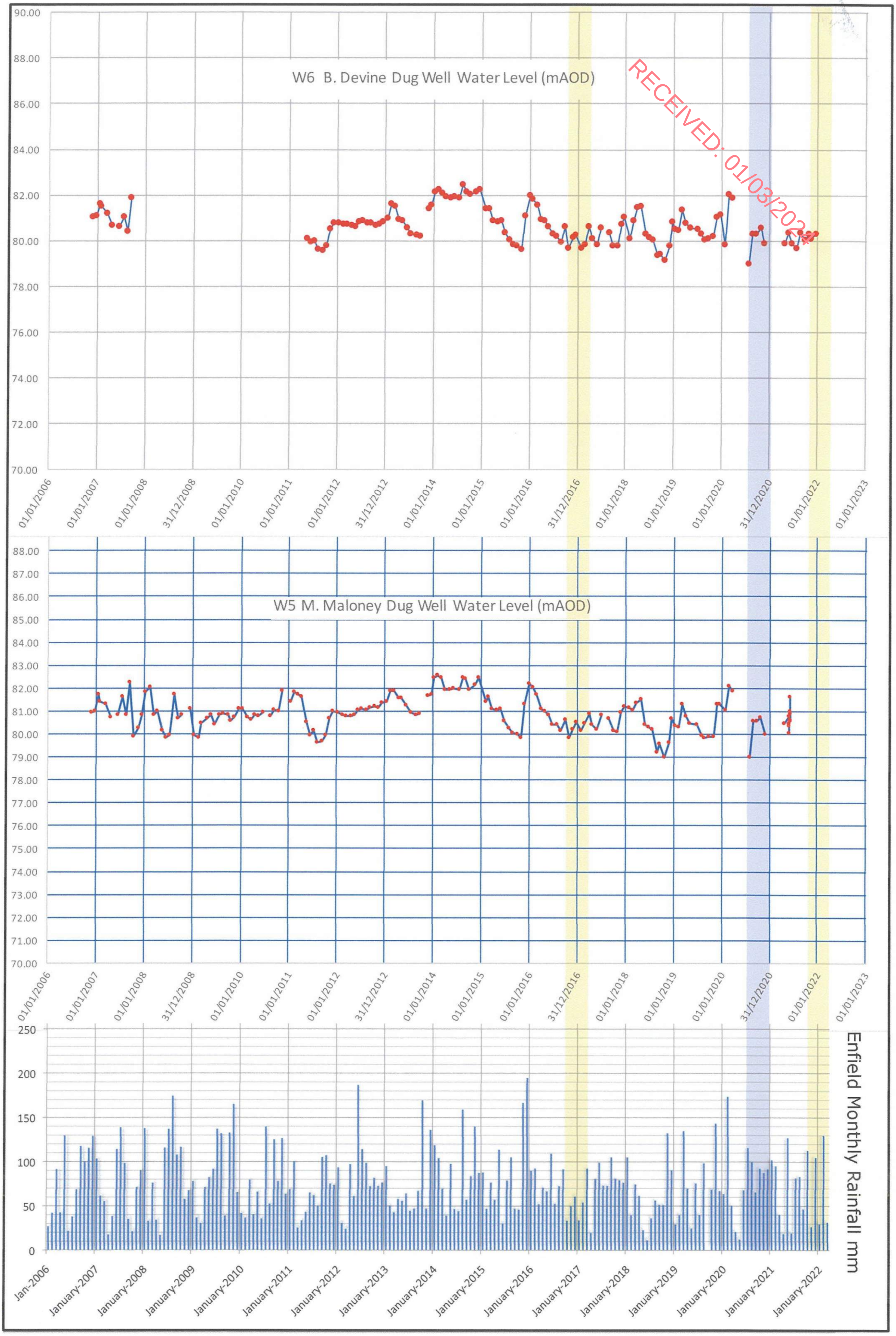
Figure 4.5 W5 and W6 Water Level hydrographs



As the borehole is close to the quarry, I think it was probably influenced by the test. The drawdown during the test appears to be about half a metre.

The rise in water levels in the winter of 2018-19 is similar in shape and magnitude in both the shallow overburden water levels in W3 and the bedrock water levels in W4.

W5 and W6 in Figure 4.5 are both shallow overburden dug wells. They appear to be in very permeable sands and gravels or sandy till, because they both appear to be able to meet the domestic water demand from multi-occupancy households even when the water level is less than a metre above the bottom of each well.

These wells are important monitoring points for Kilsaran because they are very close to the western side of the quarry, and if pumping from the bedrock in the quarry were found to draw down the groundwater levels in the shallow over burden aquifer, then the water supply for these homes would be at risk.

Though the water level record was broken by the two Covid periods of lockdown and social distancing, it was reassuring to see that the water levels in both wells did not go down during the main long pumping test in the summer and autumn of 2020. In fact the levels rose in response to the heavy late summer rains during the test. The lack of response to pumping from the boreholes in the quarry, indicates that probably there is a low permeability, or impermeable, layer, separating the shallow aquifer, tapped by W5 and W6, from the underlying limestone bedrock groundwater system. The boulder clay and yellow clays overlying the Waulsortian at the edge of the quarry, shown in Figure 2.23 and 2.24, maybe the layer that forms this separation between the shallow and the deep groundwater systems.

Across the road from these two wells, there is a large pond apparently sustained by shallow groundwater, that also appears to be unaffected by activities in the quarry and remained full during the test.

There is much additional useful information in these shallow groundwater hydrographs extending for over 16 years. For example, water levels in both wells are high in 2014 when Sarah Blake started measuring water levels in St Gorman's borehole and the spring was flowing, and both wells show unusually low water levels in 2016-2017 when St Gorman's spring did not flow. The shallow well monitoring provides evidence of recharge and lack of recharge, that correlates well with W3 and St Gorman's Well hydrographs.

Figure 4.6 shows the record for a borehole and a very shallow dug well. Measurements in borehole W7 were discontinued in 2016, but measurements started in the shallow well W8 across the road at the start of 2017.

Figure 4.6 W7 and W8 Water Level hydrographs

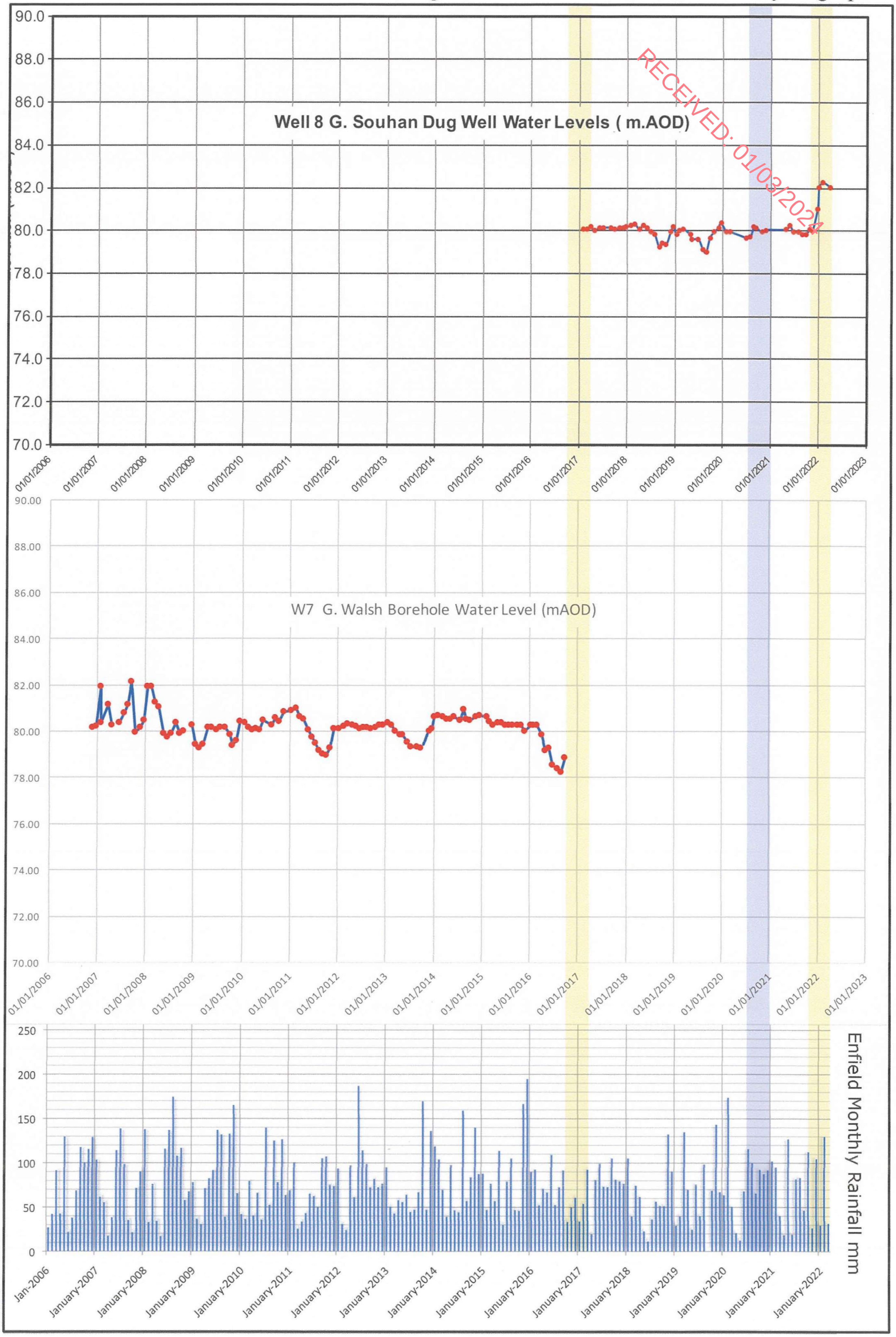
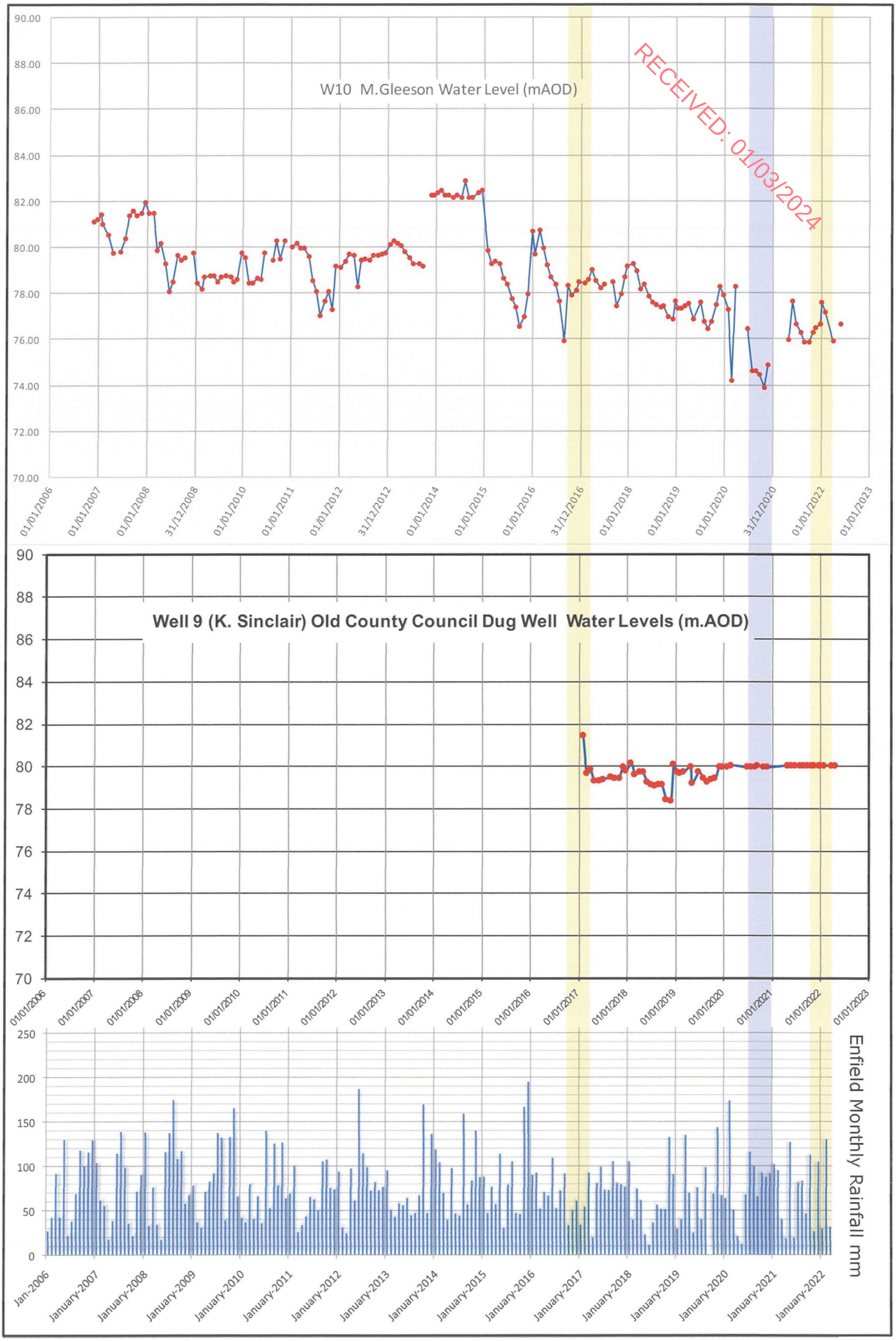


Figure 4.7 W9 and W10 Water Level hydrographs



Souhan's dug well W8 is in an extension to the house. Like W3, W5 and W6, it is shallow but productive. The water level appears to rise and fall about a metre between winter high and summer low. It does not appear to have been affected by the main long pumping test in 2020. It rose by 2 metres in November–December 2021. Given the preceding seasonal fluctuations, this appears unusual, but the Diver data from W3 also showed a rise of over 2.5 metres at the same time, though starting earlier with the heavy rain in August and October. It is possible that the generally lower water levels in W8 are mainly levels affected by pumping on the weekdays when measurements were taken, and there was perhaps a change in use of the well in the late autumn in 2021 into January 2022.

Figure 4.6 shows the water levels in the borehole W7 where there appears to be a small, downward gradient in the low water levels at the end of the summer recession. The levels at the end of each summer recession appear to have gone down by 2 metres over the course of ten years. Again, the decline started over 7 years before the quarry started pumping out water. Other examples of this long term trend are discussed below.

Figure 4.7 shows the water level in an old County Council shallow dug well with a an old hand pump (W9). This well became part of the monitoring programme in 2017 after W7 became inaccessible. The first three years show a normal subdued seasonal response that fluctuates little after December 2019.

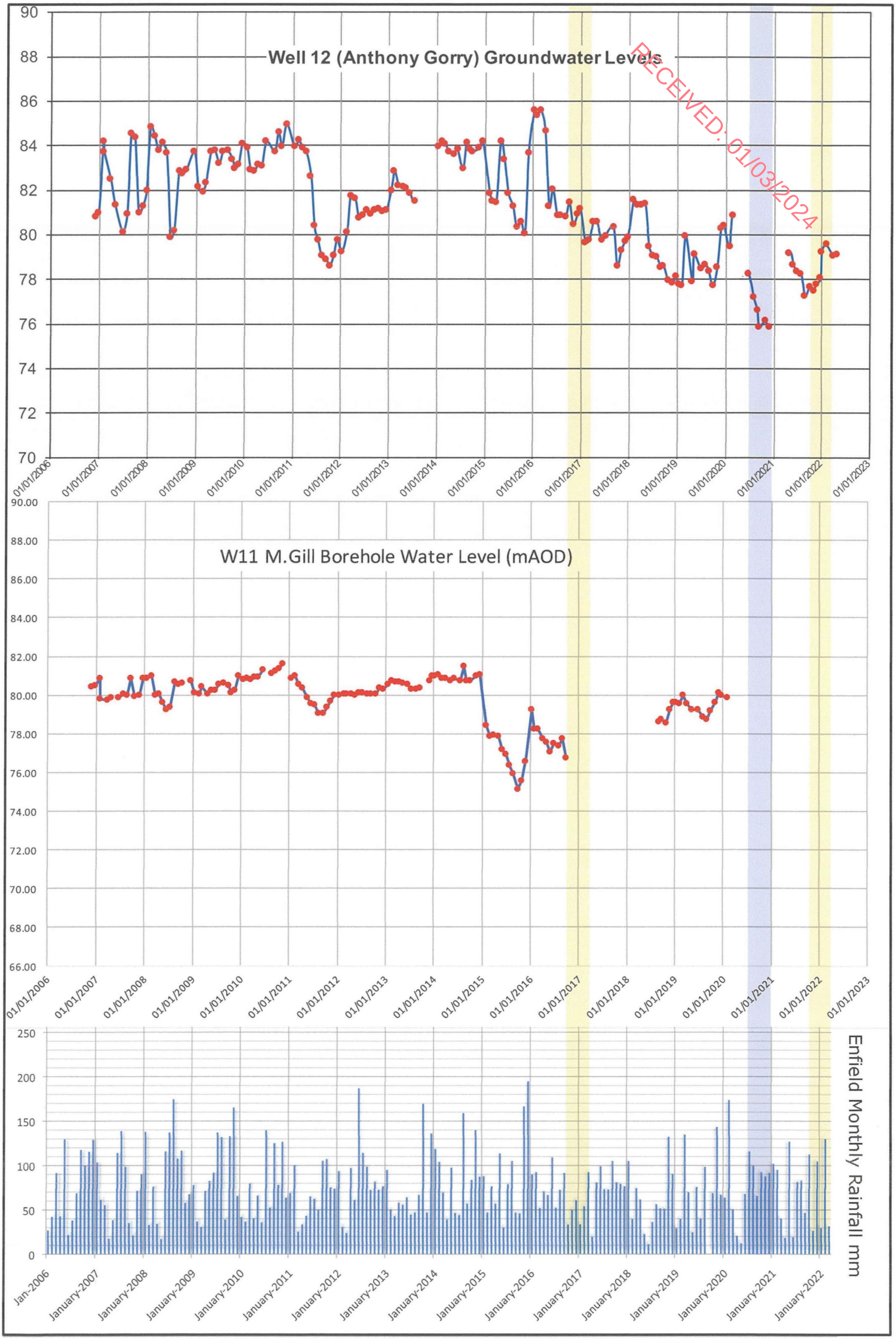
W10 is an important borehole because it is drilled into 'the saddle' between Rathcore and Ballinakill hills revealed in the conductivity maps and sections described in Chapter 2. Unfortunately, there is no log of the borehole drilling. Therefore, there is no bedrock geology information to correlate with the geophysics.

The borehole supplies a house and garden. On a site visit to measure water levels in 2020, I found that the pump was working continuously. The water level in the borehole was more than 50 metres below ground level. Normally it is around 7 metres below ground level. I later found out that a tap had been left running in a greenhouse overnight and throughout that day.

From this circumstantial information, it is possible to deduce that the borehole does not have a high sustainable yield. This deduction is also supported by the steep rise and fall in water levels after rainfall and in the summer recession, but some of these measurements may relate to the water level at the time being influenced by preceding pumping.

There are two gaps in the data in 2020 caused by Covid restrictions, but the measurements made during the main long pumping test in the quarry in 2020 appear to show the lowest seemingly 'natural' or non-pumping water level in the borehole. There is another low water level in February 2020, that may also relate to pumping in the quarry, via a pressure effect in

Figure 4.8 W11 and W12 Water Level hydrographs



the limestone conduit system. At the time of this low water level in W10, water pumped from the quarry boreholes was being re-circulated inside the quarry; i.e. it was being pumped from the karst conduits, but recharged back via the quarry floor into the karst system. A close inspection of the hydrograph for W10 appears to indicate that pumping in the quarry may lower the water level in borehole W10 by about 2 metres.

The data from W10 also shows a downward gradient in the end of the summer recession levels over the 15 years of the monitoring record. The gradient appears to be relatively steep in the early years. The gradual fall over the 15 years seems to be about 4-5 metres.

Figure 4.8 shows the record for borehole W11. It is sited across the road from borehole W10. Borehole W11 shows the same steep recession of water levels throughout 2015 as seen in the record for W10. In both boreholes the recession is about 5.5 to 6.0 metres. There is no record for W11 for the dry winter in 2016-17, and only a short record for 2018-19. The top of the borehole has been sealed and covered, and is no longer available.

Figure 4.8 also shows the hydrograph for borehole W12, which is due south of the quarry excavation.

It is only 240 metres from the southern edge of the present excavation. It is 475 metres from the nearest pumping borehole in the long test. The only domestic borehole closer to a quarry pumping borehole is borehole W4.

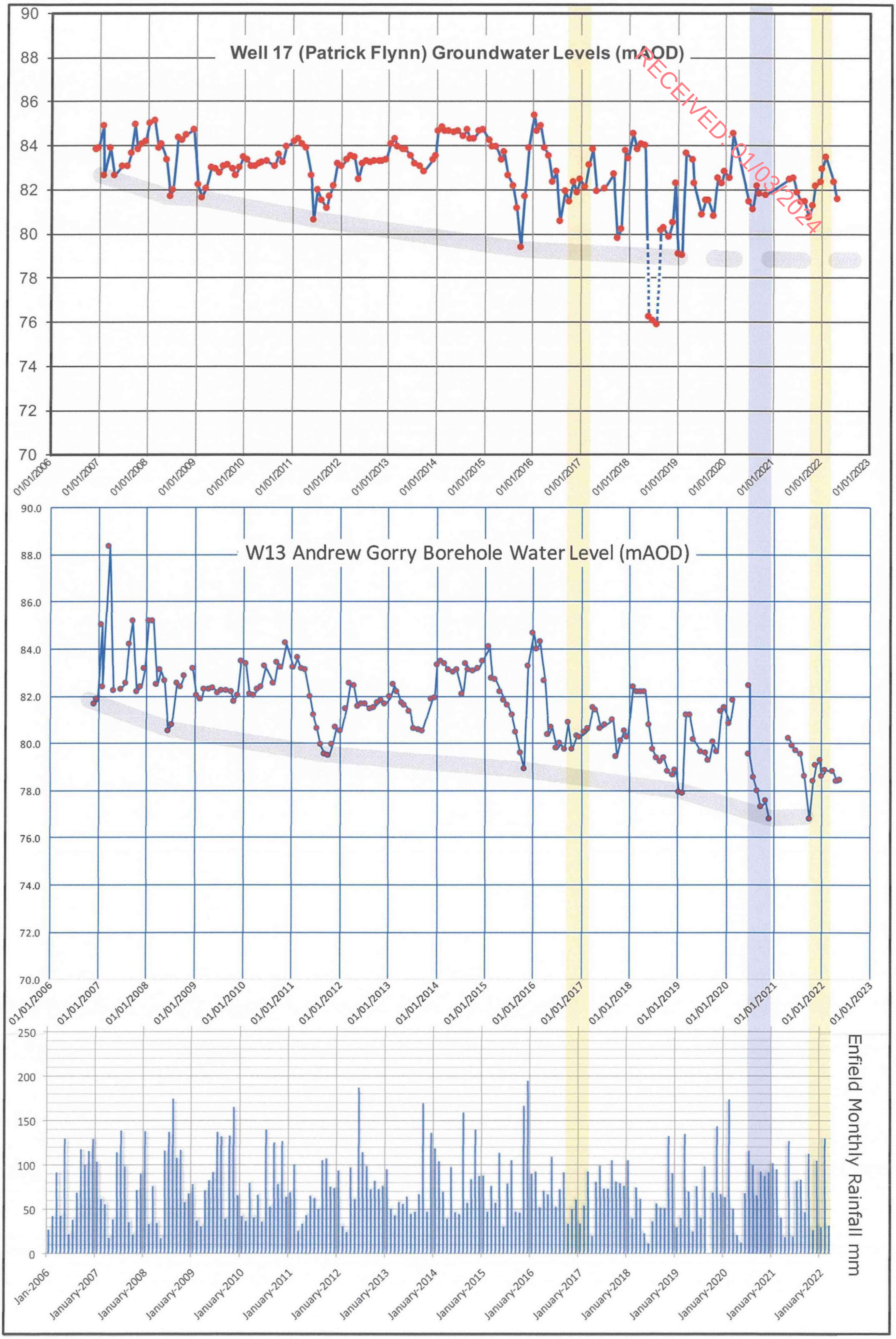
The water level record shows a 10 month 6 metre recession in 2011, then a general rise in water levels until the start of 2014 where levels remain nearly static. Then there is a sharp fall, and rise, and fall in 2015, in response to rainfall in May and November/December 2015. After a sharp recession in early 2016, water levels seem to decline by four metres over the next three years. Water levels eventually rise by three metres by the start of the Covid lockdown in March 2020.

We collected data from W12 during the long pumping test in the quarry, and water levels fell in W12 steadily during the first three months of the test by 2.2 metres. They then stayed level until November 2020. Due to miscommunication on my part, no water level measurements were taken during Covid restrictions in December 2020, January and February 2021, but during the supplementary winter pumping test in the quarry the water levels in March 2021 were 3 metres higher than September-October- November 2020.

Looking at the hydrograph overall, it appears that the long pumping test from July to December 2020 lowered the water level in borehole W12. As there was no measurement in February 2021, it is not clear if the winter supplementary test had an effect on water levels in W12.

Close to borehole W12 is another borehole owned by the Gorry family.

Figure 4.9 W13 and W17 Water Level hydrographs



The hydrograph for W13 is shown in Figure 4.9. The pattern of the rise of water levels in response to rainfall, and the recession of water levels in summer in borehole W13 is almost the same as the fluctuations seen in the hydrograph for W12. It is unlikely that both boreholes were being pumped at the same time, therefore the water levels that were measured are probably a real measure of the natural or static water level in the bed rock limestone .

There was a long recession throughout 2011 and other long recessions in 2015, 2016 and 2018. There was a final long recession or drawdown of water levels at the same time as the long pumping test in the quarry boreholes in 2020. Though the recession in 2020 is roughly the same magnitude as previous recessions, it is probable that the recession in 2020 was a drawdown of water levels created by the pumping of boreholes in the quarry.

Another notable feature of the hydrograph for both boreholes, and also other boreholes monitored in the programme, is the trend of a gradual fall in the water levels at the end of the main summer recessions each year.

I have drawn a faint grey line joining the lowest water level in the main recessions since 2006. It can be seen that the line starts at a level of about 82 metres AOD and declines over 15 years to 77 metres; in other words, a fall of five metres.

The quick logical assumption would be to think that, because these boreholes are very close to the quarry, and pumping from quarry boreholes seems to affect their water levels, then the pumping from the quarry is the probable cause of the gradual decline in water levels.

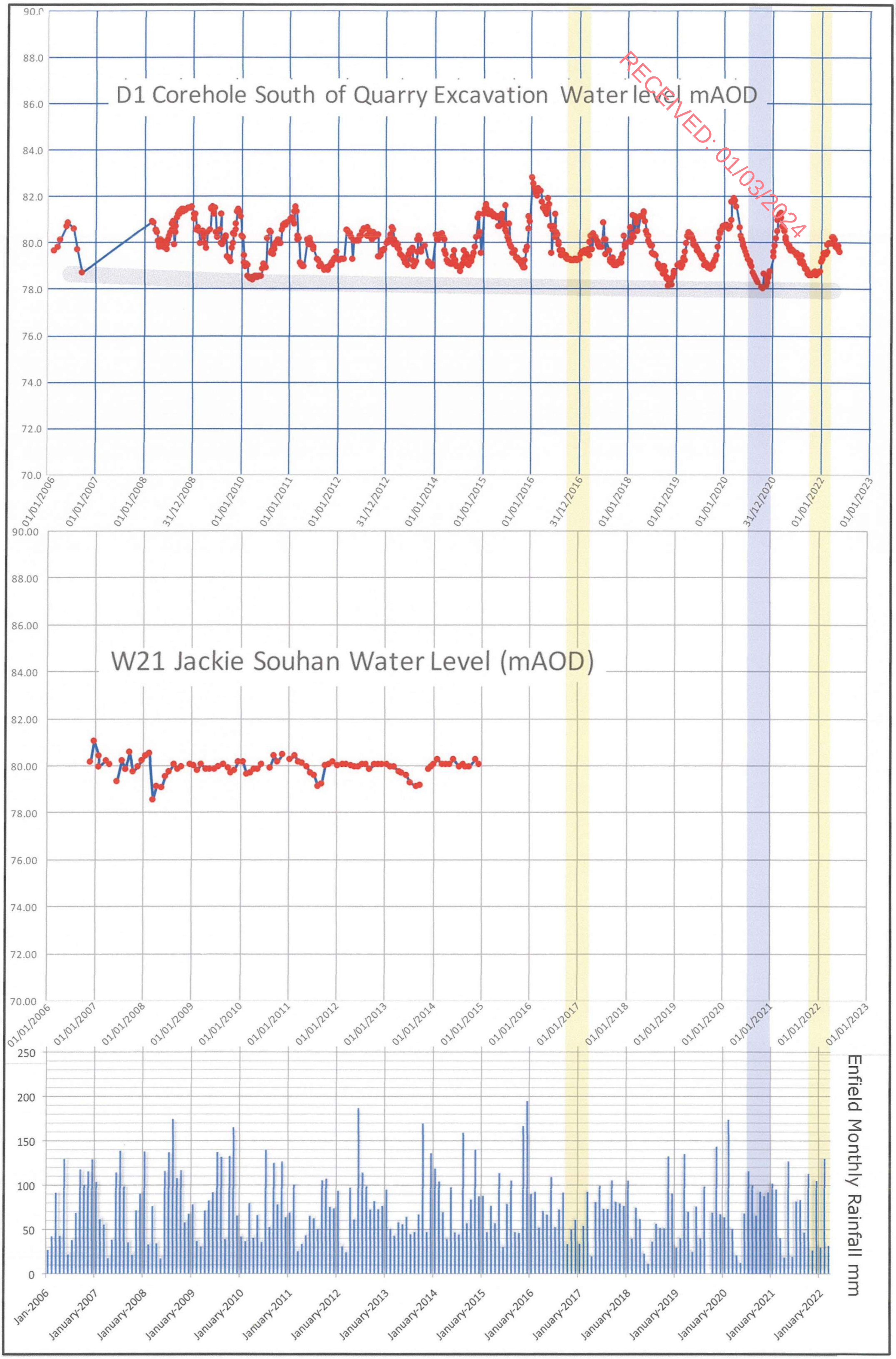
The problem with the quick assumption is that the quarry did not start to pump any water out of the quarry until October 2013. Before October 2013, the quarry floor was many metres above the level of the winter water table. All rain falling on the quarry soaked into the ground, and there was no need to take water out of the quarry to keep the working floor of the quarry dry.

The changes in the pattern of rainfall and other options will be discussed at the end of this chapter and in Chapter 5.

Borehole W17 shown at the top in Figure 4.9 is for a domestic borehole to the southeast of W13 and the quarry excavation. It shows a pattern similar to W12 and 13 of winter highs and summer recessions. However, it does not show any evidence of a fall in water levels during the long pumping test in the quarry in 2020. The water level was higher in September, October and November than it had been in July at the start of the test.

The difference in response of the water levels to the pumping test in the quarry in W12. W13 and W17 probably confirms the geological interpretation in Figure 2.50. This figure shows that bedrock encountered in borehole W17 is the Lucan formation, whereas W12 and W13 appear

Figure 4.10 W21 and D1 Water Level hydrographs



to have penetrated the southern tip of the Rathcore Waulsortian limestone block. Comparison of the data from W17 with the data from W12 and W13 indicates that the groundwater system in the Waulsortian is separated from the groundwater system in the Lucan by the Carboniferous age fault seen in the geophysics. This separation is not only seen in the response to pumping in the quarry. It is notable that during the pumping test the water levels in W12 and 13 was 4 - 5 metres lower than the levels in W17. In other words this an indication that the Carboniferous normal fault is a barrier boundary between the two formations, and not an open conduit. This is in line with the conclusions from John Paul Moore's research that roughly east-west aligned Carboniferous age normal faults are not open and alignments of preferential karst weathering and the formation of karst conduits.

I have drawn a pale grey line along the end of summer recession levels for W17, for comparison with the same line on W13. The decline in water levels in W17 until 2015 is similar to W13, but thereafter the rate of decline diminishes.

There does not appear to be evidence to show that the pumping from either the sump or boreholes in the quarry affects water levels in borehole W17.

There are three months of anomalous low water level readings in June, July and August 2018 that fall below the expected levels. It may be that each of the three monthly measurements were made at a time when the borehole pump was working or had just stopped working.

Figure 4.10 shows the hydrograph for W21 up until the end of 2014. It seems that dogs outdoors during the day have prevented monitoring beyond 2014.

Figure 4.10 also shows the measurements for core hole D1. This hole is in a field of pasture about 150 metres south of the edge of the quarry excavation, and 370 metres from pumping borehole 1 during the long test. The hydrograph shows water levels fluctuation within a small range of about 3 metres between winter highs and summer lows. The pale grey line joining the lowest recession points shows a very slight decline of about half a metre over the 15 years data. The limited range of annual fluctuations and other characteristics of the D1 hydrograph are similar to the hydrographs of nearby shallow dug wells. Though the core hole would have penetrated the Waulsortian limestone, it seems probable that the water levels in the core hole are actually the water levels in the sandy till overburden on the flanks of the hill. Even though the core hole is so close to the quarry excavation and the pumping boreholes, the water level during the long pumping test showed no evidence of an excessive drawdown caused by the long pumping test. The recession in the summer of 2020 was almost identical to the recession in the summer of 2018 when there was no long pumping test.

The minimum water levels are about 3 metres above the quarry floor at 75 metres AOD.

Figure 4.11 D2 and D3 Water Level hydrographs

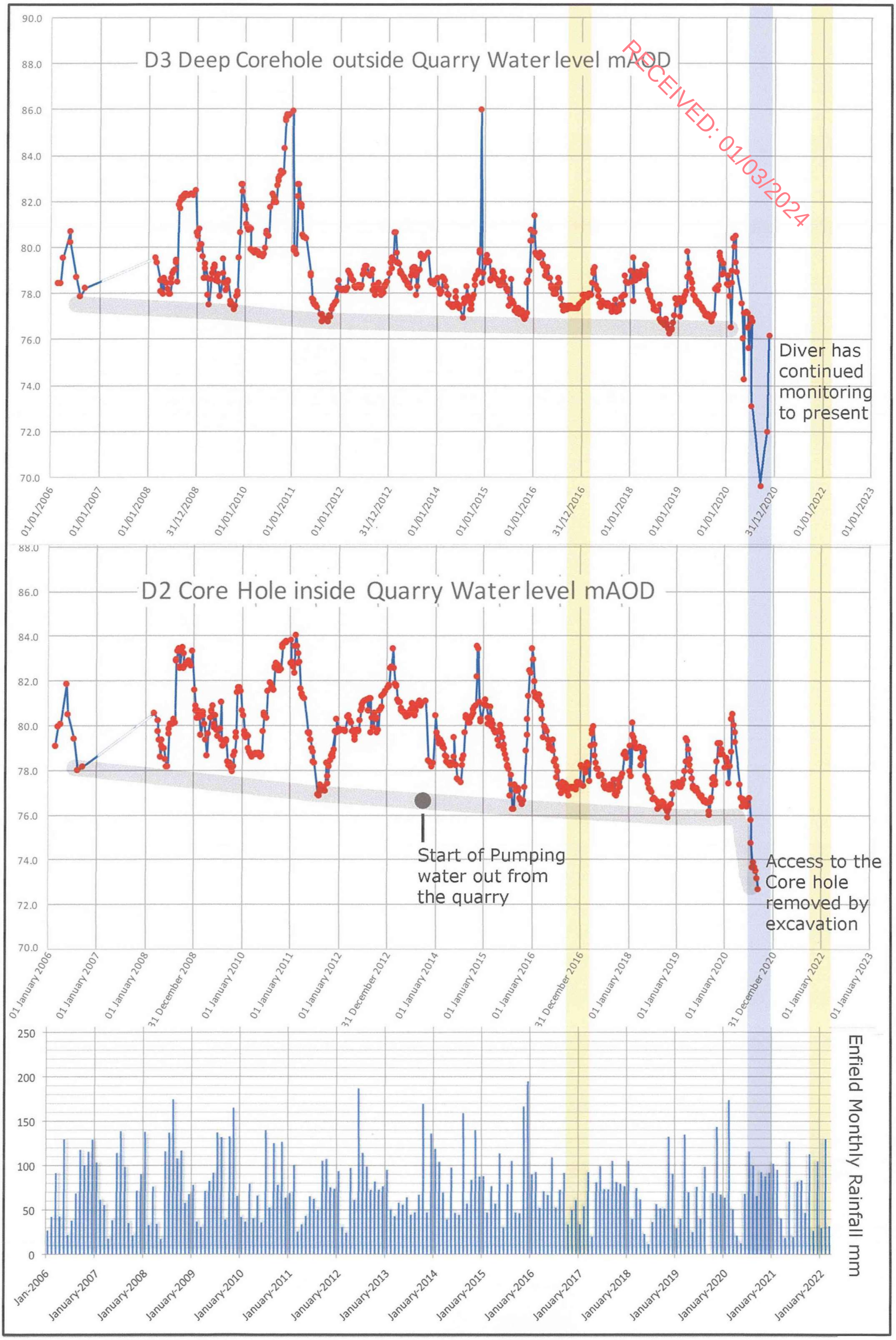


Figure 4.11 shows the hydrograph for core holes D2 and D3.

D2 was originally located in a field of pasture on the southern flank of Rathcore hill, but the quarry extended towards it until in late 2020 access was lost during blasting.

I have drawn a grey line along the deeper summer recession levels. It is informative about the limestone at this end of the quarry, that even when the dry quarry floor at 75 metres was just a few metres away from the core hole the water level in the core hole was a metre higher than the quarry floor. It is a small indication that the Waulsortian limestone in this area is massive, and that there are few open cracks in the limestone in the south of the quarry.

The core hole responded clearly to the long pumping test. The water was levels in the core hole dropped four metres in the first three months. A similar response to the pumping was seen in two exploration boreholes at this end of the quarry. They are described below.

I have marked the date of the start of pumping from the quarry in 2013 on the hydrograph. It is notable that the pumping from the quarry did not cause a drop in water levels in D2. It is also notable that the water levels in D2 continued to rise and recede with the same amplitude as before 2013. Pumping from the sump of the quarry did not either lower the water levels in the core hole or suppress the amplitude of the seasonal fluctuations. The only clear evidence of the effect of pumping from the quarry was during the long pumping test when water was pumped from deep boreholes.

Core hole D3 at the top of Figure 4.11 is located to the northwest of the quarry excavation, and 75 metres northeast of the shallow dug well W3 that depends upon a groundwater resource in the overburden.

The water level in D3 is about 10 metres below the water level in W3. Therefore, the water in the overburden is perched.

One of the common features of perched groundwater resources is that they can be ephemeral. During times of recharge, they can appear to contain plentiful water, but in the summer when there is less recharge, the perched water drains away and the aquifer becomes dry.

The dug well W3 provides a reliable water supply for a family home.

Core hole D3 has a water level above Ordnance Datum that is similar to the water level in D2 on the southern side of the quarry excavation. D3 is 350 metres north of the borehole 3 that provided the largest sustainable yield throughout the long pumping test. It can be seen that the long pumping test had a large effect on the water levels in D3. At one stage of the test the water level in D3 went down to 69.5 metres AOD.

The water level in D3 was not affected by the start of pumping from the sump in the quarry in October 2013.

Figure 4.12 D4 Water Level hydrograph

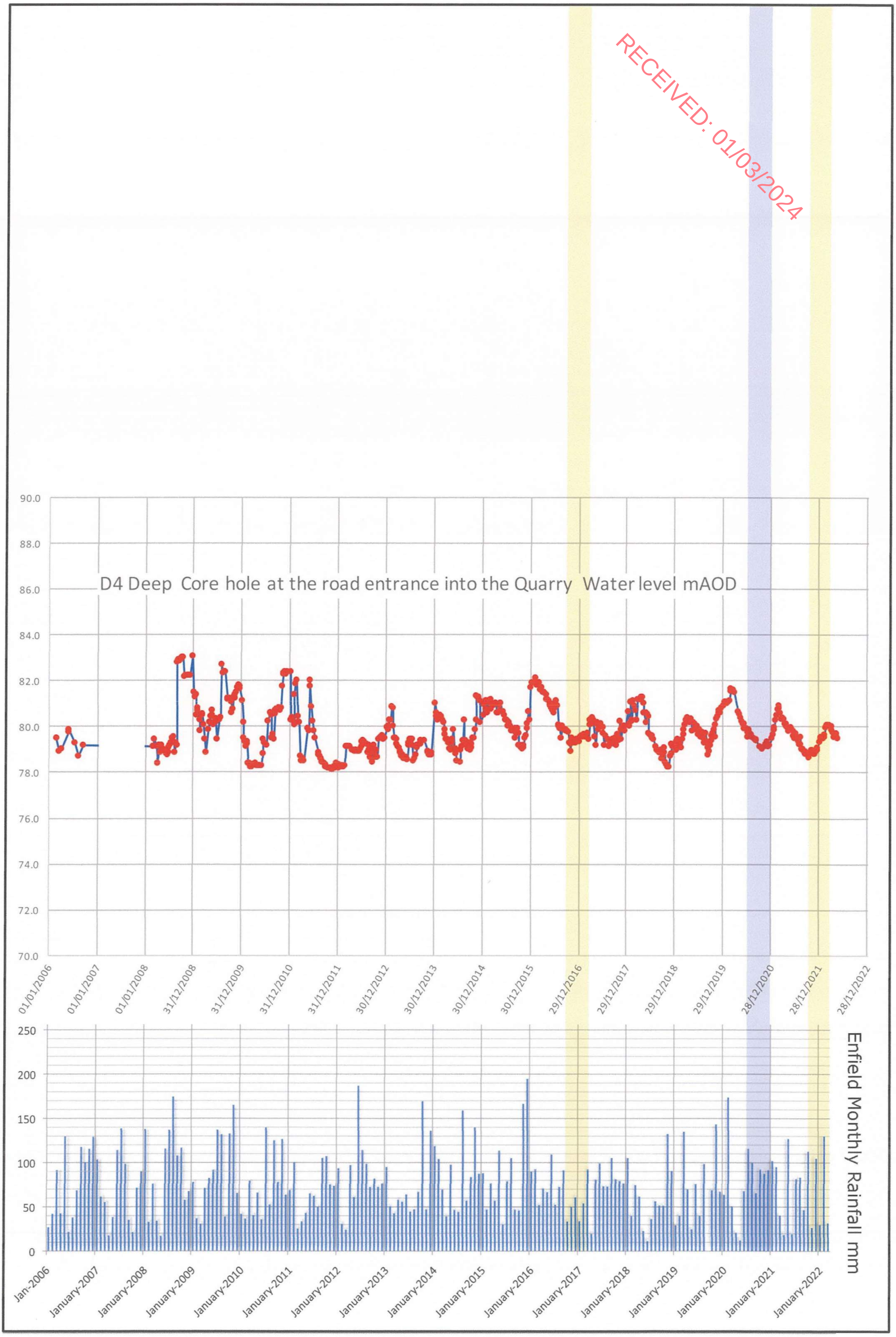


Figure 4.12 just shows the hydrograph for core hole D4.

This core hole is at the road entrance into the quarry. The hydrograph does not show any gradual decline in water levels over the 15 year record. The fluctuating water levels stay within a relatively narrow amplitude of about four metres.

The water level in D4 does not appear to have been lowered by the start of pumping from the sump in the quarry in 2013. In fact it may have risen slightly because the settlement pond and wetland for removing turbidity from the quarry discharge, are within 50 metres to the south. Any seepage from these would recharge the shallow groundwater system.

The water level in the core hole does not appear to have been affected by the long pumping test in 2020.

It appears likely that the water level in D4, like D1, represents the water level in the perched aquifer in the overburden, and not the water level in the bedrock below. The water level elevation above Ordnance Datum and the amplitude of the seasonal fluctuations is similar to those in dug well W3 about 400 metres to the north east.

4.3 Diver Water level pressure transducer measurements

Figure 4.13 is an extension of the graph for domestic shallow dug well W3 shown in Figure 4.4.

It contains the water level measurements made by a Diver pressure transducer from January 2019 to July 2022 in W3.

The Diver instrument has taken readings of water pressure and temperature every 10 minutes. The water pressure measurements made by the instrument are converted to the depth of the water column above the instrument by subtracting and correcting for barometric pressure changes using pressure data from a 'Baro diver' kept on the quarry floor. Manual sounding line measurements of the water level below the reference point, and a surveyed elevation for the reference point, are used to convert the water column data into the water levels above Ordnance Datum shown in the graph in Figure 4.13.

The blue line is a hydrograph showing the water levels in the dug well. The hydrograph does not form a fine line at this multi-annual timescale. It is about 10-15cm thick, because there are 10 – 20 pumping episodes each day with a small drawdown during each pumping episode to supply the demand from the house and garden. The drawdown is usually less than 15 cms during each pumping episode. The well has not failed to provide an adequate domestic water supply. Even in October 2021 there was still over 1.2 metres depth of water above the pump intake during pumping.

Figure 4.13 Dug Well W3 Water Level and Temperature 2019 - 2022

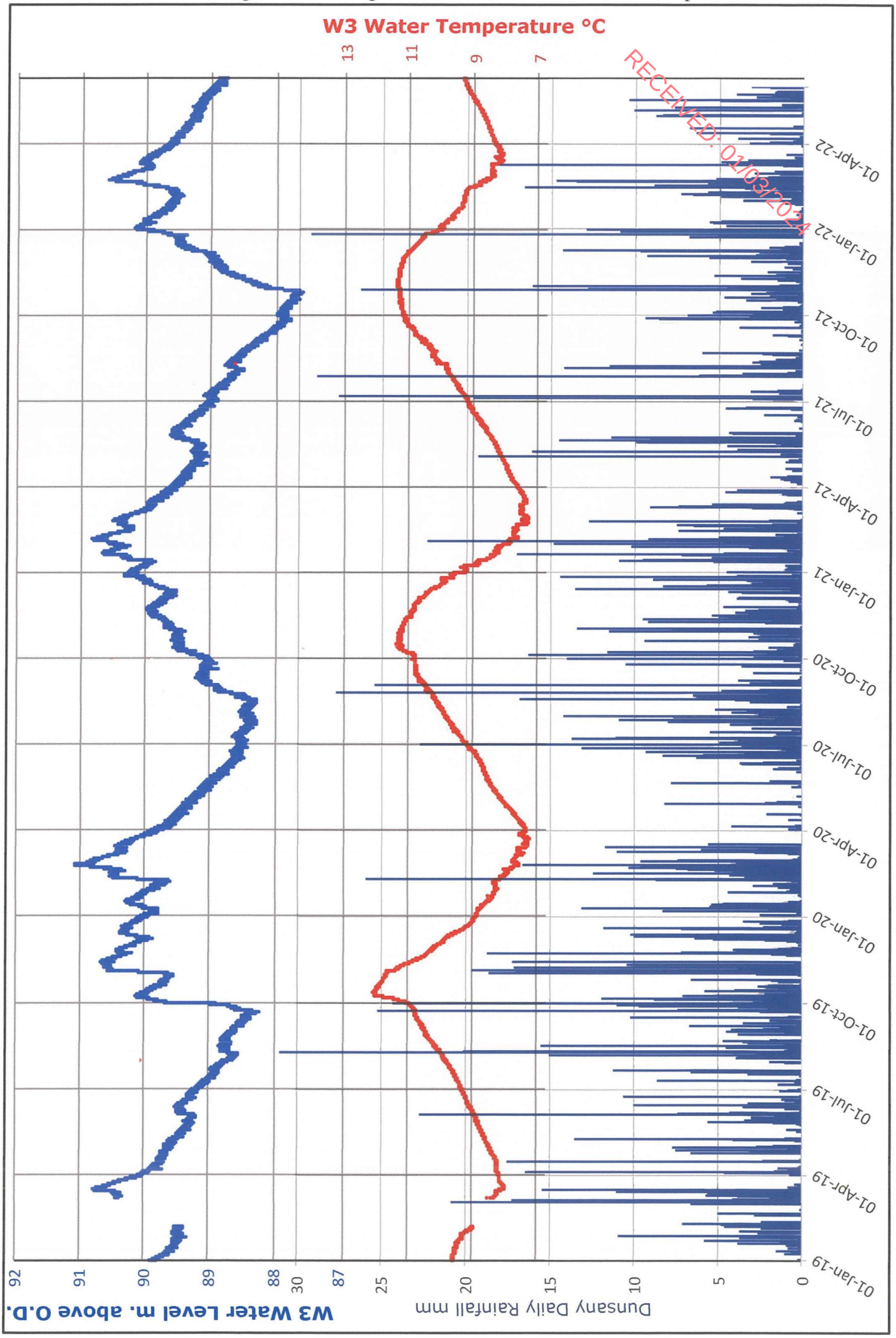


Figure 4.13 also shows the daily rainfall totals for Dunsany for comparison with the hydrograph. The data is from the Dunsany synoptic station because the Enfield rain gauge data is not available for the full period of the Diver record.

It can be seen that the hydrograph consists of a three and a half years of winter peaks and summer recessions. Along the graph there are small and large sharp peaks, or rises, in the water level in the well which correspond to individual days with heavy rainfall or several days with heavy rainfall. This occurs in both winter and summer; for example, between June and October 2019.

Though the pattern of winter high water levels and long summer recessions repeats each year, the graph shows that the date for the end of the summer recession changes from year to year.

In 2019 the recession ends in mid September. In 2020 it ends in August, during the long pumping test in the quarry. In 2021 it ends in late October.

The start of the summer recession varies less. It usually starts in late February to mid March. The final high water levels occurred in March 2019, in February 2020, in February 2021, and in late February 2022. The graph shows that groundwater recharge occurs over six months in 2020 – 2021 and only over four months in 2021 – 2022. The recession preceding the latter recharge period was also the longest; nearly nine months.

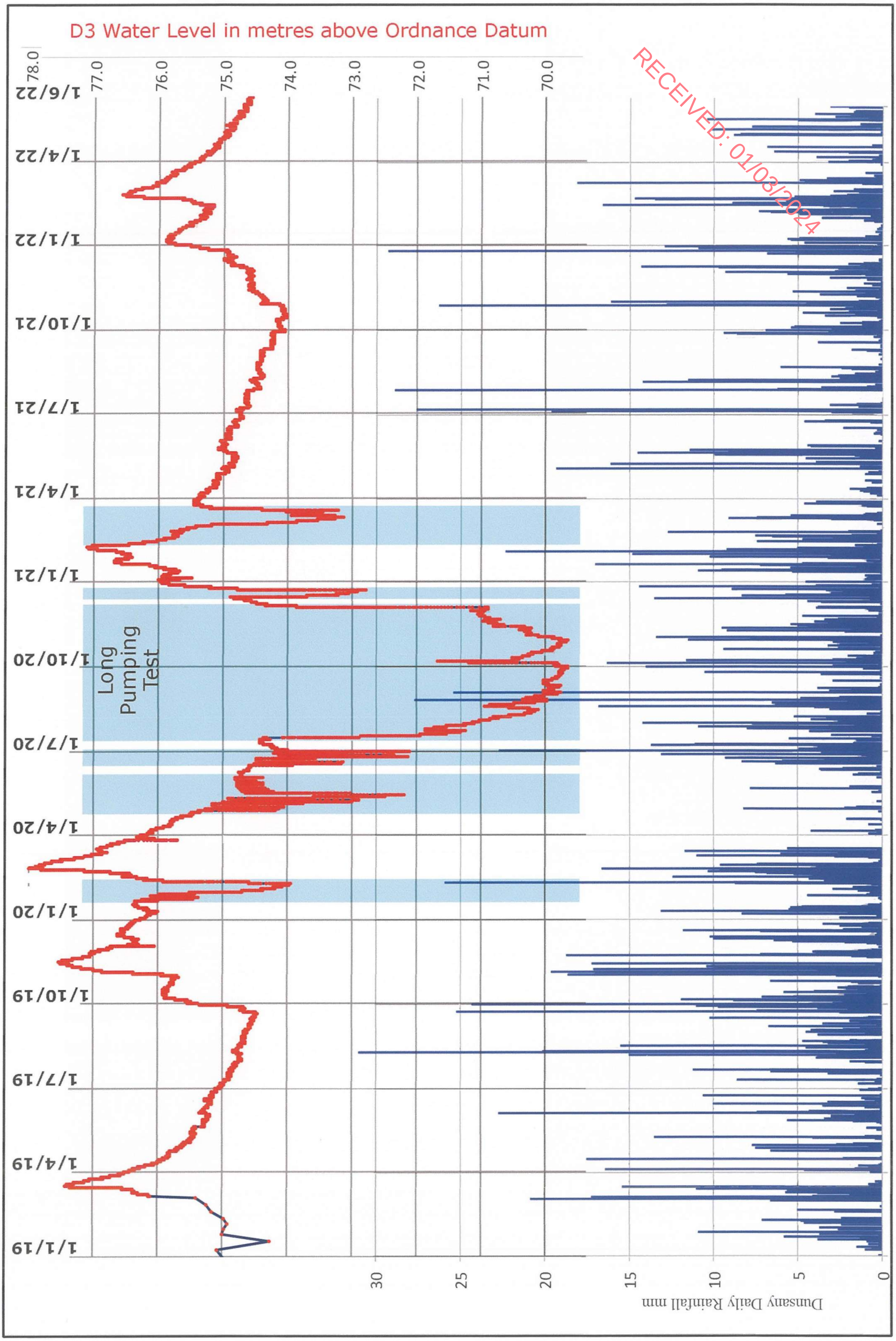
The water level in the overburden at W3 is close to the surface. It can be less than 1metre below ground level in January – February each year. In summer it can be over 3.5 metres below ground level.

Figure 4.13 also shows the temperature of the groundwater in this dug well. The dug well is covered, and it is located inside an insulated concrete well house with a closed door. The Diver instrument is at 5.5 metres below the well cover, at the bottom of the well. It is probable that the temperatures recorded by the Diver are representative of the temperature of shallow groundwater in the overburden aquifer, and not the air temperatures.

It is commonly assumed that the temperature of groundwater remains constant throughout the year, and it is roughly a reflection of the average of winter and summer temperatures. The advent of instruments such as the Diver has revealed at W3, and in shallow boreholes and wells elsewhere, that shallow groundwater temperatures are not constant.

At W3 the lowest temperatures are in late February = March after winter rainfall has percolated through cold soil and recharged the aquifer. Temperatures start to rise in spring as soil temperatures increase. The rise in groundwater temperatures is partly caused by heat conducted through the warming soil, and partly by rainfall falling through warm air percolating through the warm soil.

Figure 4.14 Core Hole D3 Water Levels January 2019 to June 2022



Heat conducted through the soil can be seen during the dry period with minimal recharge in April 2020 and in March – April 2021.

The highest temperatures do not occur in mid or late summer. They occur in mid October to mid November showing how rainfall during times with cool air temperatures is picks up heat as it percolates through the warmer soil.

The monitoring of W3 has been important because the temperature data and the response of the water level to rainfall recharge can be compared with a similar long term data set from the borehole next to St Gorman's spring. This data from W3 will be discussed further in the next Chapter of this report, that focuses on St Gorman's spring.

Figure 4.14 shows the Diver pressure transducer data for deep core hole D3, close to dug well W3, as a hydrograph. The measurements are made by the instrument at 10 minute intervals. The water levels represent the level of the groundwater in the limestone below the overburden. The water levels range from 78 metres OD down to less than 70m OD. The hydrograph shows a response to single days of high rainfall and prolonged rainfall over several days. This shows that the limestone groundwater system is receiving rainfall recharge, even though at D3 the limestone is overlain by overburden containing a perched aquifer. Recharge is getting into the limestone groundwater system in areas such as Rathcore hill and the quarry, where the overburden cover above the limestone is thinner.

The main feature of the hydrograph for core hole D3 is the significant fall in water levels in the limestone penetrated by the core hole when the pumps in boreholes 1, 2, and 3 inside the quarry are operated. The fall in water levels appears to be almost immediate on this multi=annual graph scale. As will be shown in Figure 4.19 the water levels in D3 start to go down about 25 minutes after the start of pumping from the quarry boreholes. There is an immediate recovery in water levels when the pumps are turned off.

The largest drawdown in the water levels in D3 occurs during the long pumping test in the quarry from 15th July to the 4th December 2020. The main periods of pumping from one or more boreholes in the quarry are shown as blocks of pale blue in Figure 4.14

The hydrograph from January 2019 to February 2020, and from April 2021 to June 2022 is the 'natural' hydrograph prior to the boreholes in the quarry being drilled and after the last pumping period from the quarry boreholes. It is significant that the elevation of the winter water levels in 2019 and 2020 were higher than in 2021 and 2022. The maximum winter water levels have declined over the past two years. The autumn, winter and spring of 2021-2022 has been exceptionally dry overall, and this is reflected in the subdued water levels in D3 in the winter of 2021 - 2022.

Figure 4.15 Core hole D3 and Dug well W3 Water Levels Januaty 2019 to June 2022

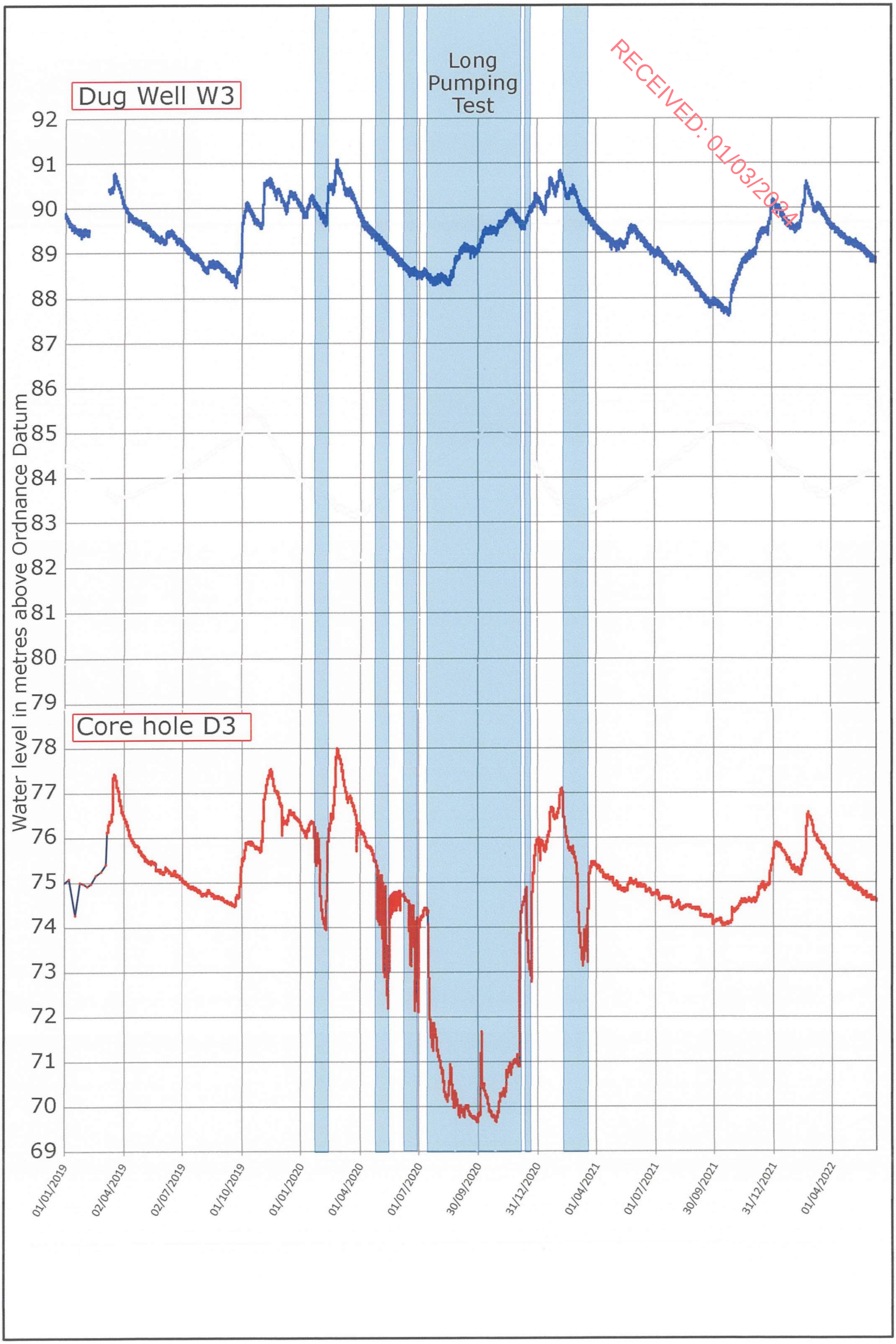


Figure 4.15 brings together, for comparison, the hydrographs for dug well W3 and deep core hole D3.

Both hydrographs are on the same vertical scale in metres above Ordnance Datum. This gives an illustration of how much higher the perched water level in W3 is above the limestone bedrock water level in D3. There is a 13-14 metre difference in elevation.

Both hydrographs rise and fall by about 3 – 4 metres each year. They both receive rainfall recharge at roughly the same time and they both rise and recede by roughly the same amount.

An important interpretation arises from the similar amplitude of the two hydrographs. An unconsolidated overburden sandy till aquifer would be expected to contain many interconnected small and large pore spaces that can be filled by rainfall recharge. In other words it would be expected that there is ample storage within the aquifer matrix to accommodate rainfall recharge.

By contrast, massive Waulsortian limestone would be expected to have no open pore spaces in the solid rock matrix. In other words, there is no space in the solid rock to store water. Water can only be stored in the spaces created by breaks in the rock. These range from isolated hairline cracks, to large karst conduit systems. The Waulsortian limestone overall would be expected to have limited storage space for recharge. Therefore, if both the overburden and the limestone receive the same volume of rainfall recharge, it would be expected that the amplitude of the rise and fall of water levels between summer and winter would be much greater in the limestone than in the overburden. It would not be unusual for the difference in water level between winter and late summer in a massive limestone to be 15 to 25 metres. (by comparison, the difference between winter and summer water levels in a fine sand aquifer would be less than 2 metres).

The similarity in the amplitude of the hydrograph for the overburden aquifer and the limestone bedrock could be interpreted three ways.

First, the recharge getting into the limestone is less than the recharge entering the overburden aquifer.

Second, the available storage in the fractures and karst conduit system in the limestone is much greater than expected.

Third, the rainfall recharge entering the limestone groundwater system is able to flow away quickly and drain out of the system. In other words the water levels in the limestone do not build up because the water is able to flow out of the system easily.

The third interpretation is unlikely because, as described in Chapter 2, the limestone under the shallow valleys in the area is overlain by clays and till. The evidence from the Boreholes at St

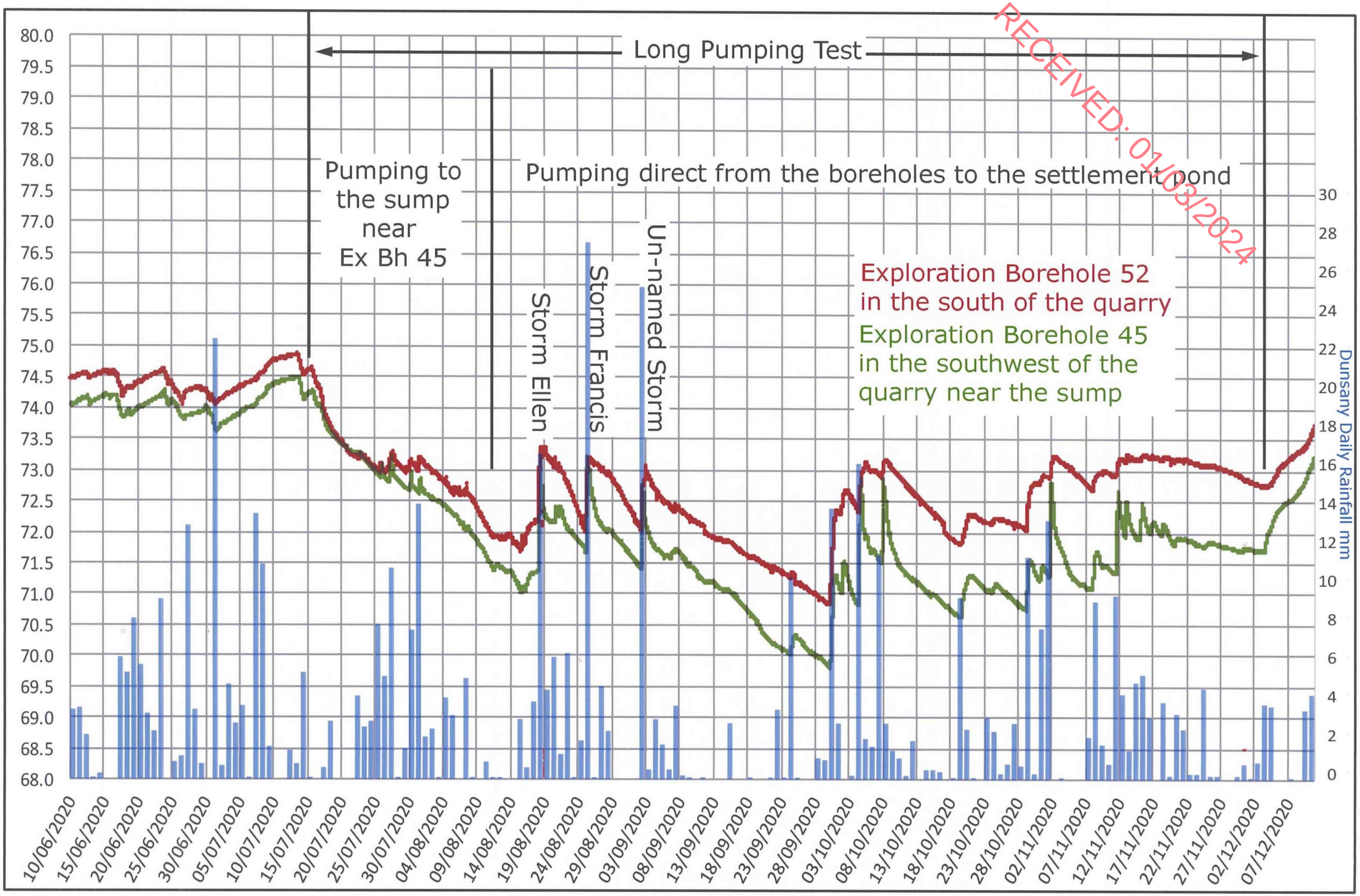


Figure 4.16 Water levels in two exploration boreholes during the long pumping test

Gorman's spring and the Longwood water supply boreholes is that the water in the limestone groundwater system is confined or sealed in by the material above. There are also no perennial large discharge springs in the area. Therefore, it seems unlikely that the amplitude of the hydrograph in the Waulsortian limestone is subdued because the water drains out of the system almost as fast as the rate at which rainfall percolates into the system. The large open conduits in the limestone would provide the potential to drain water quickly out of the system, but the exit appears to be blocked by the overlying overburden.

The second interpretation is possible. The evidence of fractures and karst conduits discovered in some areas under the quarry, plus the evidence from the BHP core holes and the EDA exploration drilling, and the airborne electrical conductivity information, all indicate that the weathering of the limestone has provided significant storage within the limestone. However, most of this storage space is already filled with water, and therefore not available to accommodate rainfall recharge. The heavy weathering, and solution widening of fractures in the upper bedrock above the level of the late summer 'water table' has provided significant potential storage to accommodate rainfall recharge, and it therefore partly explains the subdued amplitude of the hydrograph.

It is also likely that the subdued amplitude of the hydrograph for D3 arises because less recharge enters the limestone system than the overburden aquifer. The combination of geology, geophysics and topography discussed in Chapter 2, indicates that rainfall recharge is likely to percolate into the Waulsortian where the overburden cover is thin and unsaturated. Rathcore hill and the spine of the ridge of Waulsortian limestone extending northeast from the quarry, Ballinakill hill to the east of St Gorman's spring, and the block of Waulsortian covered by gravels in the Cullentry townland in the north, are the obvious areas where recharge could enter the Waulsortian groundwater system.

The hydrograph for D3 compiled from the Diver pressure transducer data is informative because it indicates that the upper and seasonally unsaturated weathered Waulsortian limestone has more storage than would be expected in a massive limestone, and yet the perched gravel aquifer also indicates that direct rainfall recharge does not enter the limestone groundwater system over the whole area.

Figure 4.16 shows Diver pressure transducer data converted into hydrographs for Exploration boreholes 45 and 52 within the quarry.

These holes are 4inch diameter and un-cased. The water level in each hole represents the water level in the bedrock, and the water level in the 'shatter zone' of broken rock on the floor of the quarry.

The data shown is from June to December 2020 during the long pumping test. The figure also shows the daily rainfall data from Dunsany.

The first notable feature of both hydrographs is the sharp response to rainfall.

The figure also illustrates the difficulty in trying to maintain a steady drawdown of water levels in a quarry where the surface is open to receive direct rainfall recharge into the bedrock.

All three rain storms in late August and early September 2020 produced an immediate sharp rise in water levels, followed by a gradual decline over the following 3 – 10 days, as the borehole pumps gradually drained the rainfall recharge out of the quarry shatter zone.

The rainfall during Storm Francis was over 27mm.

Over the last 7 years the quarry staff have tried to channel drainage from the sides, and the stockpiles of overburden, into the quarry floor. The objective was to bring all runoff can flow into the quarry floor, and eventually be drawn into the sump at the southwest corner of the quarry.

The approximate area receiving rainfall either directly onto the quarry floor, or contributing run off to the quarry floor is roughly 18 hectares. An intense rainfall event of 27mm, without making a deduction for evaporation losses, would generate nearly 5,000 cubic metres of water. The pumping boreholes would take approximately 2 days to remove this quantity of water alone.

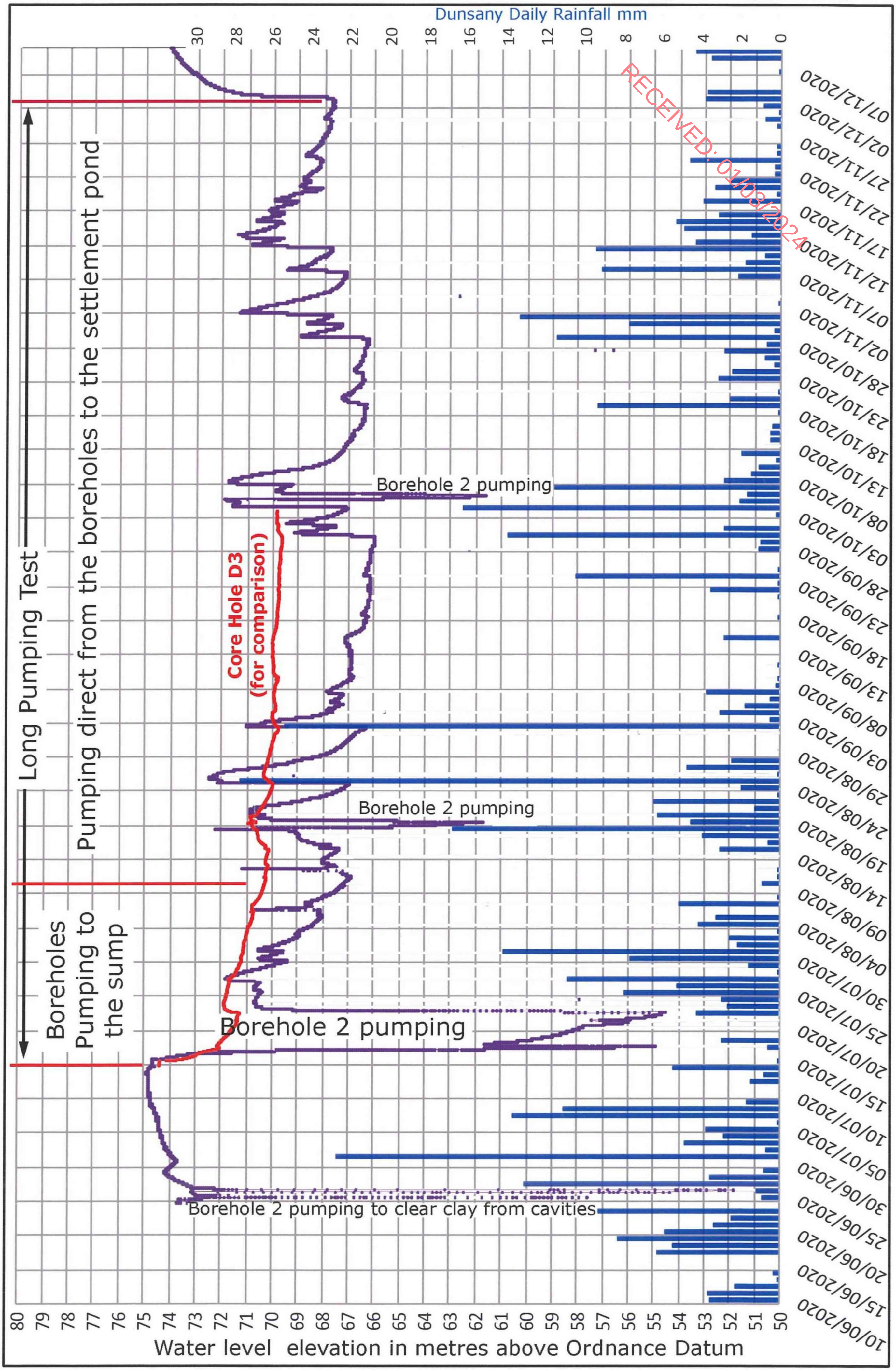
The spike in water levels during each storm and the gradual drawdown of levels shows the effect of the rain, and the struggle of the borehole pumps to try to bring the groundwater levels back down to the levels before the rain storms.

Fortunately, after the un-named storm on the 3rd of September, there was a dry period until the next heavy rain on the 30th September. The maximum drawdown of water levels in both boreholes occurred just before this rainfall.

Pumping from boreholes 1 and 3 only managed to drawdown water levels in exploration boreholes 45 and 52, in the south and southeast of the quarry, by about 4 metres. This was less than the corresponding drawdown of water levels measured in deep core hole D3 outside the quarry to the north, which is nearly twice as far away from the pumping boreholes. This difference indicates that the conduit system under the north central part of the quarry, tapped by the pumping boreholes, has a better hydraulic link to the north than to the south.

As described in Chapter 2, the exploration borehole drilling based on the structural geology survey, could not find any subsurface zones in the south of the quarry with large well developed karst conduits. For example, seven exploration boreholes (including borehole 45) were drilled

Figure 4.17 Borehole 2 Water levels June to December 2020 during the long pumping test



in a determined effort to find karst cavities next to the infilled karst depression in the southwest of the quarry, that is thought to be on the alignment of northeast to southwest Cenozoic faulting. The relatively small drawdown in exploration boreholes 45 and 52, plus the results of exploration drilling, appear to provide strong evidence that the rock and weathering of the rock under the southwest central and southern part of the quarry is different. It indicates that the rock is more massive, less fractured and contains fewer and smaller karst conduits than the northern part of the quarry. This general interpretation is further complicated by local heterogeneity. The water level elevations and response to pumping for these two exploration boreholes is different, except when pumping borehole 2 was pumping for a week at the start of the test.

It would normally be expected that the water levels in an observation borehole closer to a pumping borehole would be more affected by pumping than an observation borehole further from the pumping borehole.

Borehole 52 is 186m. from pumping Borehole 1, and 208m from pumping borehole 3, whereas borehole 45 is 192m from Borehole 1 and 245m from Borehole 3. Yet it can be seen that the drawdown in exploration borehole 45 is greater than in borehole 52. This may be an indication that the Cenozoic fault does exist, and has extended karst solution weathering in the direction of borehole 45, even though no significant cavities were encountered in exploration borehole 45 or the other six boreholes drilled nearby.

Figure 4.17 shows the hydrograph for pumping borehole 2. The water elevation vertical scale is 2.5 times the vertical scale in figure 4.16.

Borehole 2 initially appeared to be a very high yielding borehole, but the yield declined dramatically when clay slumped across the borehole from cavities below 25 metres depth, and blocked the flow up the borehole from productive cavities below 50 metres depth.

Borehole 2 was pumped at 25m^3/h from the 15th to the 22nd July, and briefly from the 18th to the 19th of August and the 5th to the 6th October 2020. Borehole 2 was not pumped after October 2020 because it could not sustain a yield greater than 8m^3/h.

The drawdown in the first week of the long test in July was about 20 metres. A larger drawdown of 22metres was achieved on the 26th June during nine hours pumping at 32 m^3/h during a proving test to clear clay and sand from the discharge prior to the main long test.

After the pump was stopped on the 22nd July, the borehole essentially was used as an observation borehole to monitor the drawdown in the karst system to the east of pumping borehole 3.

Borehole 2 is 47 metres from pumping borehole 3 and 99 metres from borehole 1.

The hydrograph for borehole 2 shows the same response to rainfall events as the other monitoring boreholes on the quarry floor, but the drawdown, after each peak caused by the rain, is more rapid, because borehole 2 is closer to the pumping boreholes.

The maximum drawdown of water levels in borehole 2 when it was not being pumped, occurred at the end of the three week dry period in September 2020. The drawdown was 9 metres.

From the middle to the end of September, the water level in borehole 2 declined by about 10cm, as if the drawdown was approaching steady state, or equilibrium conditions.

The hydrograph for deep core hole D3 until the end of September has been overlain on the hydrograph for borehole 2 for comparison.

It can be seen that, as expected with a more distant observation hole, the overall drawdown is less in D3, but water level in D3 also declined by about 10cm over the same period. The slope of the graph for both D3 and borehole 2 is almost the same from mid September to the end of September.

With reference to Figure 4.16 it can be seen that the small decline of 10cm in borehole 2 and D3 was in marked contrast to the fall of 1.5m in water levels in exploration boreholes 45 and 52 over the same time period.

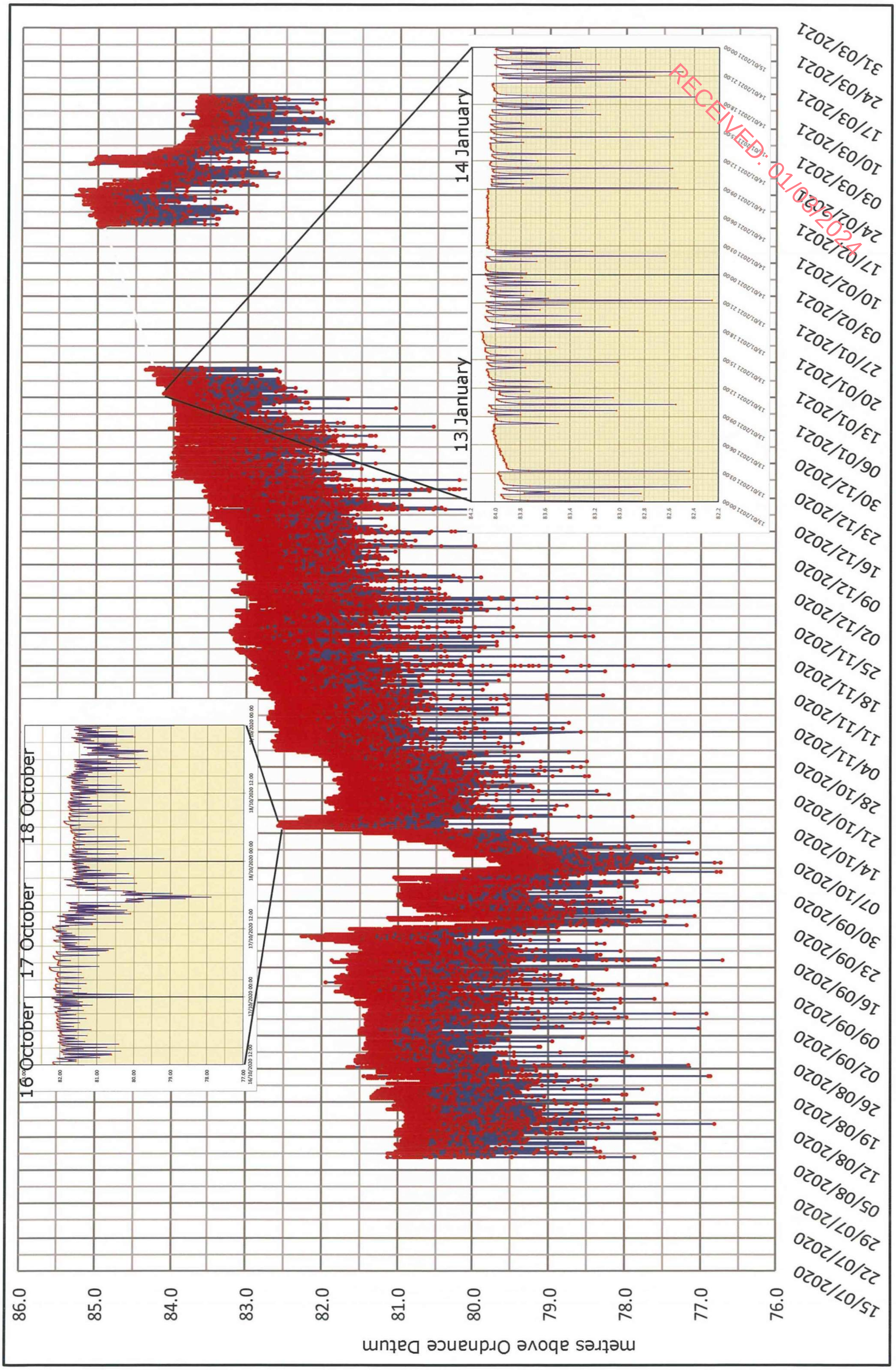
This comparison is informative. It shows that core hole D3 and borehole 2 are both connected to the large open karst conduit system being tapped by the two pumping boreholes. As the pumping boreholes draw water out of the conduits, the fall in water pressure at the pumping boreholes is rapidly transmitted throughout the karst system. So that, as equilibrium is approached, water levels decline at a similar rate.

The hydrographs for the two exploration boreholes 45 and 52 show that these holes are not connected directly into the same open conduit system. Instead their water levels reflect the withdrawal of water from limited storage in a system of small, tight cracks, or zones of granular dolomite, in a large mass of solid bedrock.

The long pumping test was carried out under difficult circumstances, with periodic stops to service the generator, high turbidity at re-starts and several heavy rainfall events leading to significant volumes of water recharging the aquifer in the quarry. However, by persisting with the test for several months there was sufficient time to observe the heterogeneity and anisotropy of groundwater flow and storage in the Waulsortian bedrock.

Figure 4.9 shows the hydrograph based on monthly manual measurements for borehole W17 (Patrick Flynn) from late 2006 to the spring of 2022. The data forms a useful long term record and can be used to see if there are any long term trends that might relate to dewatering activity

Figure 4.18 W17 - Farm borehole - example of short pumping & steep drawdown periods



in the quarry. There were five manual measurements made during the long pumping test and these showed a fluctuation in the water level in the borehole of just over 1 metre.

The bedrock geology was not recorded during the drilling of this borehole, but it was recollected that the limestone drill cuttings were dark grey or black. Based on this and the interpretation of the geology in Figure 2.50 the borehole was probably drilled into the Lucan dark grey limestone and shale formation.

After the first data from borehole SG4, 1.8km from the quarry, appeared to indicate a response to pumping at the start of the long pumping test, I decided to install a Diver pressure transducer in borehole W17 to find out whether there was any evidence that pumping from the boreholes in the quarry would have any impact on water levels in the Lucan Formation some distance from the quarry. Borehole W17 is about 900 metres from borehole 1 in the quarry.

I also installed the Diver in W17 for a second purpose; to find out the range of water levels during frequent pumping from a borehole used for both a farm with livestock, and domestic purposes.

Figure 4.18 shows the Diver hydrograph for borehole W17 from the 10th August 2020 to the middle of March 2021, with a month gap in January – February 2021.

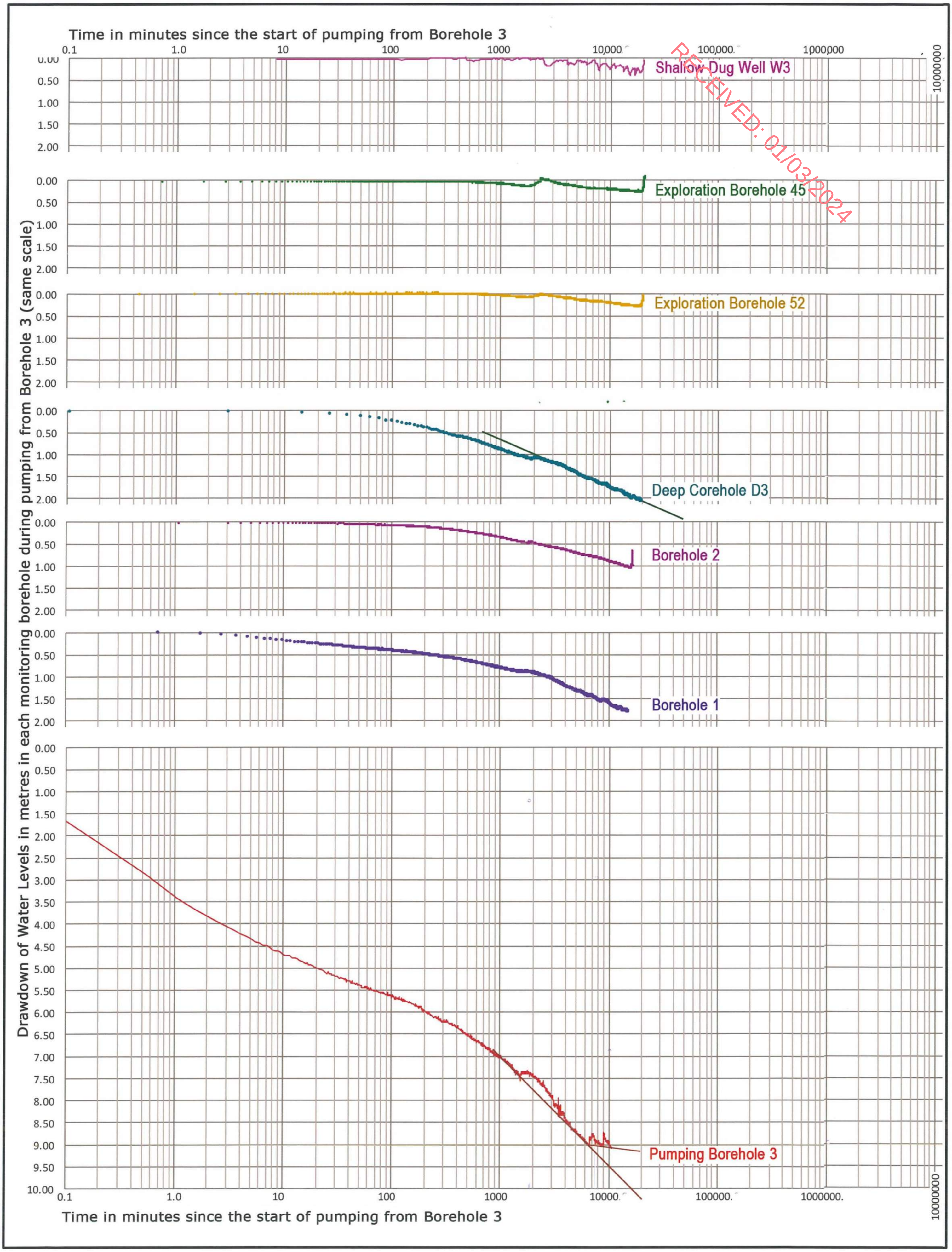
The Diver instrument was set to take readings at 5 minute intervals in order to capture the water level changes during the short pumping episodes typical of a borehole used for livestock and domestic purposes.

Figure 4.18 provides a good illustration of the frequency with which a pump is turned on and off when a borehole is used by a farm with livestock and a house. The data points are in red. The lines joining the data points are in blue. The blue lines draw attention to the depth of the drawdown in the borehole in each short-lived period of pumping.

The hydrograph is cluttered with data points and lines. In order to provide more clarity, there are two enlargements of parts of the hydrograph shown in the figure. One enlargement shows the intensity of pumping in mid October 2020. On the 17th October there were several very brief periods of pumping between midnight and 6am. The water supply system probably contains a pressure vessel. When the pressure falls in the vessel the pump turns on to re-pressurise the system. These brief periods of pumping during the night may suggest that there is a small leak, or dripping tap in the water distribution system that slowly releases pressure. Eventually, the pump turns on to restore the pressure.

Later on in the day there is a prolonged period of pumping between 4 and 7pm. This may relate to a farm activity requiring water.

Figure 4.19 Water levels during pumping of Borehole 3 29th January to 10th February 2020



The second enlargement shows less pumping on the 13th and 14th January 2021 during the Level 5 Covid-19 lockdown between the 31st December and 31st January.

The main hydrograph and the enlargements show that when the pump turns on for even brief periods there is a drawdown of water levels ranging from 0.5 to 2.5 metres. This is in contrast to the drawdown of less than 10cm needed to maintain pressure and supply for domestic purposes seen in the hydrograph for dug well W3. The demand and pumping rate are probably not be the same, but the data indicates that the limestone tapped by borehole W17 is is hydraulically less efficient at yielding water than the overburden gravel aquifer drawn upon by dug well W3.

The hydrograph for W17 illustrates how manual 'spot' manual measurements of water levels in this borehole during the daytime could give readings anywhere in a range of 2-4 metres below the 'natural' (non-pumping) water level.

For example, a manual water level measurement was made at borehole W17 on the 28th October 2020. The level reduced to Ordnance Datum was 81.73m AOD. The Diver data for the 28th October shows that the water level varied between 79.5m to 81.9m AOD. This is a range of 2.4metres over a 24 hour period. This may provide one explanation for the seemingly anomalous low water level manual readings recorded in W17 during the summer of 2018 and shown in Figure 4.9.

The daily range of water levels in other water supply boreholes, for homes and farms, would probably be similar. This may be an alternative explanation for manual records of low water levels in W10 and W11 during the long pumping test in the quarry in 2020, and in W4 during 2021 and 2022.

Figure 4.19 shows how the Diver data can be used to provide a valuable insight into the speed of response in monitoring boreholes to the pumping from a borehole in the quarry.

There are several potential pumping periods that could be used, but during most of them the pumping rates were not constant.

The pumping of borehole 3 from the 29th January to the 10th February 2020 is the best example of prolonged pumping at a constant rate. This was possible because one borehole was pumping continuously at the same pumping rate, there were no major rainfall events to recharge the groundwater system in the quarry until the 10th, and the generator did not require servicing and was not stopped.

Borehole 3 in the quarry was pumped at 86m^3/hour, or just over 2 million litres a day. This pumping rate put a reasonable stress on the karst groundwater system and created a drawdown of water levels in several boreholes.

Unfortunately, the Diver pressure transducer was mistakenly withdrawn from borehole 3 on the afternoon of the 5th February. However, the pump continued working, and pressure transducers in the observation boreholes continued to record the drawdown in those holes.

Figure 4.19 shows plots of water level data with the same vertical normal scale and logarithmic time scale on individual graphs for six boreholes and one dug well.

The time scale starts at 0.1 minutes after the start of pumping in borehole 3.

The water pumped from Borehole 3 was discharged by a long 6inch pipe to a flat part of the quarry floor about 50 metres from the sump in the south western corner. The discharged water contained clay initially, but the turbidity cleared within three hours. Discharging the water onto the zone of shattered rock on the quarry floor allowed the clay to settle out amidst the broken rock before the water seeped laterally into the sump. The sump pump was operated throughout the test.

At the bottom of the figure is the plot for pumping borehole 3. It shows a steep drawdown for the first 40 minutes, followed by a slight decrease in the gradient until 200 minutes, and then a steepening gradient until 1500 minutes, when there is a slight rise caused by rainfall. Thereafter, the water level continues to decline until at 6,000 minutes the drawdown flattens with two small rises caused by further rainfall. The record stops at 10,000 minutes, or 6.9 days.

The water levels in dug well W3 are shown at the top of Figure 4.19 for comparison with the other monitoring holes.

As discussed above, W3 is not affected by pumping from the boreholes in the quarry, as it monitors a perched water level in the overburden aquifer.

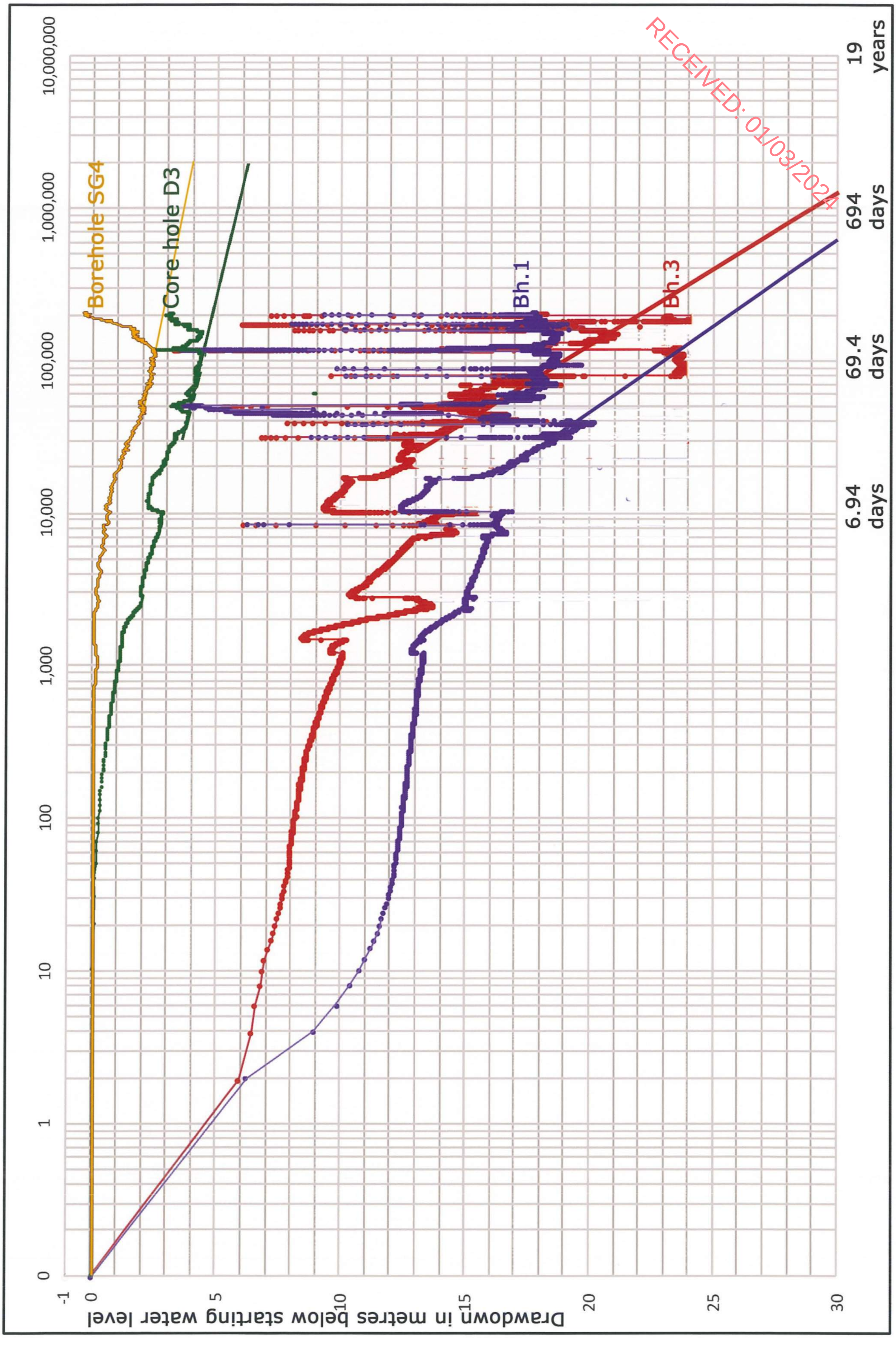
The data from W3 shows that water levels in the overburden recede during the test. This is a small natural recession of 25-30cm starting at 2,000 minutes and ending with a rise in levels due to rainfall of 8mm on the 8th and 25mm on the 9th February.

Figure 4.19 shows that a similar recession of water levels occurs in Exploration borehole 52. This indicates that the effect of pumping borehole 3 had not reached the southeast corner of the quarry within 20,000 minutes. The lack of response in exploration borehole 52 may have been muted by the discharge of water to the quarry floor near the sump.

The graph for exploration borehole 45 appears to show water levels starting to fall after about 600 minutes. The levels then rise due to rainfall between 2,000 and 3,000 minutes and then continue to recede until 20,000 minutes.

The recession of water levels in exploration borehole 45 superficially appears to suggest that the water levels were drawn down by the pumping in borehole 3. However, it is likely that the drawdown in exploration borehole 45 is a combination of the drawdown created by the

Figure 4.20 Long test 15 July to 3 December 2020 Semi log drawdown chart



pumping from the nearby sump and pumping from borehole 3. The discharge of water to the quarry floor did not appear to raise water levels in exploration borehole 45.

The pumping from borehole 3 created a response in deep core hole D3 within 25 minutes of the start of pumping, and created a total drawdown of 2 metres by 20,000 minutes. The water level fell in D3 consistently throughout the test. The water level decline did not show any sign of flattening off that might have indicated that an equilibrium or steady state was being approached. In other words, though the draw down in borehole 3 appears to be reaching a steady state, the impact of pumping continues to spread out through the conduit system to D3 and beyond.

The advantage of semi-log plots is that gentle curves on an arithmetic time scale are converted into straight lines. The slope of the straight line can be projected into future time.

As an example of the value of plotting drawdown data on a semi-log plot; the drawdown over one log cycle on the graph (from 2,000 to 20,000 minutes) in core hole D3 is roughly 1.2metres. Therefore, the projected drawdown at the same rate after a further log cycle would be an extra 1.2metres.

By further extension; the projected drawdown would be 3.2metres after 200,000 minutes pumping, 4.4metres after 2million minutes pumping, and 5.6metres after 20million minutes pumping.

20 million minutes is roughly 38 years.

Behind this straight line projection is the assumption that borehole 3 is being pumped continuously at 85m^3/h, conditions in the groundwater flow system remain the same (e.g. no sudden collapse of clay in a major conduit that blocks flow), and that there is no rainfall to add water into the groundwater system in the limestone, and raise water levels in core hole D3.

The latter assumption is obviously incorrect, and the projection of the drawdown over such a long time-scale is unrealistic.

However, the projection gives a feel for the order of magnitude of the drawdown created in the karst conduit system at a distance of 330metres to the north of the pumping borehole 3, when the borehole is pumped at 85m^3/h. (Figure 4.20 discussed below shows a more realistic perspective of the drawdown at higher pumping rates and the effect of rainfall).

Figure 4.19 shows the drawdown in boreholes 1 and 2. They were not being pumped at the time. Borehole 1 is 59 metres to the west southwest of borehole 3, whereas borehole 2 is 47 metres to the east southeast.

Borehole 1 started to respond to pumping from borehole 3 within 3 minutes. The drawdown reached 1.75metres within 16,000 minutes.

Borehole 2, though nearer to the pumping borehole did not respond for 30 minutes and the water level was only drawn down by 1metre in 16,000 minutes.

These observations indicate that the karst systems encountered by borehole 1 and borehole 3 are well connected, whereas there is less connection with the karst conduits encountered by borehole 2 to the east.

The data on the graphs demonstrates the heterogeneity of the connections within the karst conduit systems, even in the small area of the quarry.

The data shown in Figure 4.19 represents drawdown in close and distant monitoring boreholes in February 2020, when water levels in the groundwater system were at winter highs.

The data illustrated an important point that pumping a single borehole at a high rate of over 2 million litres per day would not, in the short term, dewater even a small area of the quarry down to 30 metres in the middle of winter. This early finding in February 2020 had a bearing on the design of the pumping test that took place in the summer of 2020, after the Covid-19 lock-down in the spring of 2020.

The test in February made us realise that it would be necessary to carry out a very long test at even higher pumping rates, in order to thoroughly stress the groundwater system, in order to estimate the pumping rates necessary to draw water levels down further below the quarry floor in the northern part of the quarry.

Usually, the drawdown in a borehole cannot be said to replicate or simulate the drawdown in a quarry, or a quarry sump, during dewatering. This is because the drawdown in a porous permeable aquifer decreases away from the pumping borehole. Water flowing through a porous aquifer to a pumping borehole has to overcome resistance or friction losses as it moves through the myriad of small pore spaces in the aquifer on its route to the pumping borehole. The friction increases as the water flow rate increases and the flow becomes turbulent as the flow lines concentrate close to the borehole wall. Therefore, for example, pumping a borehole might create a drawdown in the borehole of, say, 30metres, but the drawdown 5 metres from the borehole, in a porous media aquifer, might be just 12 metres. 20 metres from the borehole, it might be just 4 metres.

The drawdown in a karst conduit system is different.

Groundwater does not have to flow through narrow pore spaces between grains of sand or gravel. Instead the water flows along conduits, the equivalent of wide diameter open pipes. The resistance to flow relates to the open diameter and roughness of the pipe, and the speed of flow along the pipe. If the flow along a large conduit is slow, then the flow will be laminar and there will be minimal friction losses caused by turbulence.

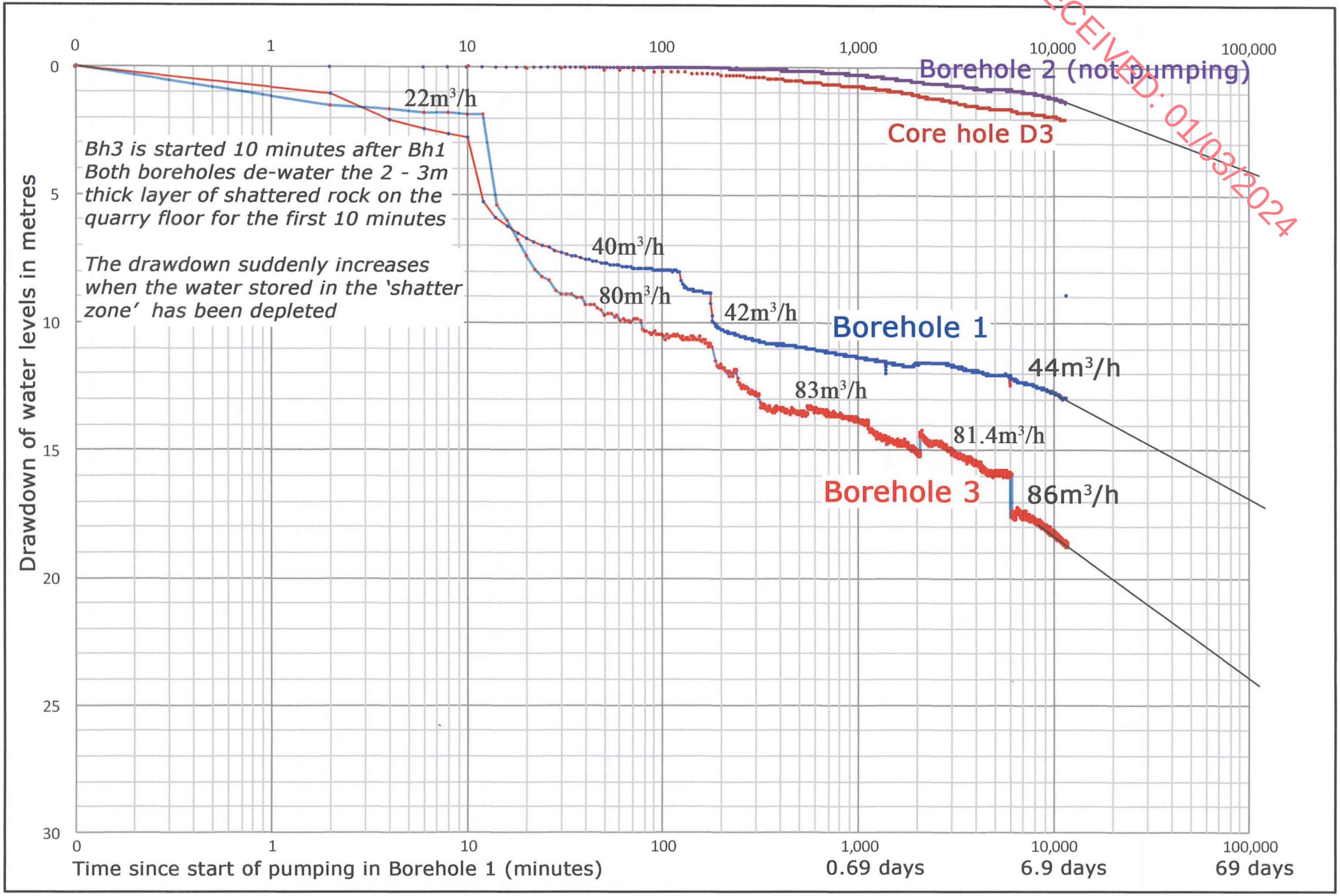


Figure 4.21 8 day pumping test 14th to 22nd December 2020

However, if there is a choke or constriction in the conduit, then there will be friction head losses as the water flow tries to force its way through the narrow part of the conduit.

The large karst conduits tapped into by a borehole are like a network of subsurface large open drainage pipes. In almost all cases the size of the conduits are greater than the diameter of the borehole. There are no head losses as water comes close to the pumping borehole. There is no concentration of flow lines close to the borehole, because water can only flow along the conduit. There is essentially no flow through the rock. Therefore, it does not matter whether a 3 metre diameter karst conduit is tapped by a borehole that is, say, 10 inches in diameter or, say, 24 inches in diameter. The yield of, and drawdown in, either diameter borehole, if they have the same pump, would be roughly the same, because the yield is dictated by the ease with which groundwater can flow through along the conduits.

The conduits currently running through the rock to the borehole also could be looked upon as akin to collector drains on an open quarry floor feeding water into a sump.

The evidence from monitoring the various pumping episodes strongly indicates that both borehole 1 and 3 tap into the same karst conduit system.

Borehole 2 taps a conduit system that is linked to the conduit system feeding borehole 1 and 3, but there maybe a constriction in the link between the two conduit systems.

Figure 4.20 shows the drawdown in the two main pumping boreholes during the long test from July to December 2020 on a semi log graph. Borehole 2 was not included in the graph because the data points would make it difficult to see the pattern of data points for the two main pumping boreholes. The data extends for more than 200,000 minutes.

A trend line has been drawn through the deeper drawdown data for borehole 3 from 20,000 minutes to 200,000 minutes. The trend line has been projected forwards to a depth of 30 metres. It indicates that at pumping rates of between 2,000 and 2,500 cubic metres per day, the water level will be brought down the final 7 metres to 30 metres in about 800 days.

Figure 4.20 also shows the drawdown data for borehole 1. There is a trend line based on the data from 20,000 to 40,000 minutes when borehole 1 was pumping at 44 m^3/h whilst borehole 3 was pumping at 65 m^3/h. This trend line projects to 30 metres in 500,000 minutes or 350 days.

The projection of the trend lines is for guidance, to provide an idea of how long it might take to bring water levels down to the base of the proposed deeper quarry at these pumping rates. The proposed deeper quarry would not be excavated down to a depth of 30 metres immediately. The first stage would be to start excavating the first extra bench down to 15 metres. This would take several years. Therefore, at combined pumping rates of the order of 2,500-3,500 cubic metres per day, it appears feasible to dewater, and control water levels for the proposed deeper quarry.

Figure 4.20 also includes water level data for two monitoring boreholes outside the quarry; deep core hole D3 and borehole SG4 at St Gorman's Well. Trend lines are shown for data from 50,000 to 120,000 minutes. During this period there was a relatively consistent recession of water levels in both boreholes, before water levels started to rise in response to autumn and winter recharge. The trend lines show that water levels in both boreholes would recede by a further 1.5 metres within 2 million minutes, if there was no rainfall recharge during that time, and pumping from the quarry continued at the above rates. 2 million minutes is 3.8 years. The trend line is just for guidance. It shows that the rate of drawdown in the karst conduit system close to the quarry is almost exactly the same as the rate of drawdown nearly 2 kilometres from the quarry. It indicates that prolonged pumping at these rates and without any rainfall will spread far from the quarry, but the actual fall in water levels will be small.

Of course to project drawdown in a scenario where there is no rainfall recharge for 3.8 years is not realistic. This is demonstrated in the graph by the rise in water levels in both monitoring boreholes after 120,000 minutes, and the eventual rise of water levels in SG4 at St Gorman's Well to a level that is higher than the initial water level at the start of pumping.

The graph shows that in spite of very prolonged pumping from the quarry, the drawdown in water levels at St Gorman's Well was counteracted, or overwhelmed, by the impact of rainfall recharge in the outer part of the zone of contribution as represented by borehole SG4. The graph shows that the rainfall recharge, closer to the quarry, counteracted the drawdown created by the pumping. The water levels in D3 rose, but they did not rise back to the levels at the start of the pumping. In other words the pumping maintained an impact close to the quarry during the autumn and early winter rains, but the impact was overcome by the recharge further out in the karst conduit system in the wider zone of contribution.

In essence, the zone of contribution (or the area affected by the pumping) contracted when recharge started to enter the system in the autumn. It would be expected that this contraction of the zone of contribution would continue throughout the winter until the end of effective recharge, normally in the spring. Thereafter, the zone of contribution would extend, and water levels further out would start to fall again, probably back down to the trend line shown on the graph. The following autumn and winter the water levels would rise again. The following summer they would fall again back to the trend line. Therefore, the trend line indicates that 3.8

years after the start of pumping, the late summer water levels in SG4 would be about 4 metres lower than the starting water level on the 15th July 2020.

It should be noted that the rise in water levels in SG4 taking place at 200,000 minutes continued during the following three months. The water levels rose by a further 3 metres above the top of the graph shown in Figure 4.20.

The water levels in SG4 are described, and interpreted in much greater detail in the following Chapter of this report.

There were several days of rain after the end of the long test in December 2020. The combination of a rapid recovery of water levels in the quarry, and the continuing rainfall lead to a precautionary decision to turn the pumps back on in boreholes 1 and 3. The objective was to lower the water levels in the quarry in anticipation of further rain over the Christmas - New Year holiday break. The idea was that pumping would create space for the anticipated rainfall, and the quarry would not become flooded by the time operations began again in January.

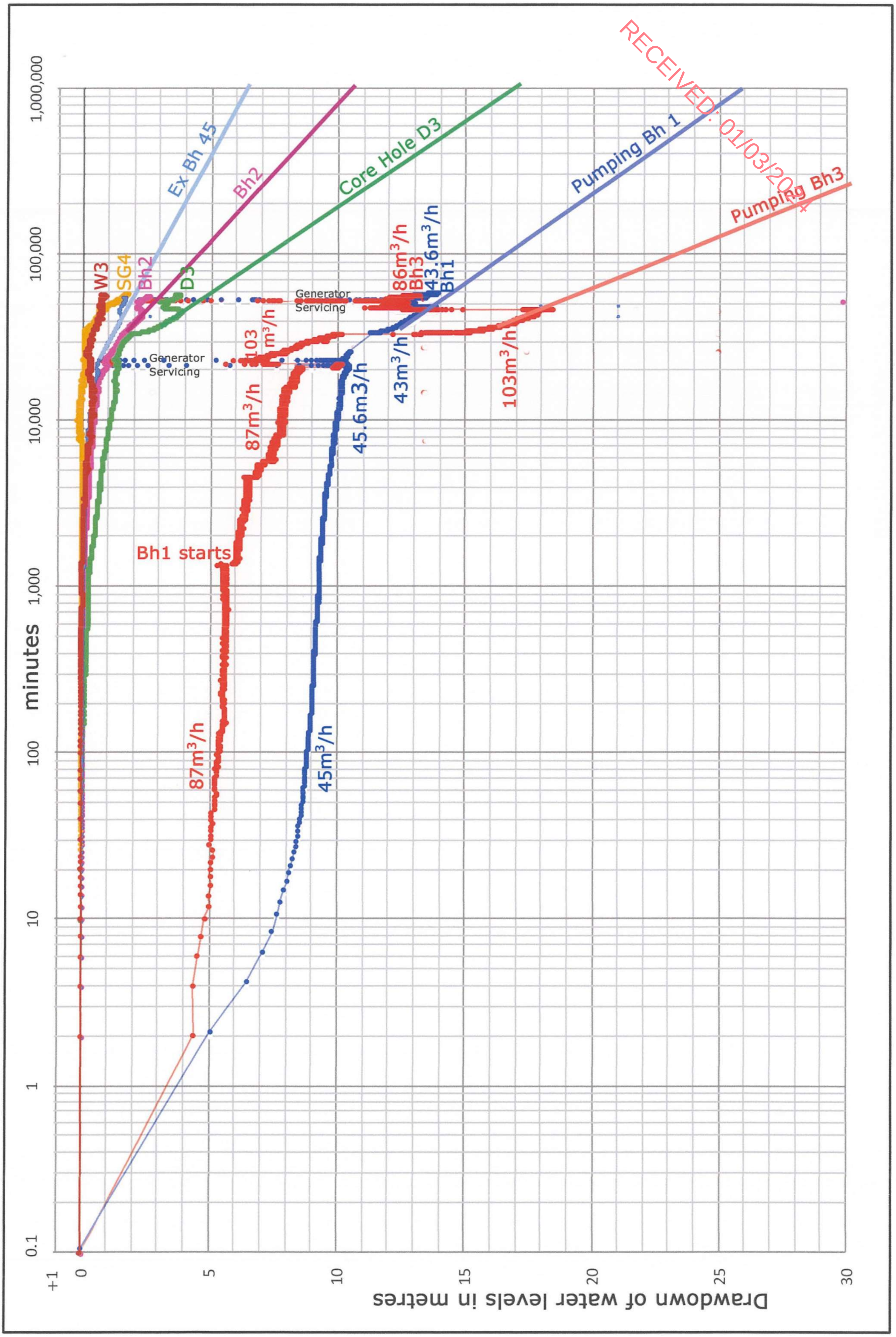
Though this strategy was unsuccessful and the quarry floor partially flooded, the eight day pumping test provided useful information. The data for this pumping is shown in Figure 4.21. The graph shows the drawdown of water levels in the two pumping boreholes. The graphs show how the drawdown responds quickly to changes in pumping rate, and how a change in the rate of pumping in one borehole quickly affects the water levels in the other borehole. This further illustrates the good connection in the conduit system feeding both boreholes.

Figure 4.21 shows the data from borehole 2 that was not pumping. For the first 400 minutes the water level in borehole 2 does not change. This borehole is sited in an area where the zone of shattered rock on the quarry floor is thick and fully saturated with water. It took 400 minutes of pumping from the two boreholes to start to lower water levels in this ‘shatter zone’. The dewatering of the shatter zone continues slowly for the next 6,000 minutes and then the water levels in borehole 2 start to fall more rapidly. A trend line has been drawn through the last 5,000 minutes that illustrates the change in gradient in this late data.

Meanwhile, and in contrast, the water levels in deep core hole D3 (which is much further from the pumping boreholes than borehole 2) responds within 70 minutes to the start of pumping in borehole 1. There is a consistent drawdown in D3 for about 10,000 minutes. A trend line is not drawn because the gradient is obvious.

The trend line through the later drawdown data for the two pumping boreholes project that the water levels would be drawn down by a further 4-5 metres over the next 90,000 minutes, showing that, even during high winter water levels, both boreholes pumping at a combined rate

Figure 4.22 Pumping Test 7/8th February to 19th March 2021



of 130 m^3/h can bring water levels down below 15 metres, the depth of the first bench of a proposed deeper quarry.

The water levels in Borehole SG4 are not shown on the graph because the water levels rose by a further metre during this short intense pumping test. The long test in the summer to early winter of 2020, showed that pumping in the quarry affected the water levels in SG4 at St Gorman's Well. The short test before Christmas 2020 indicated that intense pumping from the quarry under winter conditions did not affect the water levels at SG4.

The water levels at SG4 rose rapidly at the end of December 2020. I decided to let natural, or no pumping conditions continue, in order to find out whether St Gorman's Well would start to fill and eventually flow after all the pumping that had taken place in the summer autumn and early winter.

Eventually St Gorman's Well did fill and flow. Artesian flow also took place from boreholes SG4 and SG7.

When flow was well established, I decided to start a pumping test to thoroughly stress the groundwater system under winter conditions, and find out whether pumping from the quarry boreholes would stop the flow from the spring and the boreholes.

I discussed the strategy with Nicholas Wilkinson, and he agreed with the objective of the experiment. We did not know how long the Well and the boreholes would continue to flow, so it was difficult to judge the best time to start the pumps in the boreholes in the quarry.

I analysed the water level data, and seeing that flow appeared to be still increasing on the 5^{th} and 7^{th} of February, I started borehole 3 at 87m^3/h on the 7^{th}. By the 8^{th} February there appeared to be no response in SG4, so I turned on borehole 1 in the quarry at 45m^3/h. The total pumping rate was then 132m^3/h, or 3.168 million litres per day. During the following days there was still no response at St Gorman's Well.

Rather than stopping after a few days or a week, I decided to keep on pumping. The test lasted for 42 days, by which time we could see that there was a natural recession of water levels in all monitoring holes, after a period with no rain at the end of February and in the first week in March.

Figure 4.22 is a semi-log graph showing the water levels for 8 boreholes and the shallow dug well W3, during the 42 day winter pumping test. Borehole 1 started pumping the day after borehole 3 but it has been plotted on the same time axis scale as if it started at the same time, in order to show the detail in the early drawdown data on the graph. The graph looks a little confused at 20,000 and 50,000 minutes because the pumps had to be stopped whilst the generator was serviced. Between the two service stoppages the pumping rate from borehole 3 was increased to 103 m^3/h, bringing the combined pumping rate up to 146 m^3/h, or 3.5 million litres per day. This is the maximum pumping rate for the two pumps. I increased the pumping rate because I could still not observe a response in SG4 at St Gorman's Well. The graph shows how there was a response to this increase with a steepening of drawdowns in borehole 1, core hole D3, borehole 2, and exploration borehole 45 at the south end of the quarry, but no immediate response in SG4 at St Gorman's Well. Eventually after a further 16,000 minutes, or 11 days, water levels in SG4 started to go down. This may have been the effect of pumping, but equally, it may have been the start of a natural water level recession caused by the paucity of rain in March 2021.

The overall evidence from the winter pumping tests is that intense pumping from the quarry boreholes does not stop St Gorman's Well or borehole SG4, from flowing in winter. It appears that the over riding factor controlling winter water levels and flow at St Gorman's Well is the local recharge into the overburden and limestone in the area close to St Gorman's Well. This will be discussed in greater detail in the following Chapter on St Gorman's Well.

4.4 Summary

The long term manual water level measurements in dug wells and boreholes, in and close to the quarry has been useful.

The number of monitoring holes is small, but the type of holes and the formations they represent is varied. There are deep boreholes into the Calp/Lucan and Waulsortian limestone formations and shallow dug wells into the overburden gravels and sandy till.

The data set is particularly valuable because it is a record of water levels in the area over a fifteen year period, when significant changes appear to have been taking place.

The main findings from the manual water level monitoring since 2006 are: -

- Ground water levels appear to have been going down (relative to Ordnance Datum) since the water level monitoring started.
- A gradual fall in water levels at the end of the summer recession can be observed in both overburden dug wells and bedrock boreholes in all formations.
- The trend in shallow wells is small, with a fall of about 1 metre over 15 years.
- The trend in the boreholes is larger and more variable. The decline is of the order of 4-6 metres over 15 years, with a 2-3 metre fall between 2006 and 2014, and 2-3 metres since 2014.

- The onset of pumped discharges from the quarry sump in October 2013, and the on-going and increasing pumping from the quarry sump, does not appear to have changed the general rate of decline.
- The importance of the finding is that the decline appears to be taking place in both bedrock and overburden water levels.
- This suggests that a natural change may have been taking place over the last 15 years.

The difference in the amount of the decline between bedrock and overburden aquifers would be expected if the decline was caused by a decrease in rainfall recharge. The percentage of open voids/pore spaces to accommodate rainfall recharge in a gravel or sandy till aquifer is much greater than the the available space in bedrock containing a few isolated fractures or conduits. Therefore, a reduction in the amount of rainfall recharge will cause a larger fall in water levels in a bedrock 'aquifer', than in an overburden aquifer.

- Though the pumping from the sump of the quarry does not appear to have caused a change in the rate of water level decline, the pumping from the quarry test boreholes did have an effect on some bedrock borehole water levels outside the quarry.
- The most notable effect was on a deep core hole D3, tapping the Waulsortian limestone, 375 metres due north of the pumping boreholes, during the long pumping test in 2020. The water level was lowered by about 4 metres.
- Water levels in two domestic boreholes in the Waulsortian only a 100 metres further away but to the south of the quarry was about 2 metres. A borehole in the Lucan formation to the south was not affected by pumping from the boreholes. The water level in a borehole to the southwest in probably the weathered Lucan was drawn down by about 2 metres.
- Pumping from boreholes in the quarry appears to have no effect on the water levels in the shallow dug wells in the area.
- Pumping from the boreholes in the quarry appeared to affect the water level in borehole SG4 adjacent to St Gorman's Well only during the early part of the long pumping test in the summer of 2020. It did not appear to have an effect in the autumn and winter or stop the spring flowing in winter. This will be described and assessed in great detail in the following Chapter 5.
- The monitoring of water levels using Diver pressure transducers provided information at very frequent intervals. The data showed that boreholes 1 and 3 tap into karst conduit systems that are well connected. It showed that borehole 2 is in a conduit system that

is less well connected to the previous system. It showed that the fractures or small conduits in the south and east of the quarry are not well connected to the karst conduits tapped by the boreholes in the north of the quarry.

- The Diver data provided important information on the speed of response to the onset of pumping outside the quarry. Water levels changed in a matter of minutes in D3 and in just over a day in SG4, nearly 2km away. This indicates that the response to pumping outside the quarry is a water pressure drop in a confined karst conduit system. This will be discussed further in Chapter 5.

Chapter 5 St Gorman's Well and Boreholes

5.1. Location and description of the site of St Gorman's Well and infrastructure

St Gorman's Well is located in the grounds of Hotwell House. Its location is shown on Figure 5.1, with its position relative to Rathcore quarry. The boreholes in the quarry used for the pumping tests, are also shown. The distance between the nearest pumping borehole in the quarry (No.1) and St Gorman's Well is 1.93 kilometres.

St. Gorman's Well is the name on the Ordnance Survey maps. It is also called St Gorman's Spring. As it does not flow or contain water for part of the year I have chosen, for consistency, to use the word St Gorman's "Well" to refer to the shallow depression in the ground. This depression can be dry, or contain a small depth of water, or it can be full of water, and water can overflow from it. I use the term "Well" to distinguish this natural, physical feature from the artificial borehole infrastructure at the site.

The Well and the boreholes are structures that contain groundwater at the same site. It is easy to assume that the characteristics of the groundwater in one, is a representation of the characteristics of the groundwater in another, but they are different structures, and provide different insights.

The Well, and the water within it, is a surface expression of the sum of several processes both at the surface and deep in the rock.

The boreholes are, in essence, voids or access shafts, open to groundwater at different levels down to their base. The main monitoring borehole SG4 is reported to be 100 metres deep, but probably terminates in a very large cavern below 90 meres, as found in the adjacent borehole SG7.

St Gorman's Well is in the northwest corner of the lands surrounding Hotwell House. It can be accessed, with permission from Mr Nicholas Wilkinson, via the farm gate entrance. A track from the gate leads up to, and then along the side of the farm buildings. It bends to the west, and down a slight gradient to the corner of the lands at the southern end of a north south aligned belt of mostly coniferous woodland.

The large field to the north and east of Hotwell House, the large fields to the west, and the belt of woodland to the north were once owned by Hotwell House. The fields to the west were sold in the early1990s. The fields and woodland to the north and east were sold in 2000.

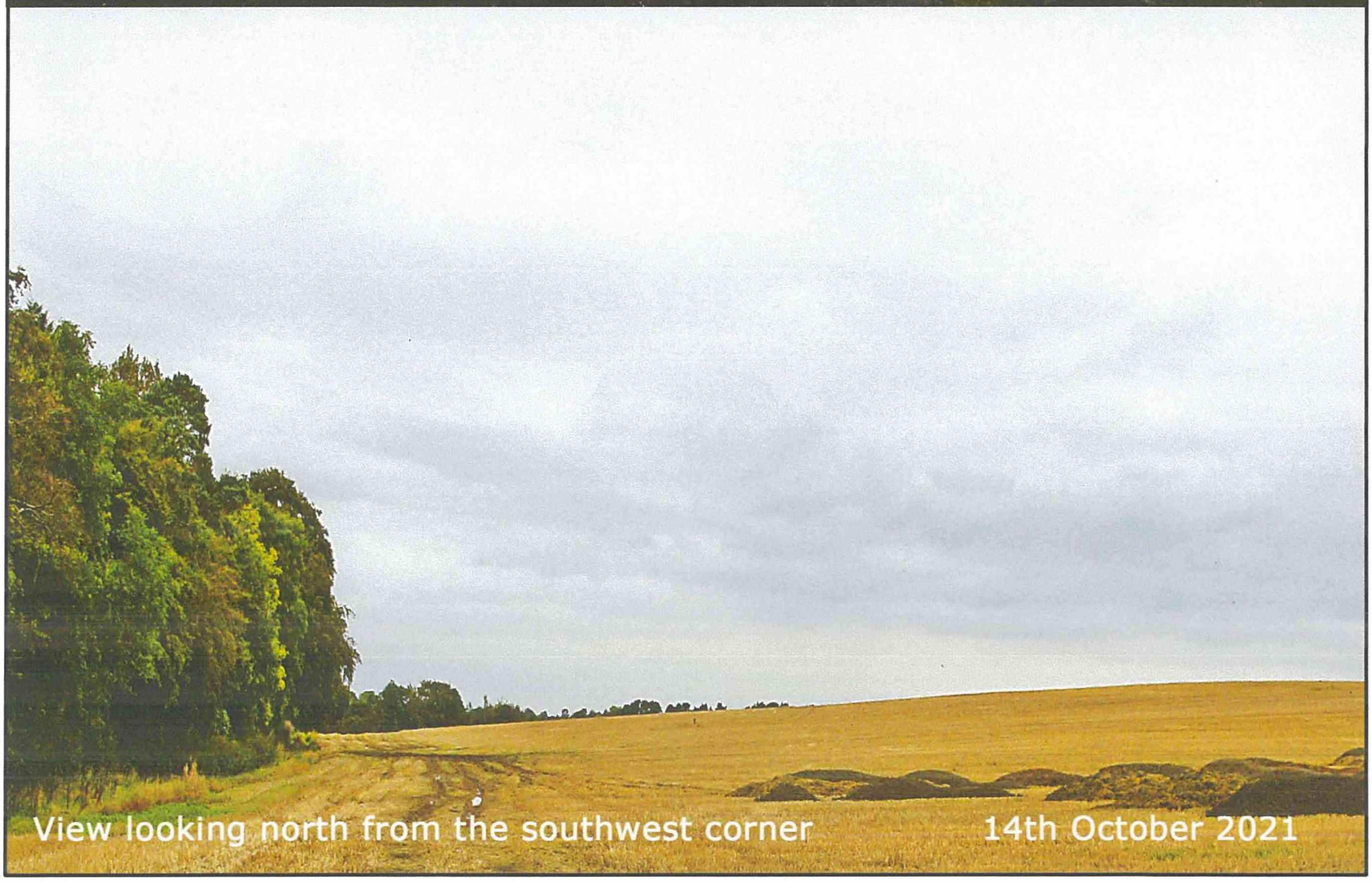
The imagery in Figure 5.1 shows arable crops growing in the adjacent fields in March 2022.

The large field, to the northeast, is up gradient of the Well, on the crest, and gentle western slope, of Ballynakill hill. It is often bare earth and stubble from September to March, with a

Figure 5.1 St Gorman's Well & Hotwell House (imagery Google Earth March 2022)

Figure 5.2 The large arable field to the northeast of St Gorman's well

View looking northeast from the southwest corner 23rd July 2021



View looking north from the southwest corner 14th October 2021 winter sown arable crop. This large field is shown in summer and autumn in Figure 5.2. Rainfall can easily percolate into the soil and sandy till overburden and gravels. The rainfall will recharge both the shallow overburden and limestone bedrock groundwater system under the hill up gradient of St Gorman's Well. The large fields of pasture further to the east on Ballynakill hill, also form a recharge area above St Gorman's Well.

St Gorman's Well is a simple, small depression between the grass access track and the southern end of the woodland. The depression is about one metre deep. There are some flat topped stones on the southern side of the depression that may have represent part of a perimeter to the well in the past.

Figure 5.3 shows a sketch of the site of St Gorman's Well. The sketch is based on a recent GPS levelling survey carried out by Fergus Gallagher and Ciara Bannon from Kilsaran.

The site consists of more than the shallow depression of St Gorman's Well. The sketch plan contains explanatory details.

The Well is shown schematically as an area of blue on the right side of the sketch. The level of the base of the Well is 75.343m above Ordnance Datum. This elevation is roughly the same as the current floor level of the Rathcore quarry.

The stones at the edge of the Well are 76.197m above Ordnance Datum. To the west of the well there is another blue area. This is a schematic representation of a recently constructed artificial pond. The pond is formed by a shallow excavation with an impermeable liner. It is about 30-40cm deep. The pond was constructed, in April 2021, by Nicholas Wilkinson, the owner of Hotwell House.

Between the two blue areas, there is a recently re-discovered borehole (SG3). This borehole was pumped, using a small petrol powered pump, to obtain water to fill the new pond.

The new pond roughly occupies the same ground as a previous pond constructed by Nicholas Wilkinson's father in the early 1980s. David Wilkinson scraped away vegetation and top soil, and compacted the subsoil to create a pond. The waste soil was used to create an island in the pond and an embankment on the western side.

This artificial pond was seen by David Burdon and Bob Aldwell during their geothermal investigation in the early 1980s, and is shown in their sketch of the site, that is reproduced in this report as Figure 2.4. In this sketch it is labelled as a 'duck pond'.

The 1980's duck pond was fed by overflow from St Gorman's Well, when water levels in the Well were high. The early 1980's was a time of above average rainfall, which will be referred to later, during which St Gorman's well flowed for most of the year, and the duck pond was a viable water feature. Subsequently, with less abundant rainfall, and only intermittent flow from

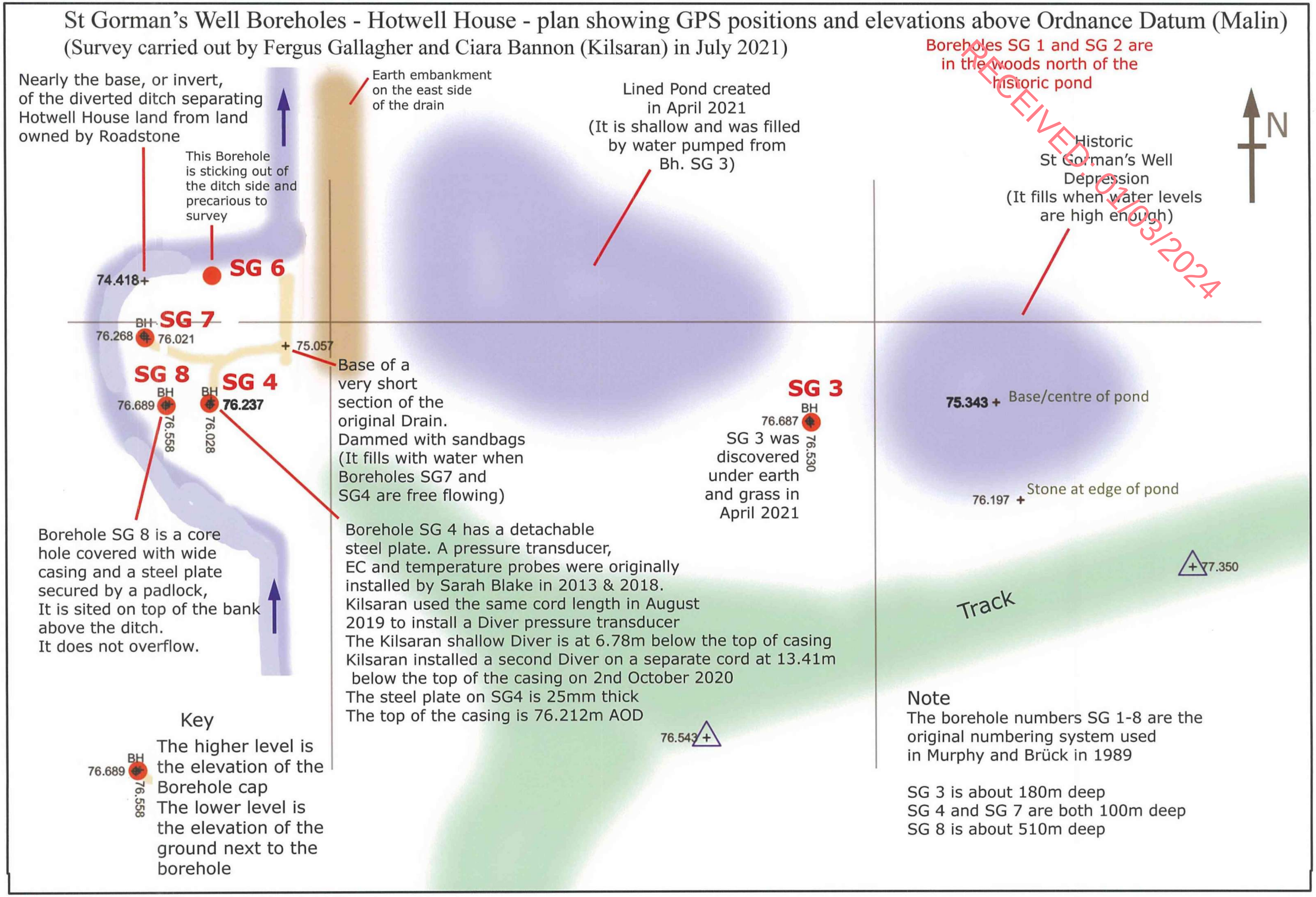


Figure 5.3 Sketch Plan of St Gorman's Well

Figure 5.4 St Gorman's Well Site March and April 2021

St Gorman's Well, the viability of the duck pond decreased. Over the years it returned to a woodland glade of brambles and fallen branches.

Figure 5.4 shows St Gorman's Well in March 2021, and the recently constructed, lined pond in April 2021. The photograph showing the Well has a thin pale blue line drawn on the grass that corresponds to the maximum height and extent of the water in the Well during the previous month. A close look at the photograph will show the perimeter stones on the south side of the grassy depression.

Figure 5.5. also has two photographs. The upper shows the small flow of water out of St Gorman's well on the western side at the time of maximum water levels in early February 2021. The flow is a barely perceptible seepage in a shallow channel through the long grass. The lower photograph shows the floor of the woodland where the Duck pond had been, and which, now, is partly filled by the new lined pond. There is a 5-15cm layer of water covering the leaves on the floor. The lower photograph also shows, on the left, the embankment covered with brambles that was created with the earth excavated to create the duck pond in the 1980's. On the other side of the embankment is a steep drop, down into the drainage ditch. This ditch is a southern extension of a drainage ditch maintained by the OPW, under the Boyne Arterial Drainage Scheme.

Returning to Figure 5.3, the grassy track leading past the Well used to cross the drainage ditch via a bridge into the field to the west. When the land was sold by Nicholas Wilkinson's father, he retained the land around the geothermal exploration boreholes drilled in the 1980s. A drain was re-excavated around the boreholes and conifers were planted on a new embankment on the east of the old drain. The old straight section of the drain was partially backfilled. A short northern section was left, and sandbagged above its confluence with the original drain heading due north. This was a measure created to make a small pool to catch artesian flow from the boreholes. The floor of this section of the drain is 75.057m above Ordnance Datum, which is roughly half a metre below the base of the Well.

There is no level information on the invert of the drain north of the bend. However, there is a level for the edge of the new drainage ditch on the northwest corner of the bend. This is 74.418 metres above Ordnance Datum. The level of the drain just north of the sandbagged section is lower than this. I estimate that is about 74.1 metres above Ordnance Datum; i.e. over 1 metre below the bottom of the depression Well.

The original alignment of the drain can be seen in the lower sketch in Figure 2.4. This sketch also shows that when water levels were high in the Well, water could flow either into the 'duck

Figure 5.5 Small flow from St Gorman's Well into the old duck pond area 5/2/2021

Figure 5.6 Groundwater flow and dry conditions at the confluence of the new curved drainage ditch with the original straight drainage ditch March and April 2021

pond', or by a straight channel to the north-south drain. It is assumed that in 1981-83 the flow from the Well was measured or estimated in this channel.

Figure 5.6 shows the end of the curved drainage ditch alignment as it meets the original drain. It can be seen that the drainage ditch is deep and steep sided. The ditch up stream is short. The ditch starts at the north side of the road 200 metres to the south. Therefore, the land being drained is small.

The upper photograph from 22nd March 2021 shows a persistent small flow along the ditch. It had not rained heavily for over three weeks, therefore the flow in the ditch was not surface overland flow, but groundwater seeping out of the overburden aquifer. The water level in borehole SG4 (6metres away) at the time of the photograph was 74.5m above Ordnance Datum; i.e. 10-20cms above the level of the base of the ditch. Therefore the water level in the overburden would have been higher than the level of bottom of the ditch.

The lower photograph shows the same view but on the 30th April 2021. The ditch is dry. There had been almost no rain in the month of April, and the water level in borehole SG4 had fallen a further 1.4 metres to 73.02 metres above Ordnance Datum; i.e. more than a metre below the level of the base of the ditch.

Figure 5.7 is a photograph of the side of the ditch at the site of borehole SG6. Its position is shown in Figure 5.3. This borehole was originally in a field, but the new curved ditch was cut around it very close to the steel casing. The photograph shows the depth of the ditch, and the groundwater flow seeping out at the base. This site is useful because, as can be seen in the photograph, there is a clean exposure of the sandy till, full of rounded and angular stones, below a thin layer of top soil, covered with drain spoil used to make up the embankment in the 1990s. The screen of trees planted after the land was sold and the ditch re-aligned, can be seen above the bank.

The St Gorman's Well site also contains a cluster of boreholes. Their original purpose and geology information is described in Chapter 2. The boreholes, and one in particular, borehole SG4, have become the infrastructure for monitoring the groundwater at St Gorman's Well site, and investigating the groundwater flow systems influencing St Gorman's Well. Figure 5.7 shows borehole SG6 which has not been used.

Figure 5.8 shows the well heads of two boreholes, SG8 and SG4, in August 2019.

The upper photograph of SG8 shows a thin steel, swivel lid pulled aside. The abundant cobwebs appears to confirm Nicholas Wilkinson's observation that the borehole has never flowed. The top of the casing is 66 cm higher than top of the casing at borehole SG4.

Figure 5.7 Borehole SG6, Exposure of Till and deep perimeter drain 5th February 2021

SG4, in the lower photograph, had a heavy steel cover tightly bolted onto the flange at the top of the casing at the time of the photograph. There was a rubber gasket between the cover and the casing.

Nicholas Wilkinson had engaged Thomas Briody and Sons in January 2018, to cut down the top of the old steel casing and weld on the new heavy steel cover and flange. The work to seal this borehole and SG7 was partly carried out as an experiment in order to see whether stopping the artesian flow from the two boreholes would increase the level and flow from the St Gorman's Well depression. A sampling point and control valve were installed in the steel lids so that the artesian pressure and flow from the boreholes could be assessed by opening the valve.

Sarah Blake had installed a Solinst combined pressure, temperature and electrical conductivity probe into SG4 in August 2018 after the works to seal the top of the two boreholes. Sarah's instrument was removed and the data downloaded in August 2019, and a Kilsaran Diver pressure and temperature probe replaced the Solinst probe. The new instrument was attached to the same cord that Sarah had used. This was done to ensure consistency of the position of the two measurements.

The secure seal on the wellhead means that the measurements made by Sarah's instrument reflect the artesian pressure and temperature in a non-flowing borehole. The difference in pressure and temperature that occurs when the steel cover is removed or loosened, is discussed in detail later in this chapter.

The lower photograph in Figure 5.9 shows the three main boreholes and their proximity. The steel cover has been pulled aside from borehole SG4. SG8 has been re-locked with a padlock, and SG7 is still closed with two bolts on the heavy steel cover.

The photograph also shows the screening trees planted in the 1990s and the green vegetation growing up in the new curved ditch behind.

The upper photograph in Figure 5.9 is a view into the wellhead of SG7. The important feature in the image is the smaller diameter steel casing inside the wider outer casing, and the gap between them. The outer casing is probably a short conductor casing merely through the thickness of the overburden and to protect the wellhead, as in SG4.

The Geological Survey of Ireland ran a video camera down the inside of the inner casing, and found that this casing extends to 54.1metres below the wellhead. There is no record, or evidence from the surface, or the video, of a grout sealing the annulus around the inner casing. Therefore, referring back to Section 4.1, water can flow up or down the annular space outside

Figure 5.8 The Well Heads of Boreholes SG 8 and SG 4 on 1st August 2019

the inner casing, and in or out of this annular space into the surrounding overburden and bedrock because there is no grout seal.

It is interesting that the original drillers had to use an inner steel casing. Casing is expensive, and it takes time to weld together the 20foot (6metre) lengths, and install them into the wider diameter hole drilled into the rock. Therefore, it was probably put in for a good reason. The most common reason would be to secure the borehole in unstable ground. In other words, the Calp formation rock they drilled through, was probably fractured and falling-in, in the upper 54 metres of this borehole. Borehole SG7 terminates in a vast cavity starting at 91 metres depth. This was illustrated in Figure 2.6.

Borehole SG4 is the same depth as SG7 but the video camera survey had to stop at 27.4 metres below the well head, because there is a coniferous tree branch wedged in the hole below this depth. The risk of the camera and its cable becoming entangled was too great to proceed further. However, smaller probes, such as the probe on the yellow sounding line tape shown in Figure 5.9, can get past the branch. The open depth of SG4 is more than 90 metres (the length of the sounding line).

Boreholes SG4 and SG7 are close together. The water levels are the same and they both probably tap into the same large cave or conduit system below 90 metres.

There is an instant response in one, to a change in the other.

The top of the casing at SG7 is 31mm above the top of the casing on SG4. Sometimes, SG4 was free flowing under artesian pressure, but the pressure was not sufficient to lift water the extra 31mm and make SG7 flow.

An example of the intimate link between the two boreholes was observed in February 2021. SG4 was flowing, but there was no flow from SG7. When I placed the heavy steel cover back onto the top of the wellhead of SG4, to restrict the flow, the water level instantly rose in SG7, and it began to flow copiously. When I lifted the lid off SG4, the water level immediately fell in SG7, the flow re-started from SG4, and flow ceased in SG7. In essence, SG4 and SG7 are duplicate ‘access portals’ into the same groundwater flow system in the large conduit below 90 metres.

Superficially, it currently may appear that St Gorman’s Well is a shallow, grassy small depression that sometimes contains water, and if the water level rises sufficiently, the Well may overflow. But the current appearance of the Well is not a representation of how it used to appear. Later in this Chapter there are photographs taken at different times in the last 20 years that show how it has changed.