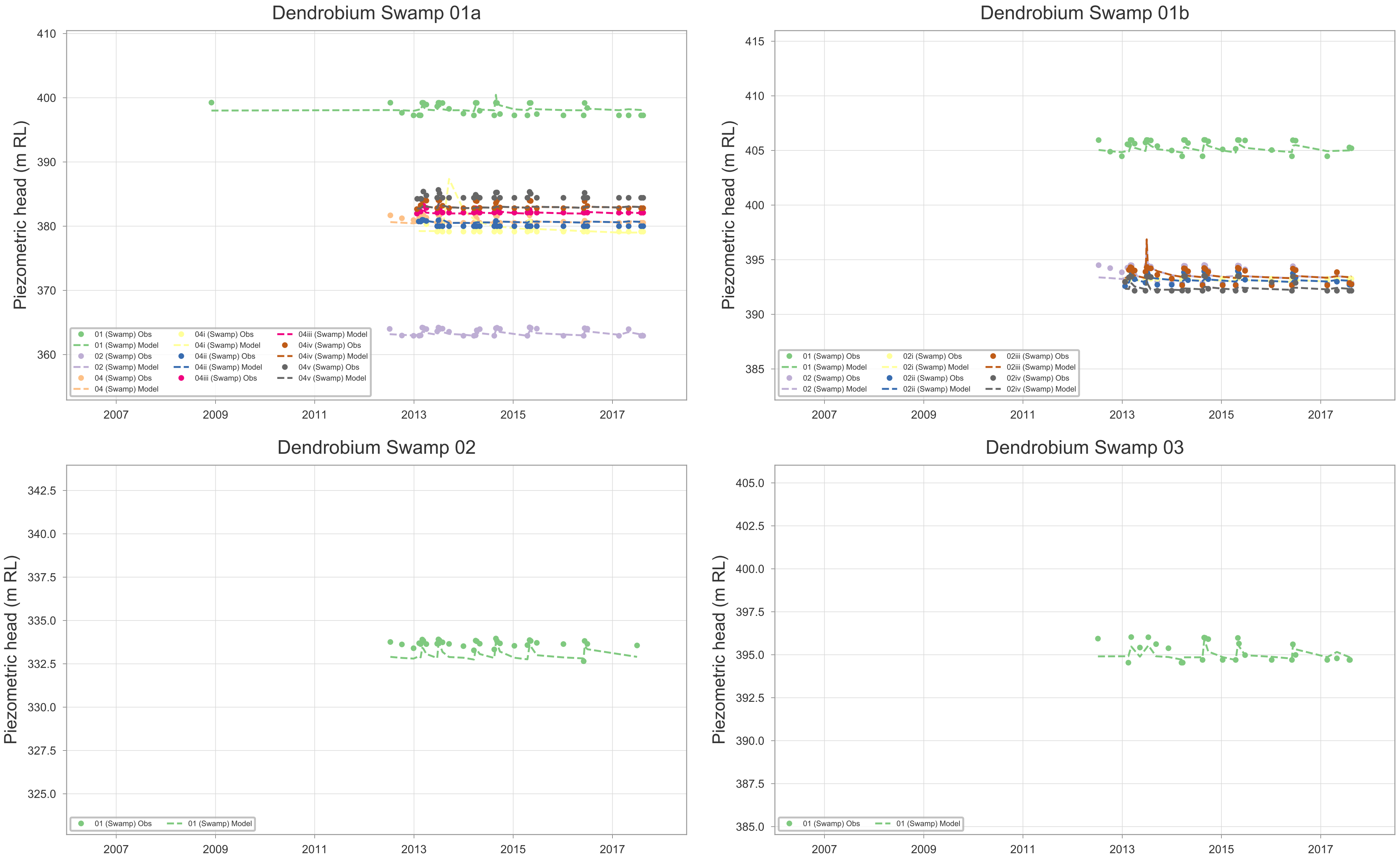
Dendrobium S2352

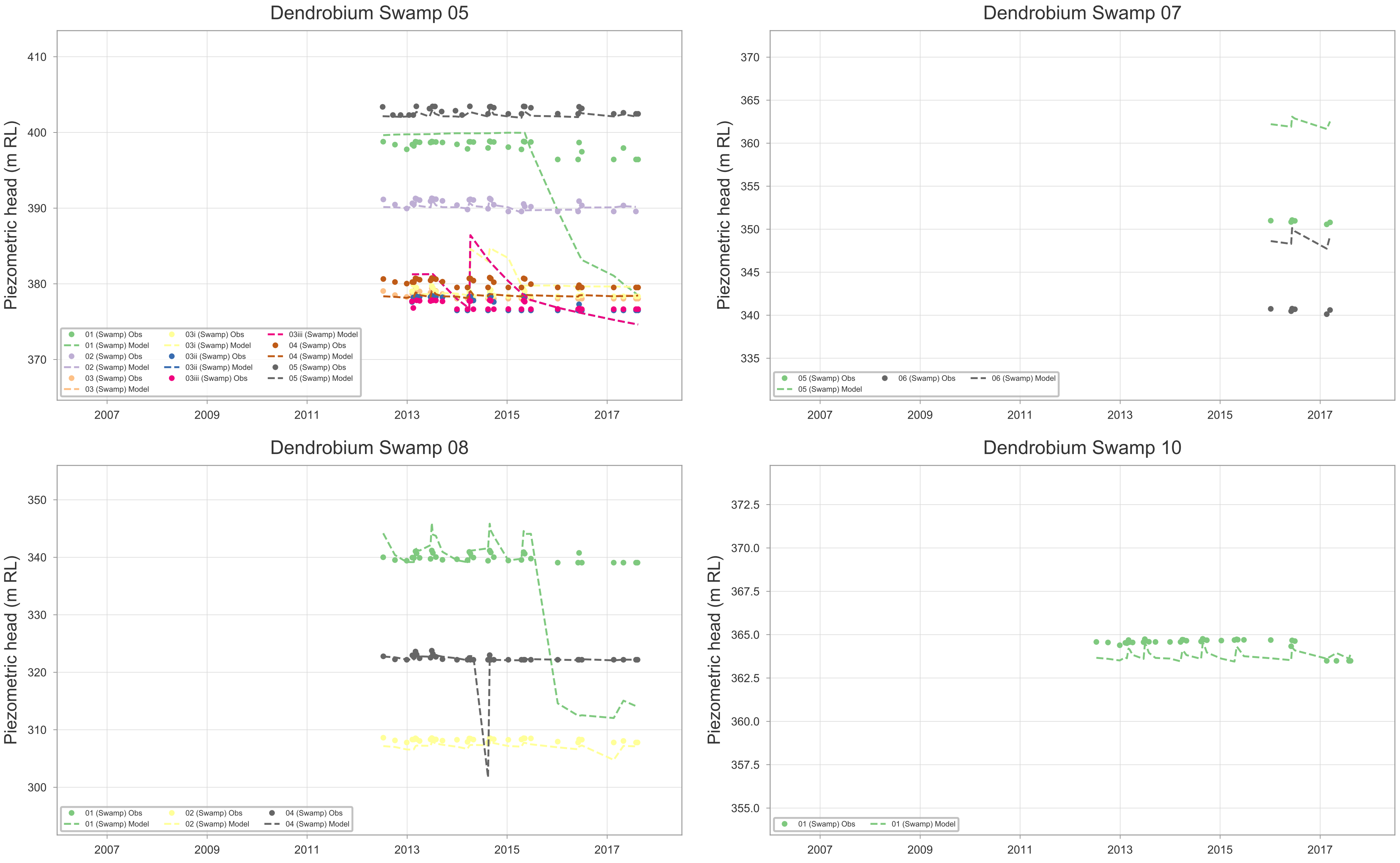

Dendrobium S2355

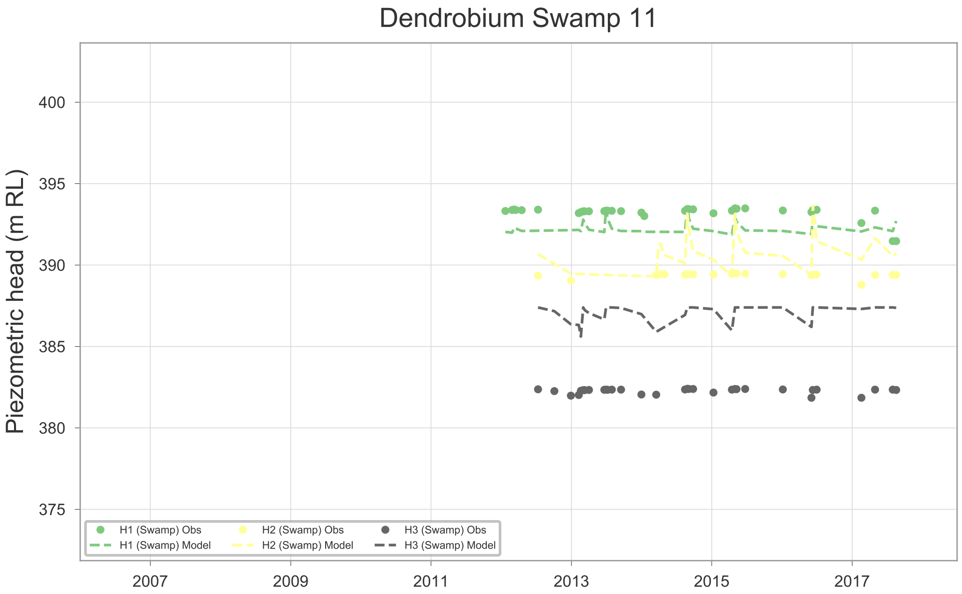

Dendrobium S2357


Dendrobium S2361

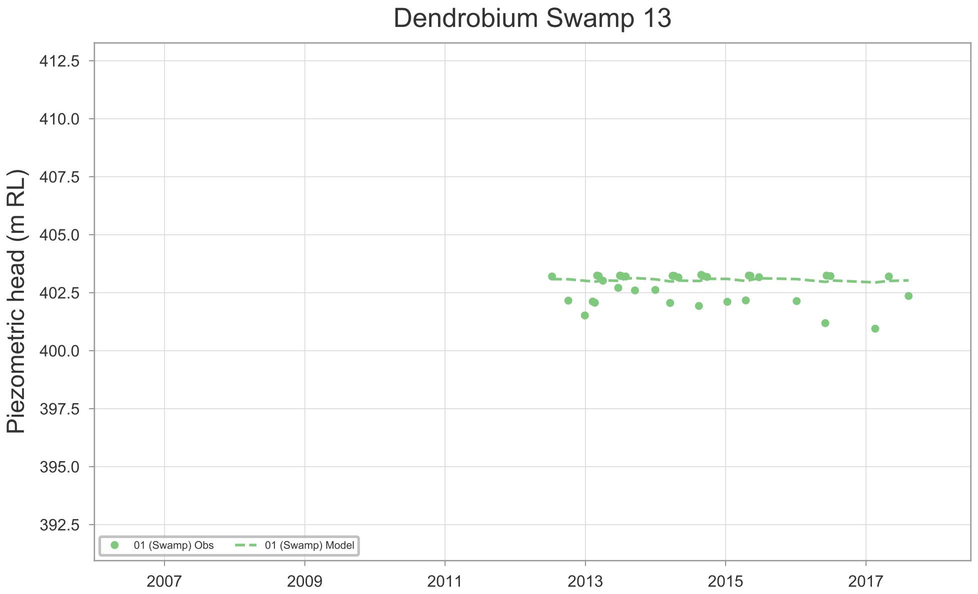

Dendrobium S2362


Dendrobium Swamp 01a
Piezometric head (m RL)
410
400
390
380
370
360
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model
02 (Swamp) Obs
02 (Swamp) Model
04 (Swamp) Obs
04 (Swamp) Model
04i (Swamp) Obs
04i (Swamp) Model
04ii (Swamp) Obs
04ii (Swamp) Model
04iii (Swamp) Obs
04iii (Swamp) Model
04iv (Swamp) Obs
04iv (Swamp) Model
04v (Swamp) Obs
04v (Swamp) Model
Dendrobium Swamp 01b
Piezometric head (m RL)
415
410
405
400
395
390
385
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model
02 (Swamp) Obs
02 (Swamp) Model
02i (Swamp) Obs
02i (Swamp) Model
02ii (Swamp) Obs
02ii (Swamp) Model
02iii (Swamp) Obs
02iii (Swamp) Model
02iv (Swamp) Obs
02iv (Swamp) Model
Dendrobium Swamp 02
Piezometric head (m RL)
342.5
340.0
337.5
335.0
332.5
330.0
327.5
325.0
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model
Dendrobium Swamp 03
Piezometric head (m RL)
405.0
402.5
400.0
397.5
395.0
392.5
390.0
387.5
385.0
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model

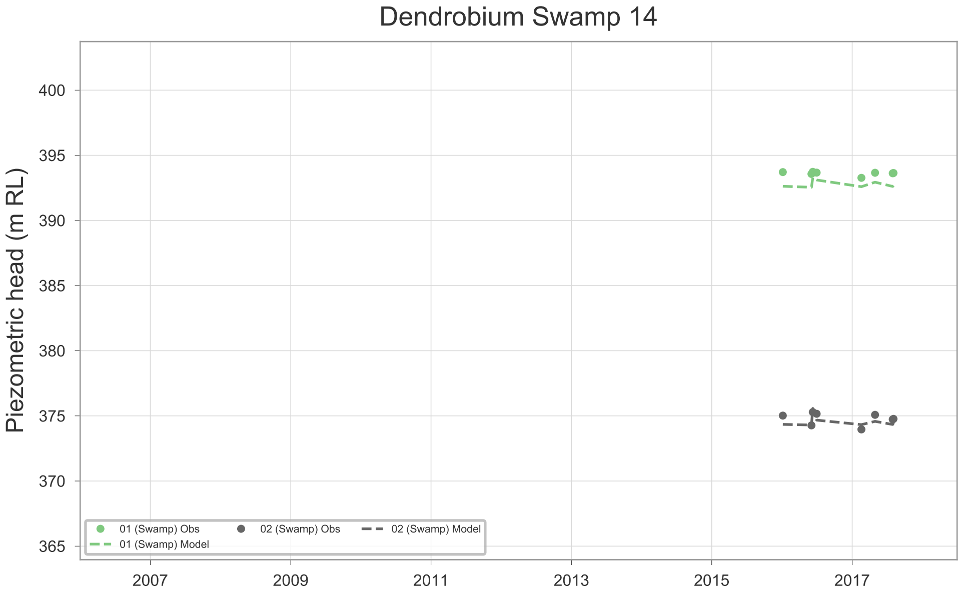

Dendrobium Swamp 05
Piezometric head (m RL)
410
400
390
380
370
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model
02 (Swamp) Obs
02 (Swamp) Model
03 (Swamp) Obs
03 (Swamp) Model
03i (Swamp) Obs
03i (Swamp) Model
03ii (Swamp) Obs
03ii (Swamp) Model
03iii (Swamp) Obs
03iii (Swamp) Model
04 (Swamp) Obs
04 (Swamp) Model
05 (Swamp) Obs
05 (Swamp) Model
Dendrobium Swamp 07
Piezometric head (m RL)
370
365
360
355
350
345
340
335
2007
2009
2011
2013
2015
2017
05 (Swamp) Obs
05 (Swamp) Model
06 (Swamp) Obs
06 (Swamp) Model
Dendrobium Swamp 08
Piezometric head (m RL)
350
340
330
320
310
300
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model
02 (Swamp) Obs
02 (Swamp) Model
04 (Swamp) Obs
04 (Swamp) Model
Dendrobium Swamp 10
Piezometric head (m RL)
372.5
370.0
367.5
365.0
362.5
360.0
357.5
355.0
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model



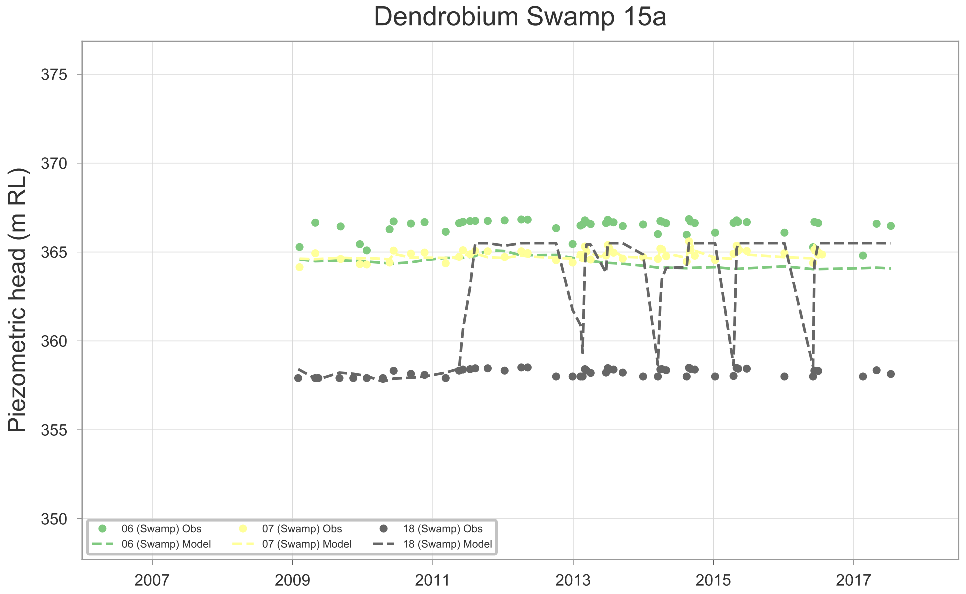
Dendrobium Swamp 11



Dendrobium Swamp 13

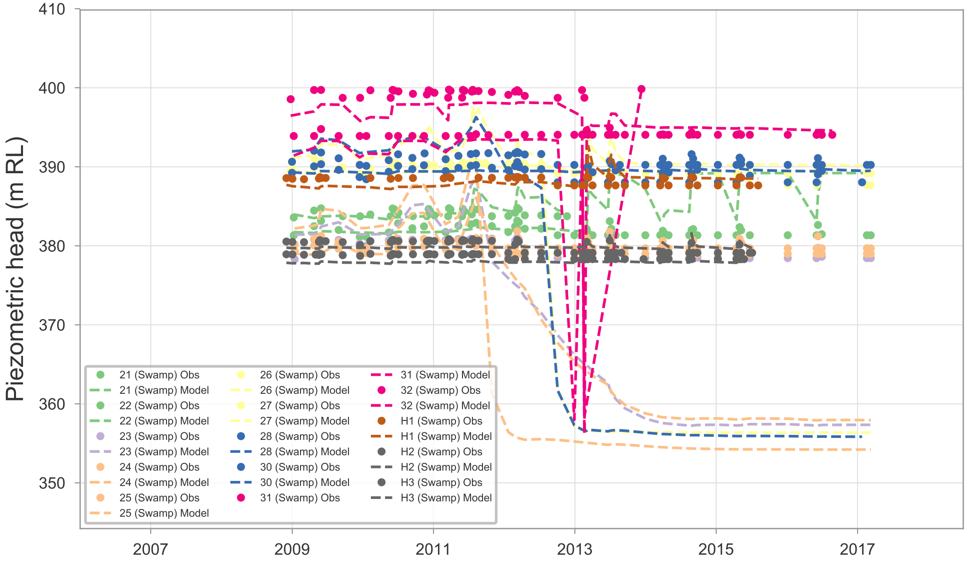


Dendrobium Swamp 14

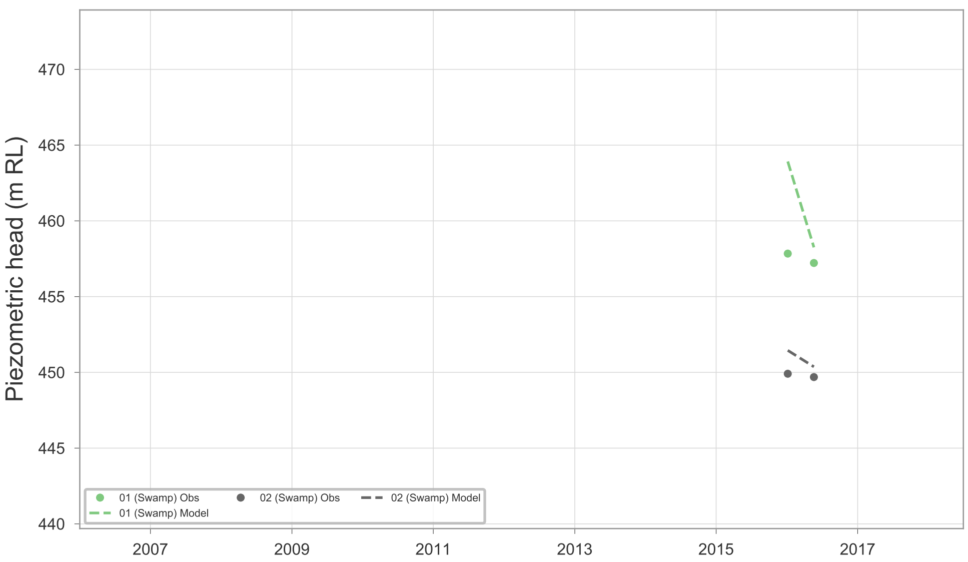


Dendrobium Swamp 15a

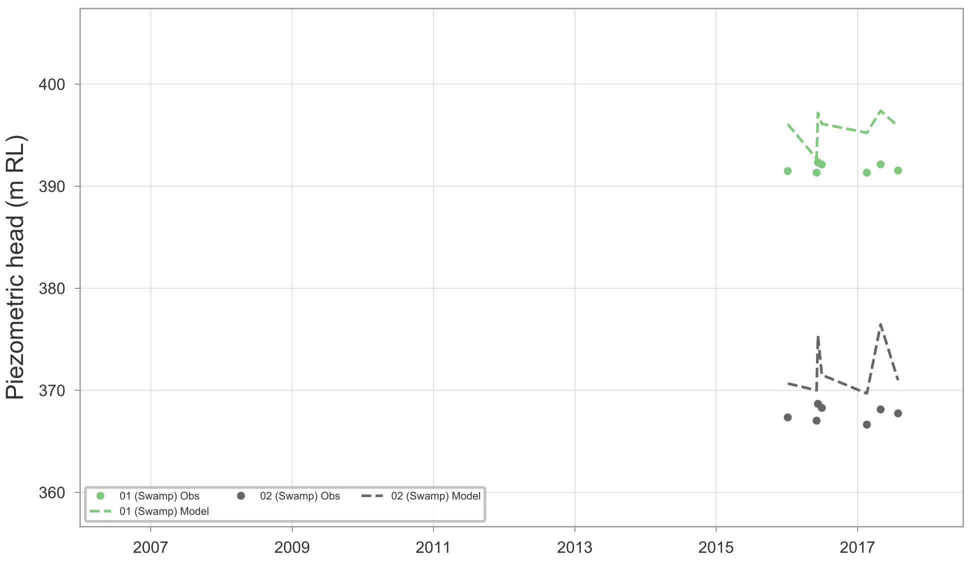
Dendrobium Swamp 15b



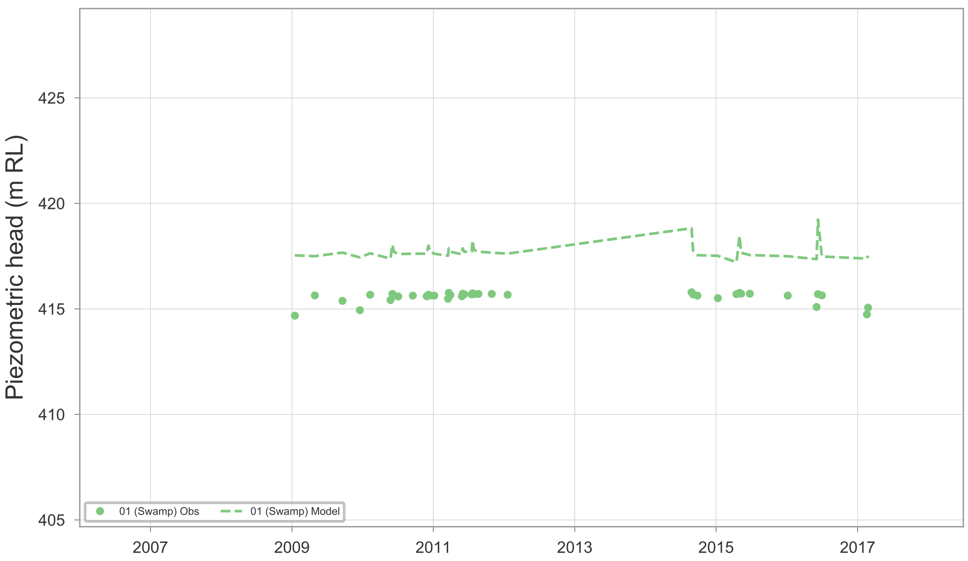
Dendrobium Swamp 22

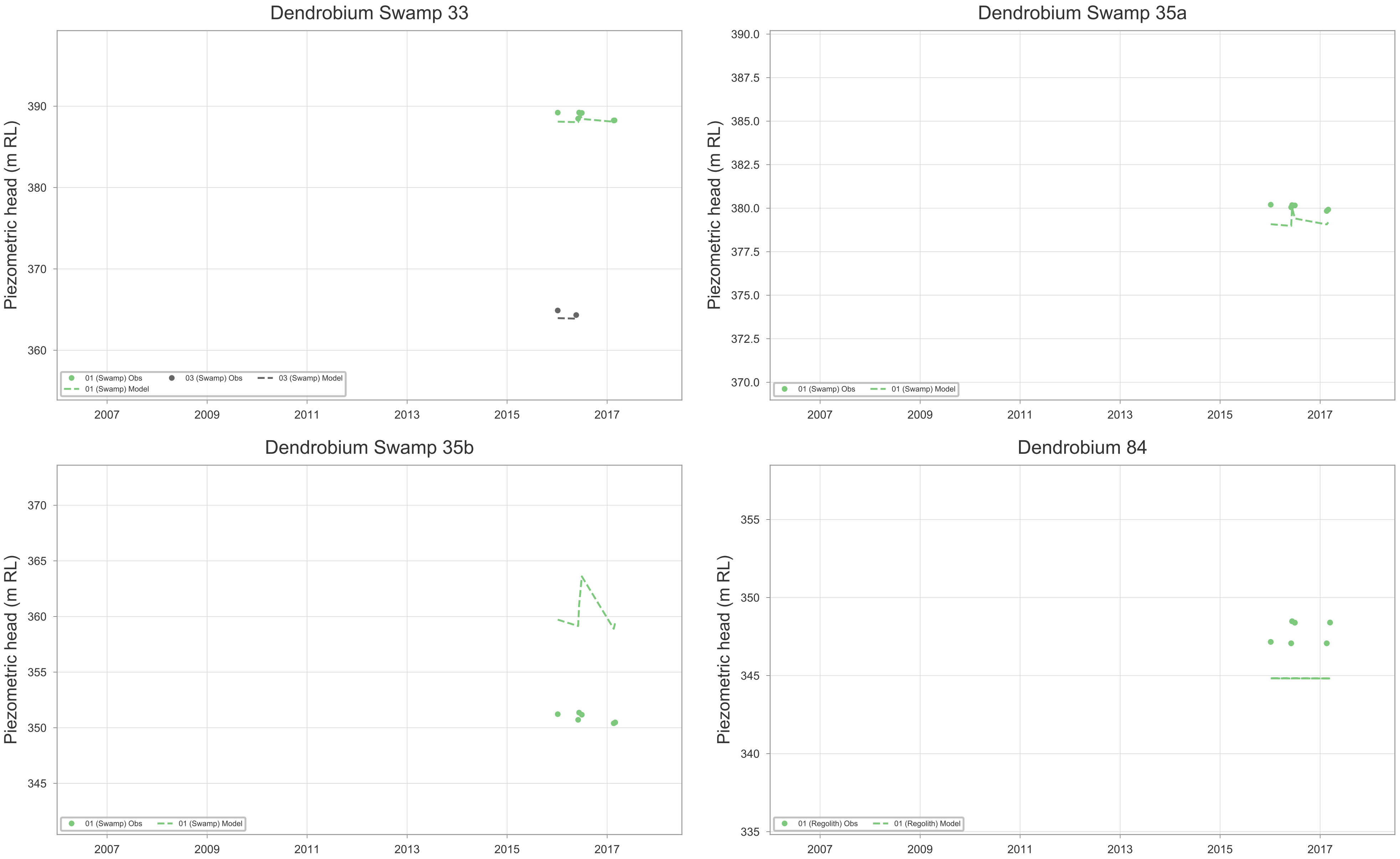


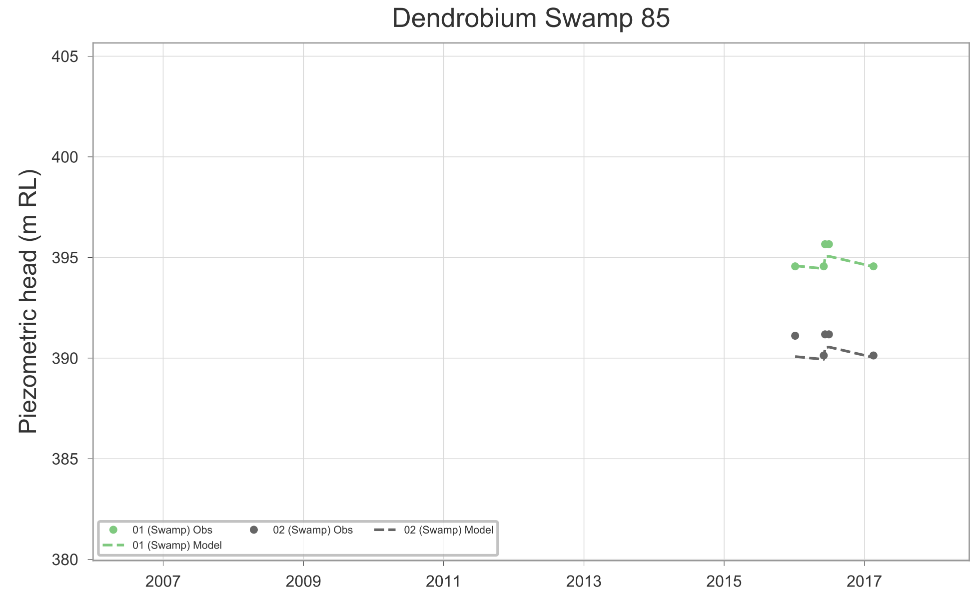
Dendrobium Swamp 23

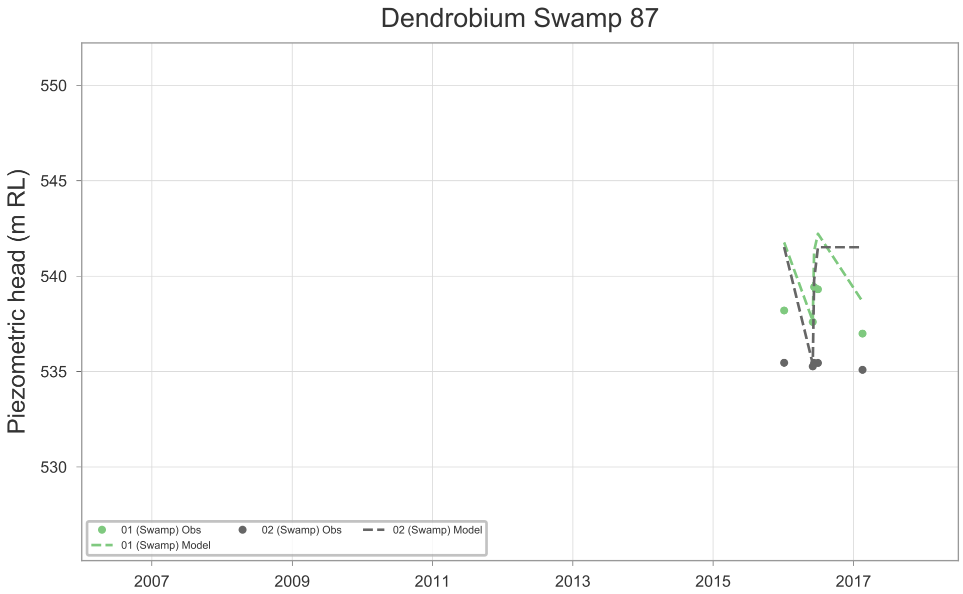


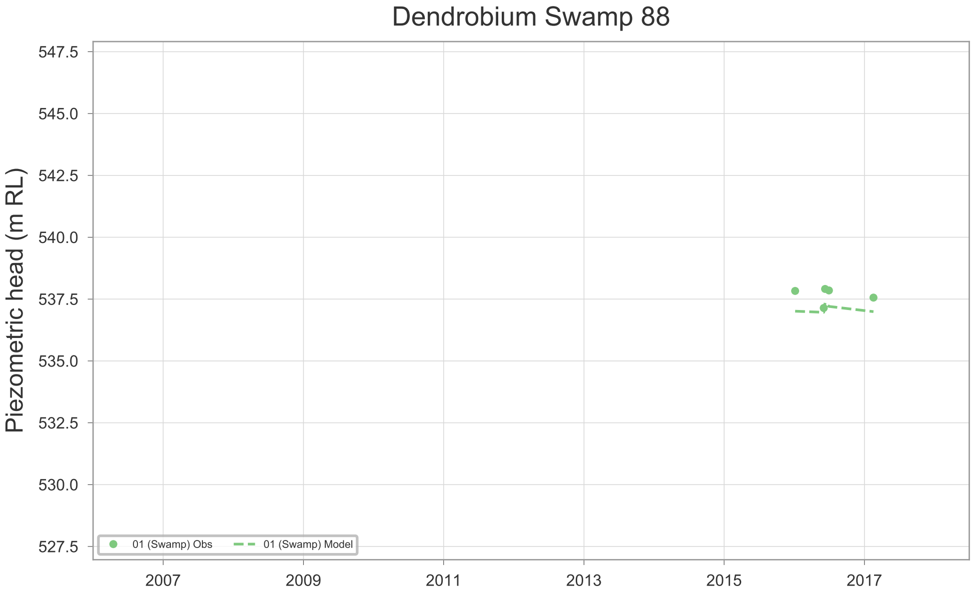
Dendrobium Swamp 25

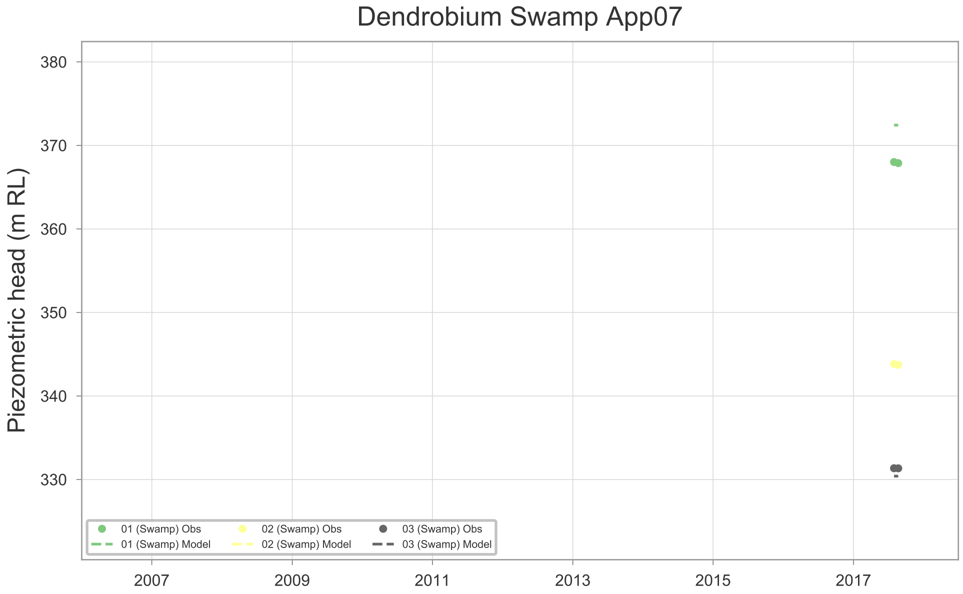


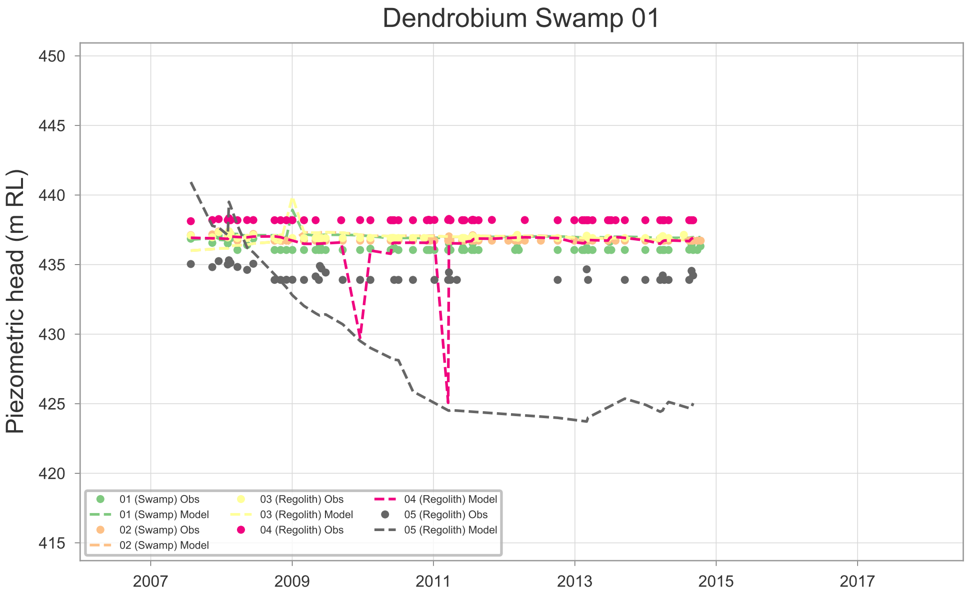

Dendrobium Swamp 33
Piezometric head (m RL)
390
380
370
360
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
03 (Swamp) Obs
03 (Swamp) Model
01 (Swamp) Model
Dendrobium Swamp 35a
Piezometric head (m RL)
390.0
387.5
385.0
382.5
380.0
377.5
375.0
372.5
370.0
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model
Dendrobium Swamp 35b
Piezometric head (m RL)
370
365
360
355
350
345
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model
Dendrobium 84
Piezometric head (m RL)
355
350
345
340
335
2007
2009
2011
2013
2015
2017
01 (Regolith) Obs
01 (Regolith) Model

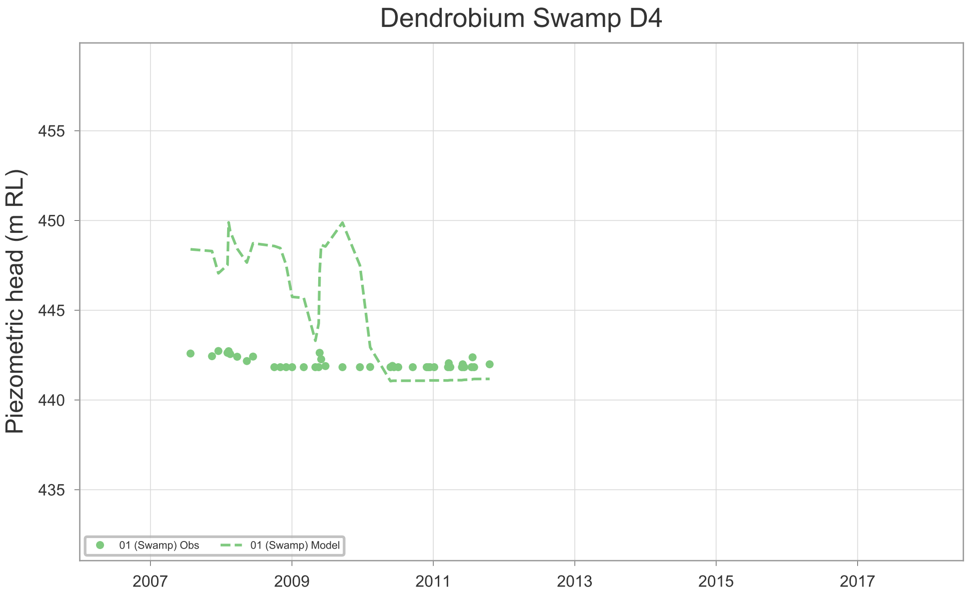

Dendrobium Swamp 85
Piezometric head (m RL)
405
400
395
390
385
380
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model
02 (Swamp) Obs
02 (Swamp) Model

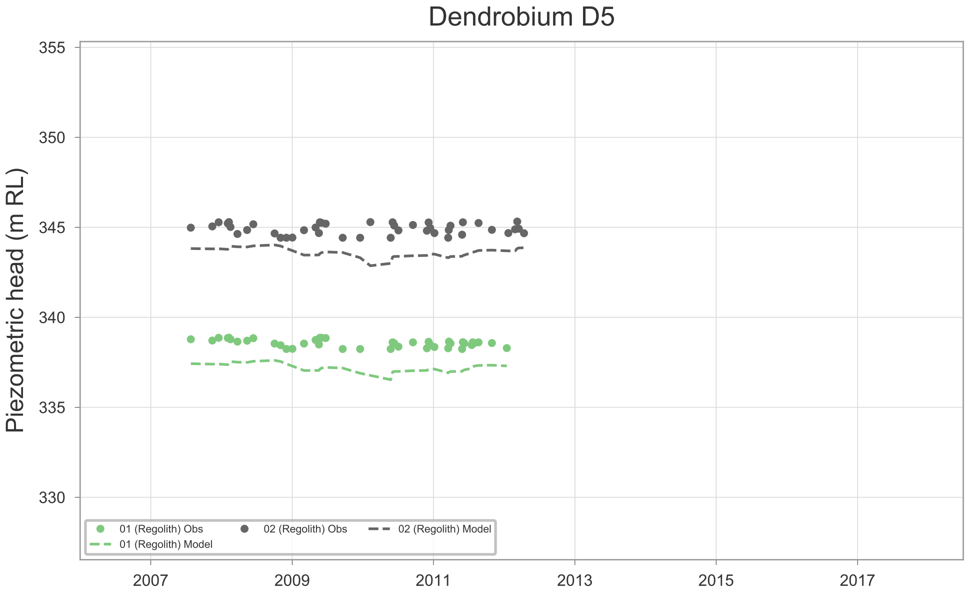

Dendrobium Swamp 87
Piezometric head (m RL)
550
545
540
535
530
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model
02 (Swamp) Obs
02 (Swamp) Model


Dendrobium Swamp 88
Piezometric head (m RL)
547.5
545.0
542.5
540.0
537.5
535.0
532.5
530.0
527.5
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model


Dendrobium Swamp App07
Piezometric head (m RL)
380
370
360
350
340
330
2007
2009
2011
2013
2015
2017
01 (Swamp) Obs
01 (Swamp) Model
02 (Swamp) Obs
02 (Swamp) Model
03 (Swamp) Obs
03 (Swamp) Model


Dendrobium Swamp 01


Dendrobium Swamp D4


Dendrobium D5