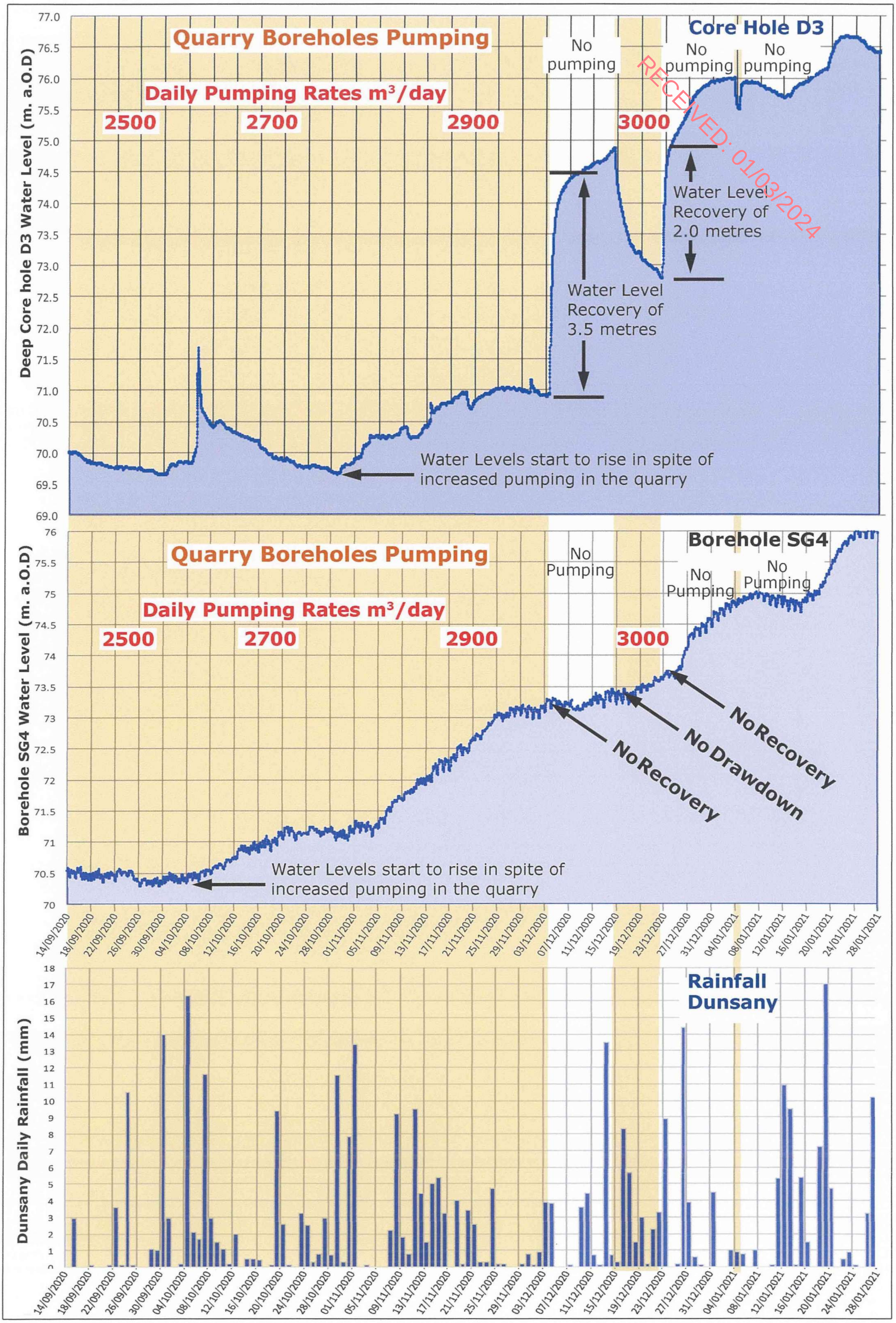
Figure 5.32 Differing water level response in SG4 and D3 at end of Test



In other words, the long test data in Figure 5.31 shows that pumping from Rathcore quarry boreholes draws down water levels in borehole SG4 during the summer, when water levels in the bedrock and the shallow groundwater system are low, but rainfall recharge into the shallow aquifer system and the bedrock in autumn and winter, becomes the dominant influence on the water levels in borehole SG4 in autumn and winter.

The sudden rise in water levels in SG4 at 110,000 minutes, coincides with heavy rainfall at the beginning of October 2020. This rainfall also brings about a rise in water levels in shallow well W3. There is a sharp rise and fall in water levels in deep core hole D3 before the natural rise from rainfall recharge. This sharp peak in the graph was a recovery of water levels whilst all pumps in the quarry were turned off for two days to replace a faulty pump in borehole 3. There was no recovery in water levels in SG4 in response to this interruption of pumping in the quarry.

When the water level rose sharply in SG4, the water temperature fell by 4°C, in a response to recharge, similar to previous years.

The long test was continued until the 3rd December 2020. The test was stopped because water levels were continuing to rise in SG4, and it appeared that the quarry boreholes were no longer creating any draw down of water levels in SG4.

To test this interpretation, the pumps were switched off and water levels monitored to see if, and how much, water levels recovered.

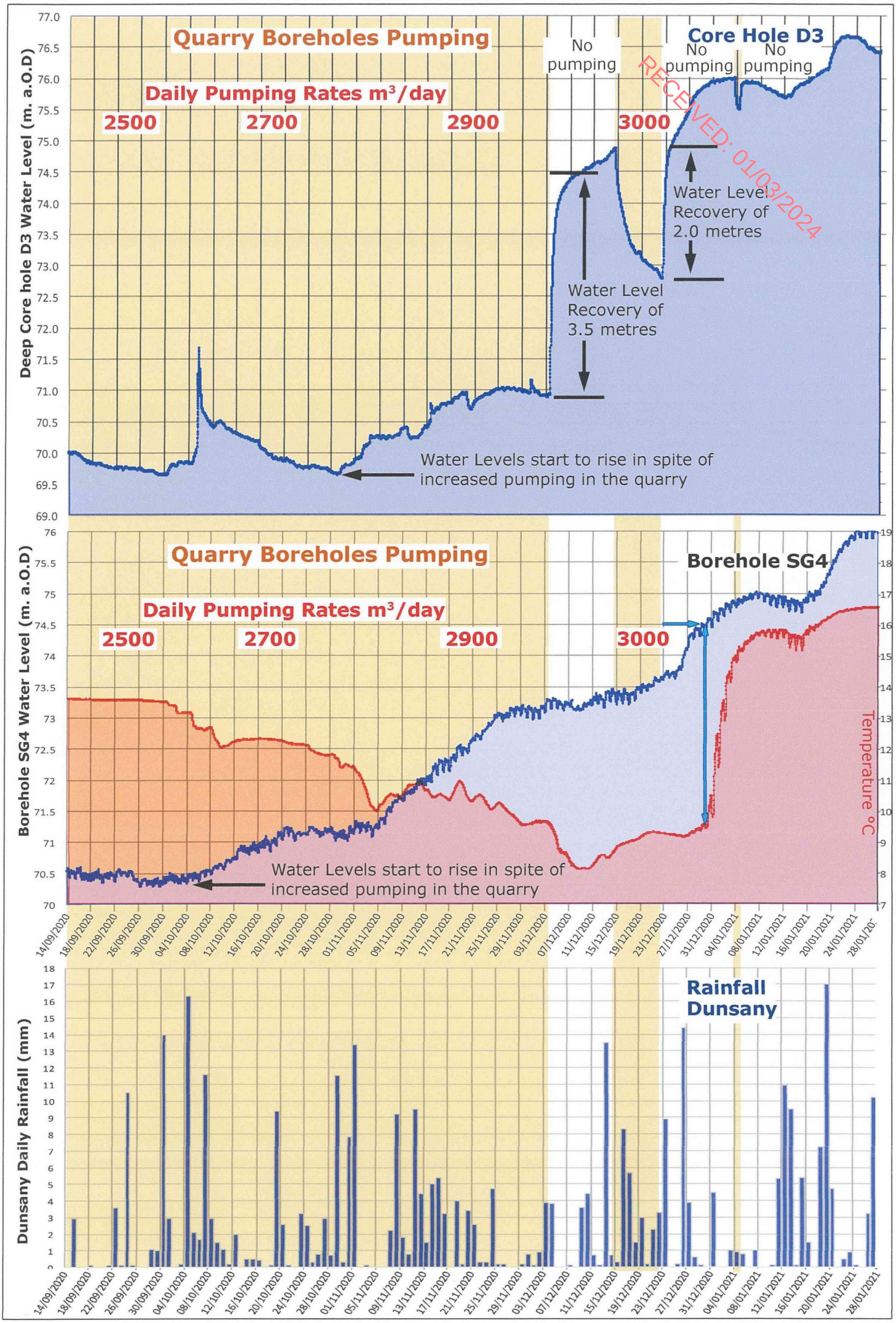
The week before the pumps were turned off had little rain, though water levels in SG4 were rising slightly in the two days prior to the shut down of the quarry pumps. It was expected that if the water levels in SG4 rose significantly in the 24-48 hours after the shut down, then this could be attributed to the end of the quarry pumping.

Water levels rapidly recovered in the quarry and in core hole D3. However, there was no evidence of a recovery in SG4. This can be seen in Figure 5.32.

Figure 5.32 consists of three time-series data sets on a natural date time scale. The data covers the middle and later stages of the long test running from the 14th September 2020 to the end of January 2021. The data for December and January after the long test is to show the period covered by a supplementary test before Christmas 2020, and the rise of water levels over the New Year.

There are light brown colour bands on all three graphs, showing the days when the quarry pumps were in operation. The combined abstraction rate from the quarry boreholes is also labelled on the graphs. The periods with no pumping have been left white.

Figure 5.33 Temperature & water level response in SG4 and D3 at end of Test



The bottom graph in Figure 5.32 shows the daily rainfall measured at Dunsany. It can be seen that the rainfall was not evenly distributed during the autumn and early winter. Instead there are 10 day periods with heavy rain separate by 6-10 day periods with little or no rain.

The middle graph shows the water levels measured in borehole SG4.

The upper graph shows the water levels for deep core hole D3. D3 is again being used to as a proxy for the rise and fall of water levels in the quarry. It is a convenient comparison to use D3 because its water levels are in the limestone bedrock and can be plotted using the same vertical scale as the water levels in SG4.

The hydrograph for D3 shows water levels going down to 69.7m AOD in September, followed by a spike recovery when the pumps were stopped to replace a pump in the quarry, followed by a gradual fall in water levels back to 69.7 metres on the 30th October. Thereafter, though the quarry pumping rate was increased, the water level in D3 rose as the heavy rain earlier in October, worked its way down through the overburden to recharge the deep water table in the bedrock.

The water levels had risen by roughly 1.5metres and plateaued by late November, just before the pumps were stopped at the end of the long test. The water level in D3 rose sharply as soon as the pumps stopped. There was a recovery of 3.5 metres in four days (see Figure 5.32).

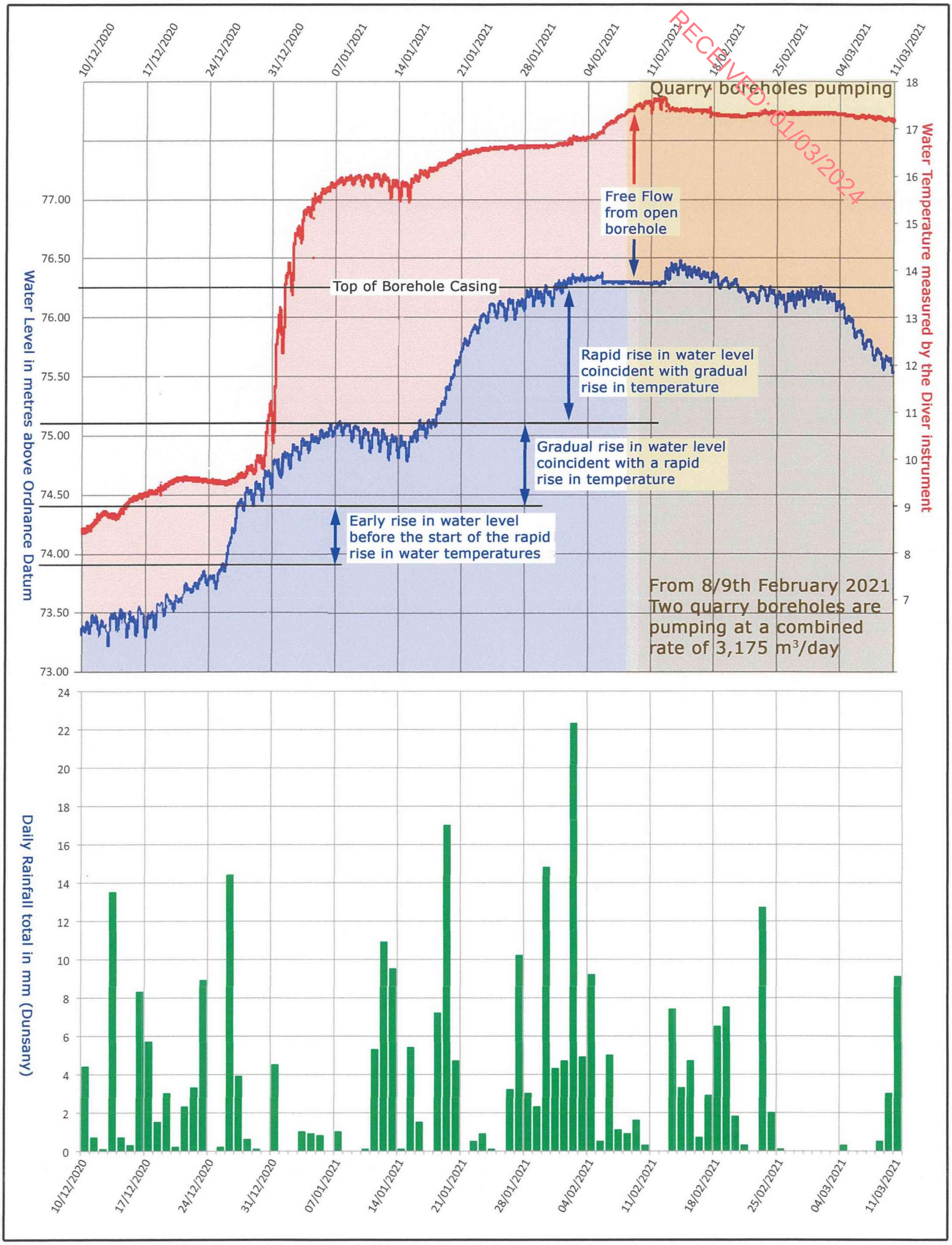
By contrast, the water levels in SG4 started rising a month before the levels in D3. The levels in SG4 rose by 3.5 metres to roughly 73 metres AOD and a small plateau just before the pumps were stopped. However, when the pumps stopped the preceding slight rise in the days before, stopped and then fell. There was no recovery in the water levels in SG4 when the quarry pumps stopped. This is labelled in Figure 5.32.

This evidence that the quarry pumps were not directly drawing down water levels in SG4 was a slight surprise. It was decided to test the apparent absence of impact further by turning the pumps back on in the quarry at the maximum pumping rate of roughly 3,000 m^3/day. The objective was to thoroughly stress the groundwater system in the limestone and see if a drawdown could be re-created in SG4.

The test started at midday on the 14th December and ran until midday on the 22nd December, when staff left the quarry for their Christmas break. (It is useful to bear in mind that the pumping tests were partly constrained by the availability of supervision as the pumps were powered by a diesel generator that required re-fuelling and frequent oil checks).

The water levels went down rapidly in D3 when the pumps were re-started on the 14th. There was no response either immediately, or over the next 8 days in SG4.

Figure 5.34 Borehole S.G.4 Water Level & Temperature December 2020 - March 2021 & Rainfall



When the pumps were stopped on the 22nd, the water level recovered rapidly in D3 and carried on rising in response to the heavy rain on St Stephen's Day. The water levels in SG4 did not respond at the end of the pumping, but did start to rise in response to the heavy rain on the 26th. The evidence from the end of summer through the autumn and into the winter, is that the pumping from the quarry did not appear to draw down water levels in SG4.

Figure 5.33 reproduces the water levels shown in Figure 5.32 but with the superimposition of a graph of the temperature changes measured by the Diver instrument in SG4. The purpose of the temperature graph is to illustrate that the stopping, re-starting and stopping of pumping from the quarry did not appear to change the pattern of falling temperatures with recharge in the autumn, followed by a sudden rise in temperatures when the water level in the borehole reached about 74-74.5m above Ordnance Datum. The level at which the temperature rose sharply is marked with arrows on Figure 5.33 for ease of reference.

This pattern of significant temperature rise at this level had occurred in preceding years and in 2021-2022. It appears that there is a consistent 'break through' water level in SG4, above which warm water rises in the borehole. The importance of the temperature graph in Figure 5.33 is that it shows that after over four months of pumping up to 3 million litres a day of water from the quarry, this annual pattern of water levels rising to a particular level, followed by a rapid temperature rise did not change.

Both figures show a single days pumping on the 4th January to lower water levels in the quarry after the Christmas break. There was a slight drawdown in D3 and no drawdown in SG4.

Towards the end of January 2021, water started to be visible in the base of St Gorman's Well (75.34 metres AOD) after heavy rainfall on the 18th, 19th and 20th January. The temperature of the water in SG4 was 16.5°C.

Figure 5.34 shows a further detail of the pattern of water level and temperature change in borehole SG4 from the 10th December 2020 to 11th March 2021. It also shows the daily rainfall from Dunsany and the start date of a final winter pumping test.

The early part of the graphs in 5.34 overlap with the timeline in the graphs in Figures 5.32 and 5.33.

Figure 5.34 highlights the stepped nature of the rise in water levels in response to periods of rainfall recharge, and how the rise stops or is reversed during and after periods with little rainfall.

The graph also shows again that temperatures rise rapidly after the water level in borehole SG4 has risen above 74.5 metres AOD. It also shows how the temperature decreased in the borehole when the water levels fell below 75 metres AOD. It appears that the column of warm water that had risen up the borehole had been cooled slightly when the upward pressure of water had decreased. This may have been caused by an ingress of cooler water from the shallow aquifer flowing under the bottom of the steel casing in the borehole.

It is important to bear in mind whilst interpreting the data from SG4, that the data is from a Diver instrument hanging on a cord just below the bottom of the steel casing. Therefore, when there is insufficient artesian pressure to push a flow of water out over the top of the casing, the Diver is measuring the temperature of water that is still slowly flowing past it, as water flows up the hole and out under the bottom of the casing and into the shallow aquifer around the borehole.

Since the end of the pre-Christmas pumping test we had observed the rise in water levels and temperature in borehole SG4 and in St Gorman's Well. The data that we had collected during the long test and the short test before Christmas in 2020, had shown that the pumping from Rathcore quarry had not created a draw down in water levels in SG4 since September 2020. However, we did not know whether turning on the quarry pumps whilst the boreholes and St Gorman's well were flowing would have any measurable effect on temperatures and water levels. In other words, the spring in St Gorman's Well and the borehole SG4 seemed to be performing normally, therefore, would this natural behaviour be disturbed by pumping from the quarry. Whilst trying to gauge the the best time to try an experiment, I was also conscious that I could not predict forthcoming rainfall and recharge, and the future duration of artesian flow.

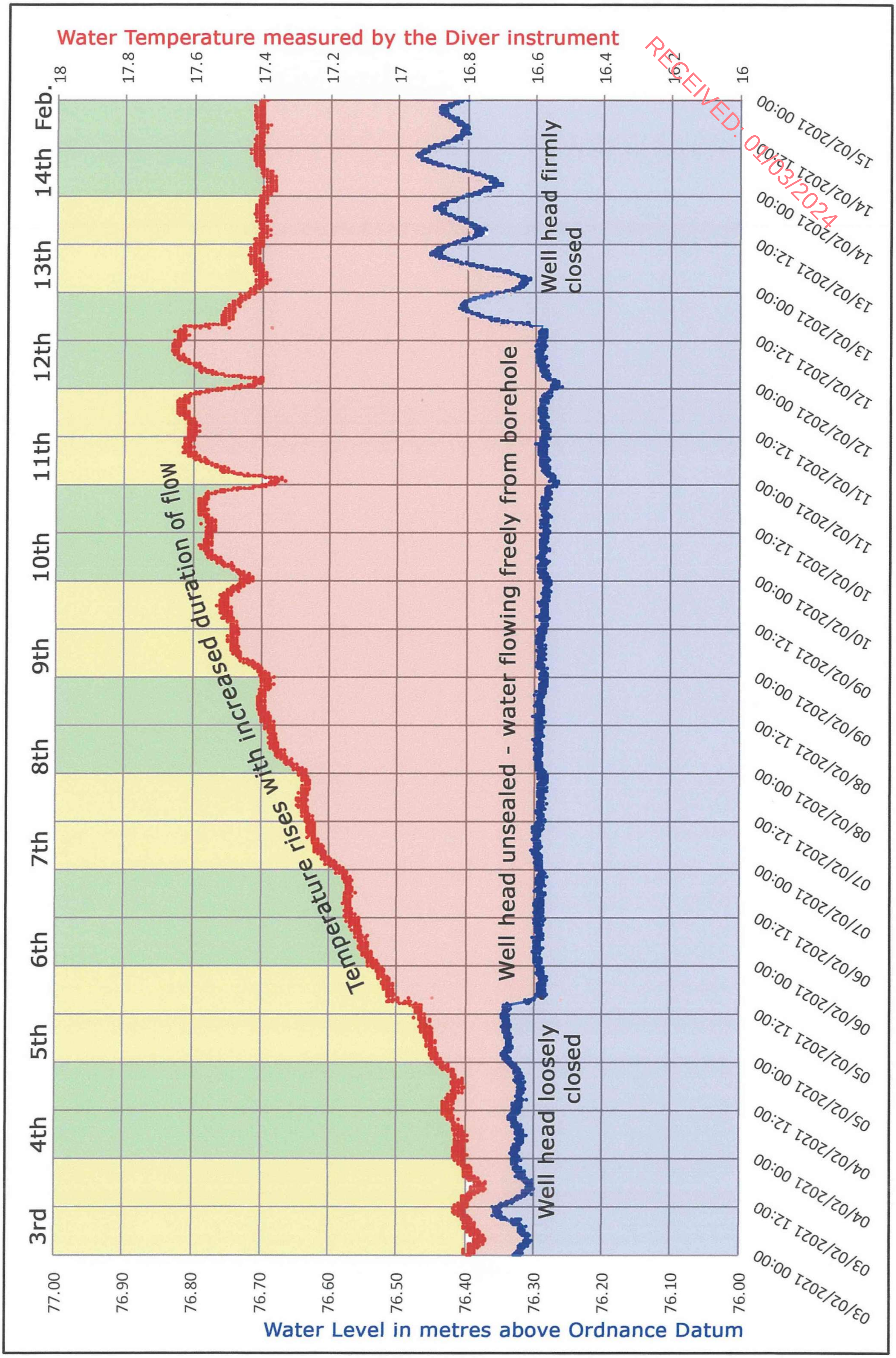
I decided to wait until St Gorman's well was full and the boreholes were flowing, before carrying out the experiment to test whether pumping from boreholes in the quarry would alter conditions in SG4. I explained the objective of the experiment to Nicholas Wilkinson before starting.

We started to pump Borehole 3 in the quarry on the 8th February at 10.30 am, pumping at 86m^3/h. We had to pump to the quarry floor for a day in order to ensure that the initial clayey water from the upper cavities in the borehole, was not sent direct to the settlement lagoon.

Borehole 1 was started on the 9th February at 09.00 am, pumping at 46.3m^3/h direct, with borehole 3, to the settlement lagoon. The combined abstraction rate was 3,175 cubic metres per day.

As can be seen in Figure 5.34, there had been very heavy rain on the 2nd February, and when we started the borehole pumps in the quarry, the water level in SG4 was at the top of the casing, and the temperature of the water in SG4 was rising.

Figure 5.35 Borehole S.G.4 Water Level and Temperature 3rd to 15th February 2021



The water level did not fall when the quarry boreholes started pumping, or in the days shortly afterwards. There was no evidence of a drawdown in water levels in SG4 within 48 hours of the pumps starting, as was seen at the start of the long test in July 2020.

(The unusual flat line and rise in the water levels and the rise in temperature just before and after the start of pumping relates to removal and re-installation of the heavy lid on the borehole, and will be described in more detail below with reference to Figure 5.35.)

The water levels in SG4 did start to decline after the 14th February. but this appeared to relate to the paucity of rainfall recharge after the 6th February.

The water levels rose again after the 25th February, seemingly in response to the 12mm of rainfall on the 23rd. Thereafter, there were two weeks of drought and the water level in SG4 declined.

Overall, the evidence indicated that the rise and fall of water levels in SG4 was controlled by the rainfall pattern, and that there was no clear evidence that pumping from the quarry boreholes was influencing either the water level, or temperature recorded by the Diver in SG4.

There was also no evidence in St Gorman's Well that the water level fell. In other words, colloquially, the Well did not suddenly dry up when the pumps were turned on in the quarry.

Figure 5.35 is an interesting graph that reveals a potentially important characteristic of the relationship between water temperature, water level and water pressure.

The graph covers the period from the 3rd to 14th February 2021. The individual days are marked in alternate yellow and green bands for ease of reference. There is a line down the centre of each band indicating midday.

Prior to 2pm on the 5th February, the heavy steel lid and gasket were loosely sitting on top of the casing of borehole SG4. The upward artesian pressure at the time was sufficient to very slightly lift the heavy steel lid, and for a small flow of water to squirt out through the gap.

I took off the lid at 2pm on the 5th to observe the unrestricted flow from the borehole. It can be seen on the graph, that when I did this, there was an immediate 6 centimetre fall in water pressure, and a small rise in temperature recorded by the Diver instrument.

The significance of the subsequent data is that it shows the temperature rising with the duration of flow, and rising and falling with the lunar tides.

The water level or pressure recorded by the Diver is not rising whilst this is happening, because the lid is off and the water can freely flow out over the flanged rim of the casing. It can be assumed that the pressure and flow is varying with the tides because the effect of the tides can be seen in the water temperature graph. When the pressure is highest the flow is highest and the temperature is highest.

Figure 5.36 Artesian flow from Borehole SG4 at 13.26hr on the 12th February 2021

It can be easily imagined that when flow is fastest up the borehole from the cave at its base, then there is less opportunity for the water to be cooled or mixed with cooler water on its upward passage.

The flow of water just after midday on the 12th February is shown in the photograph in Figure 5.36 for ease of reference.

The heavy steel lid was firmly placed back on the top of the borehole as an experiment on the 12th February to observe the build up in pressure, and an increase in flow from the adjacent borehole, SG7.

It can be seen that the pressure in SG4 built up over the next few days. The temperature rapidly dropped by 0.2°C when the lid was placed back on SG4. However, this temperature still remained at 0.6°C above the temperature on the 4th February.

I have used the term 'break through level' to describe the sudden rise in temperature when the water level in borehole SG4 rises to about 74.5m AOD.

The experiment with lifting the lid in February 2021 appears on a small scale to have created an artificial 'break through' or release, for the water temperature.

This raises the possibility that the temperature of the water in SG4 relates to the ease with which the water can flow out of the borehole.

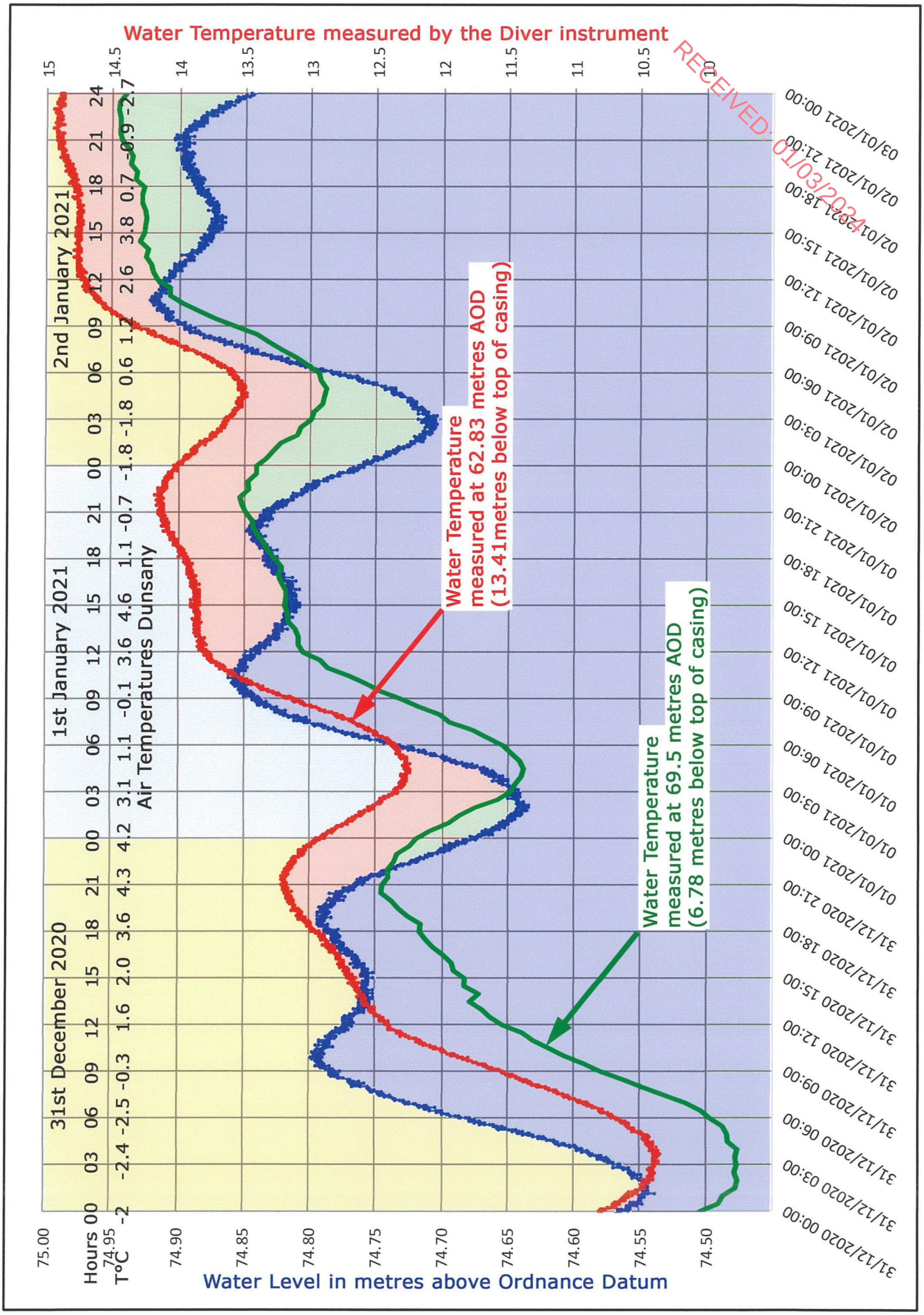
The hydraulic model proposed for SG4 by Sarah Blake is a piston flow. Which is where a particular conduit, somewhere in the karst conduit system, suddenly becomes full of water and this exerts a downward pressure, causing water to flow through a previously non-flowing section of the karst conduit system. This concept may still apply, but the data collected during the experiment shown in Figure 5.35 points to the flow not only being controlled by the piston but also by the ease with which the flow can exit the conduit.

In other words the temperature of the flow is partly controlled by the flow rate.

This observation may help explain the difference in water temperatures shown in the long graph in Figure 5.19. When Sarah Blake was monitoring temperatures in the winter of 2014/15, the water flow was un-restricted because there was no cap or lid on the borehole (see Figure 5.16) The borehole flowed for all of January 2015, and the temperature rose by 1.5 degrees during this uninterrupted period of flow.

By contrast, in the winter of 2018-2019, the heavy steel lid had just been fitted and was firmly secured with 12 tight bolts. Though the pressure in March 2019 was higher than in January 2015, the temperature did not rise above 17°C in March 2019 because there was no flow. Similarly, in the following winter, the steel lid was still secured in November 2019, and though there was sufficient pressure for flow, the temperature again did not rise above 17°C.

Figure 5.37 Borehole S.G.4 Water Level & Temperature over the New Year 2020-21



I loosened the steel lid by removing the bolts on the flange in February 2020, and when the water pressure increased in March 2020, there was flow and the temperature rose to over 18°C. The maximum temperatures in winter recorded by the instruments shown in Figure 5.19 are controlled by whether the borehole is sealed or un-sealed.

To further understand the sharp rise in temperatures before the borehole starts to flow, I have compiled Figure 5.37. It shows the water level and temperature in SG4 over just three days; 31st December 2020, 1st and 2nd January 2021. This is the central part of the five day period when the temperature of the water rose from 9°C to over 15°C.

The three days show large tidal fluctuations because there was a full moon on the 30th December 2020. The maximum tidal amplitude for the water levels in SG4 was 25cm, on the 31st December.

Figure 5.37 shows the water temperature data from the two Diver instruments suspended at different depths in borehole SG4. The 'Shallow Diver' is suspended on the cord used by Sarah Blake for her Solinst instrument in 2018-19 is 6.78 metres below the top of the borehole casing. The 'Deep Diver' is the second instrument that I installed at 13.41 metres below the top of the casing.

To accompany Figure 5.37, I have drawn a schematic section through the St Gorman's site. This is Figure 5.38.

The purpose of Figure 5.38 is assist in understanding the temperature and water level data in Figure 5.37 (and subsequent Figures) in the context of the construction of borehole SG4, and the topography and geology of the St Gorman's Well site.

Figure 5.38 is a west to east aligned schematic section. There is no horizontal scale, but there is a detailed vertical scale. There is a considerable vertical exaggeration (approximately 10 times) in order to show clearly the relative elevations of the Diver instruments, and the small differences in elevation of the well heads, the base of the Well depression and the base of the new ditch, or drain, that curves around to the east of the boreholes.

The depth to the top of the Calp bedrock is based on Frank Murphy's findings when drilling borehole SG8. The depth to the top of the bedrock below St Gorman's Well is not known because a borehole has not been drilled down through the base of the Well depression. The fault zone between the Waulsortian encountered in SG3, and the Calp encountered in the upper part of boreholes SG4/7 and SG8, is shown with a roughly north south alignment, as shown by both Burdon and Murphy in the their sketch sections in the 1980s.

A schematic depiction of cracks, open bedding planes and karst conduits is shown in the two bedrocks. The possibility of a semi permeable zone of crushed rock and clay along the fault is also shown.

The schematic section draws attention to the difference between the boreholes, in particular SG4, and the depression forming St Gorman's Well. The former are artificial structures tapping into the large karst conduit at 90+ metres depth. The latter, St Gorman's Well, is a natural structure above, probably, a tortuous network of small and large vertical karst conduits, permitting an upward flow of water from the same large karst conduit system at 90 metres. In other words, the artificial borehole structure permits an open or uninterrupted link down to the deep large conduit, whereas the link between the Well and the deep conduits is through tortuous natural passageways formed around boulders and blocks of Waulsortian limestone.

The schematic section shows how the water level has to rise before the Well fills and water flows out of the Well. The section shows how there was a small natural gradient between the base of the Well and the old ditch, and how now there is a steeper gradient between the base of the Well and the bottom of the new deeper ditch.

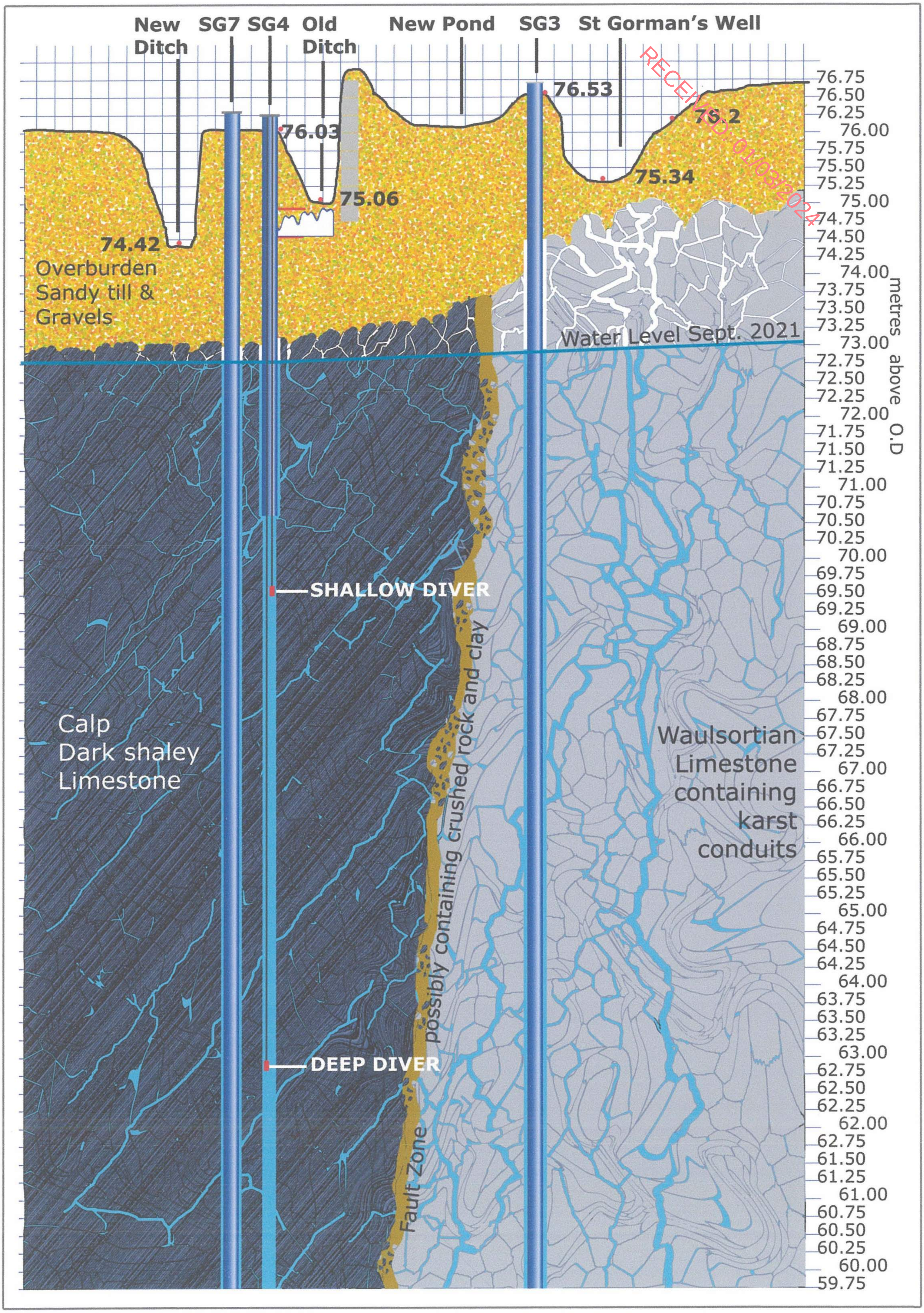
Finally, it can be seen that there are two blue lines below the water table level on each side of the borehole casing in all three boreholes. These blue lines and the white lines above depict the open annulus around the outside of the steel casings in the bedrock. The annulus arises because, before casing is installed into the hard bedrock section of a borehole, it is necessary, usually, to drill a hole in the rock that is wider than the outer diameter of the steel casing. Drilling a hole that is wider than the casing means that the casing can be lowered easily, rather than hammered or forced, into the hole. The casing is a loose fit. The width of the annulus around the casing is usually at least an inch if the casing is central in the hole. This means that there is a gap around the casing in the bedrock section, up or down which, water can move. There is no annulus shown around the casing in the overburden section. This is because even quite freestanding overburden usually slumps in against the casing over time.

A groundwater level (water table) is shown in figure 5.38 for low water level conditions in September 2021. There was no water in St Gorman's Well, and the ditch was probably dry because there had been very little rainfall in late August and early September 2021.

Returning to Figure 5.37; it can be seen that the temperature recorded by the shallow Diver is cooler than the temperature recorded by the deep Diver. The difference varies but it is usually 0.7-0.8°C. This shows that water is being cooled as the water column rises in the hole.

The temperature rose by nearly 3 degrees Celsius in the first 18 hours on the 31st December. There was no peak in the temperature with the first 'high tide' at 10 am on the 31st December,

Figure 5.38 Schematic Section St Gorman's Well and Boreholes



but the second 'high tide' at 7pm was followed by a temperature peak about two and a half hours later.

This pattern of a high water level followed 2-3 hours later by a high temperature level in both Divers, was repeated across the three days.

The level of the water is below the top of the casing, therefore each rise in water level is not bringing a flow of water over the top of the casing.

The data indicate that each tidal rise of the water level is bringing warmer water into the borehole and past both Diver pressure transducers.

If, for the sake of example, the borehole was considered to be like a closed tube, open at the bottom into the large karst conduit at roughly 90 metres below ground level, or -15metres AOD, and open to the atmosphere at the top, then, it is possible that the temperature might rise 2.5 hours after the high water level because a slug of warm water has been pushed into the bottom of the tube, and the warmth of this water becomes distributed up the hole, past the Divers, by convection currents.

However, if the whole static column of water in the borehole had reached an even temperature, then it would be expected that the temperature of the water around the Divers should remain roughly the same when the water level goes down just 15cms over the following 6-7 hours on the 'low tide'.

To clarify, a column of water with an even temperature distribution would not be expected to cool at the position of two Diver positions equally by 1°C in 6 or 7 hours, without some external influence. The shallower water might cool but the deeper water would be expected to cool less. It doesn't. They both cool by the same amount.

To assess whether, theoretically, the upper water could be cooled rapidly during the two nights on the graph, the air temperature recorded each hour at Dunsany synoptic station is given along the top of the graph.

Borehole SG4 is lined with steel casing down to 5.5m, as shown in Figure 5.38. The steel lid was not airtight when the data was recorded. When the water level goes up air is pushed out of the top of the borehole. When the water level goes down, air will be sucked back into the borehole. During the night of the 31st December – 1st January the air temperature at Dunsany dropped from 4°C to 1.1°C. The following night, of 1st – 2nd January, the air temperature at Dunsany went down to -1.8°C.

Therefore, a small quantity of frosty air could be drawn into the casing, and the steel casing also was being chilled at the surface to either near zero or below zero. The relatively warm water and air inside the steel casing could be losing heat through the steel during both nights.

Air temperatures alone could be the reason theoretically for the cooling of the water inside the casing, but whether this cooled water would sink to 6.7 metres and 13.4 metres depth, equally, within 7 hours is unlikely.

I have inserted two small short red lines next to the borehole casing in SG4 in the section in Figure 5.38. I have placed a miniature version of the water level hydrograph shown in Figure 5.37 between the two red lines for scale and reference. This shows the elevation and amplitude of the water level rise and fall in SG4 over the three days shown in Figure 5.37.

It can be seen that the lower red line is below the level of the base of St Gorman's Well, but is above the level of the base of the new ditch. Therefore, if the water level in SG4 represents both the level in the borehole and the level of the water table in the overburden, then water had the potential to flow from the overburden into the ditch. If the water level in the borehole does not reflect the water table level in the overburden, and is above this water table, then there is a potential for water to flow from the borehole, via fractures in the bedrock and via the annulus around the loose casing, into the rock and the overburden. Conversely, if the water level in the borehole is lower than the level of the water table then there is the potential for water to flow from the overburden via the bedrock fractures and annulus into the borehole.

It is evident from the numerous detailed hydrographs, shown as figures in this report, of the water levels and temperatures in SG4, that the temperature of the water does not oscillate with the same amplitude throughout the year. It appears that when the water level is above roughly 74.25 to 74.75 metres above Ordnance Datum then the temperature rise and fall with the tides has a bigger amplitude.

Whereas, in summer, when water levels are usually below this level, the water level tidal fluctuation is the same, but the temperature fluctuation is much diminished. A good example can be seen in Figures 5.23 and 5.25.

Therefore, though the water level in the borehole is always influenced by the tidal effect on the pressurised groundwater system deep in the bedrock, the tidal movement of water does not necessarily bring about a change in water temperature in the upper part of the borehole where the Diver instruments are located. Warmer water may be moving in an out of the base of the borehole at -90+ metres throughout the year, but there is no evidence of a significant flow of warmer water up the borehole when the water levels are low. Yet the temperature of the water in the borehole remains warmer than the normal temperature for groundwater of around 9.5-10.5 °C.

The data suggests that the borehole is not a sealed tube, and that warmer water is either coming in, in small pulses, from the cave at the base, and the warmth is being distributed through the

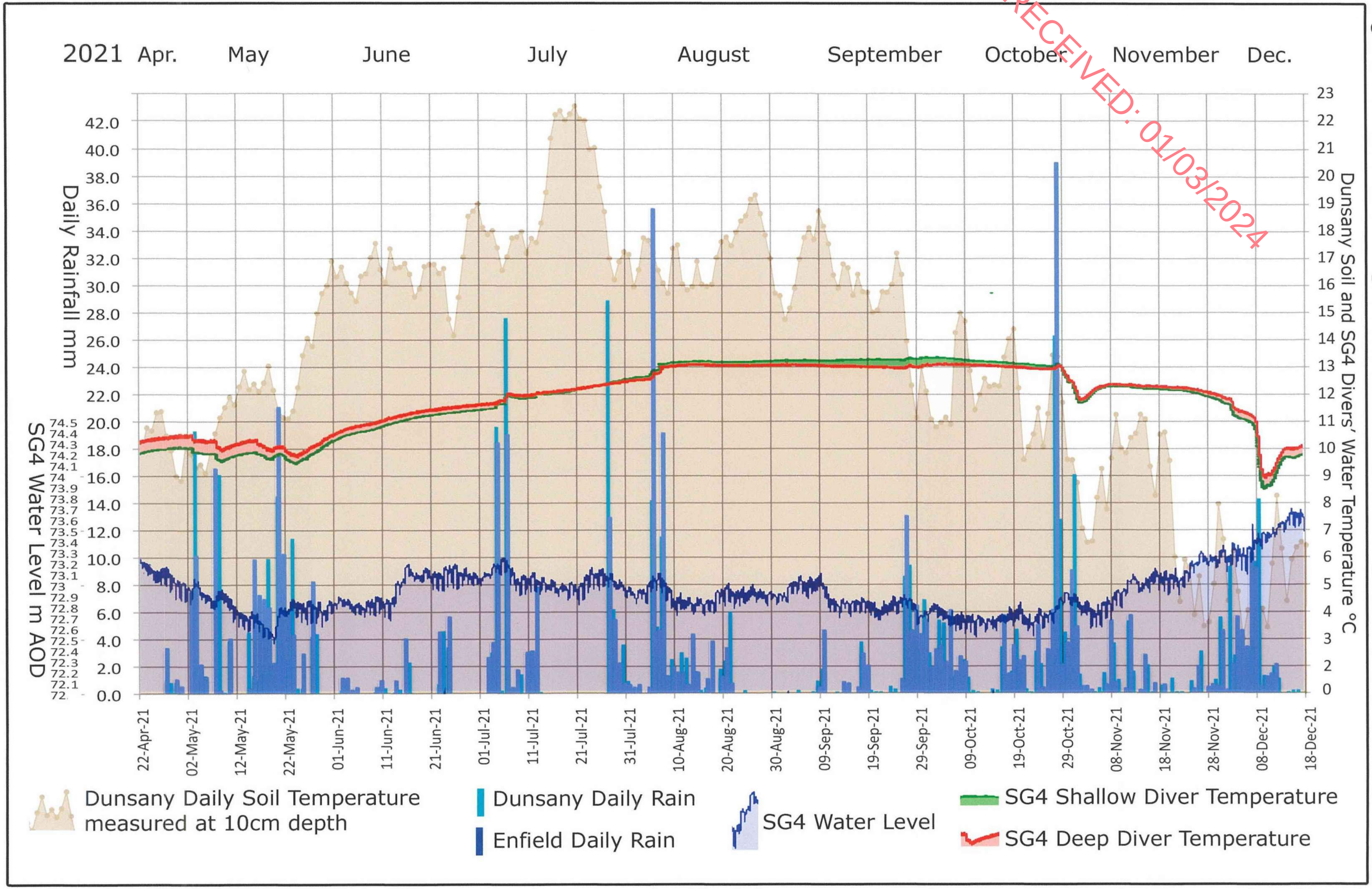


Figure 5.39 SG4 Water Temperatures at 2 levels, Soil Temperature, Water Level & Rainfall

water column by convection, or there is a very slow flow up the hole throughout the year. The speed with which it is flowing up the hole depends upon flow in at the base, and the ease with which water can get out of the hole through the sides.

Before the water level rises to the top of the borehole and freeflow takes place, the water cannot get out of the top, or through the casing. Therefore, if it is flowing, up the hole it must be flowing up the hole and out into the rock at different depths. This means that it is possible that the borehole is distributing warmer water out into the rock, and therefore there is a 'pool' of warmer water around the borehole in the rock.

Warmer water could also be rising up through the rock around the borehole, but the water would have to make its way through the network of smaller cracks and joints in the rock, whereas flow up the borehole is unrestricted and relatively easy.

If water is able to flow out of the borehole with each pulse of the 'high tide' it means that water can flow back into the hole with each 'low tide'.

The water level graphs give the visual impression that water is pulsing up and down the hole with the tides, and the temperature graphs indicate the same, but it would be more realistic to think in terms of water pulsing up, and flowing out of the borehole sides. Then, when the tide turns, water from the rock flows back into the hole. Most of this water would be the water that had flowed out on the high tide, but there would probably have been some cooling and mixing in the rock outside the borehole, and hence the water flowing back into the hole would be cooler. This forms a reasonable explanation for the drop in temperatures recorded by both the shallow and deep Diver instruments as seen in the three days of data shown in Figure 5.37. This Figure shows data at a time of significant water level and temperature rise, and as can be seen on the temperature graph for the two Divers, the temperature of the shallow Diver is cooler than the temperature of the deeper Diver. This is probably because water outside the borehole at a shallow depth and in the overburden, is likely to be recent winter rainfall recharge with a lower temperature than the water in the Calp bedrock 7 metres below. Therefore, the blend of cooler shallow water mixed with warmer borehole water, flows in and out of the hole with each pulse of the tides.

The purpose of this very detailed assessment of water level and water temperature data is to try to determine what these data represent, and having done so, to determine the the varying significance of the different components of the groundwater systems functioning at different times of the year at the St Gorman's Well site. Then, with this understanding, assess whether pumping from the Rathcore is significant at different times of the year.

Figure 5.39 shows water temperatures from two Divers, water levels, daily rainfall and soil temperatures from the end of April 2021 to the middle of December 2021. This is a period of low water levels in SG4, and no pumping from boreholes in Rathcore quarry.

The daily rainfall shown along the bottom of the graph is from two Met Eireann stations, Dunsany and Enfield, because during the spring and summer there are several days when either station records heavy rainfall, whilst the other records no rainfall or less rainfall.

The soil temperature is from the Dunsany station, which records daily soil temperatures measured at 10cm below ground level. Daily maximum and minimum air temperatures alternatively could have been shown on the graph, but there would have been a clutter of data points that obscured other data.

The soil temperatures were chosen because they give an idea of the warmth of the soil through which effective rainfall would pass, before percolating down further to the shallow groundwater system. These soil temperatures might represent the warmth of the soil in the large fields in the recharge area of Ballinakill hill just above St Gorman's Well. The purpose of the graphs is to show the link between rainfall, water levels and the temperature of the water at the two levels of the Diver instruments in SG4.

The graph starts on the left showing conditions after the high winter water levels and high winter water temperatures have declined. By May 13th the water levels had fallen to 72.6 metres above Ordnance Datum (below the water level for September 2021 shown in the section in Figure 5.38). The water level was probably within the bedrock and the overburden was unsaturated. The temperature recorded by both Diver instruments at the end of April was just above 10°C. The water temperature recorded by the deep diver was warmer than the water recorded by the shallow Diver.

Two heavy rainfall events in early May appear to cause a small rise in the water level in borehole SG4, and a small fall in the temperature measured by both Divers. It can be seen that the soil temperature was similar, or lower than the groundwater temperature. Therefore, it is reasonable to interpret the combined data as representing cool recharge percolating through the overburden, and flowing into the borehole.

After the heavy rain recorded around the 6-8th of May the water levels continued to go down and the temperature rose slightly. Then in Mid May there were ten days of significant rain. Water levels rose again and temperatures fell, but after these events there was minimal rain. Water levels remained constant and water temperatures rose. This trend remained, with the exception of a sharp rise in water levels around the 15th May without a corresponding record of significant rain from either rainfall station, or the Mullingar synoptic station. If rainfall caused this rise in water levels, then it must have been an isolated and local heavy shower not picked up by any rain gauge in the area.

Whilst the water temperatures steadily rose by about 2°C in June, the difference in water temperature between the two divers decreased during a time when the soil temperatures were consistently above 15°C. The temperature of the shallow water was becoming warmer relative to the temperature of the deeper water. Eventually, with very heavy rain in the first week in July, the water levels rose and fell sharply, and the temperatures rose slightly at both levels to become the same. This occurred at a time when soil temperatures were above 17°C. A similar very heavy rainfall event with a rise and fall of water levels and a sharp small increase occurred in the first week in August. What is significant about the event in August is that the temperature of the groundwater at a shallow depth in the borehole became warmer than the groundwater deeper in the borehole. It can be seen on the graph that the green line moves above the red line. This small difference remains through to the end of the summer and into the early autumn.

It ends with the 39mm rainfall event on the 27th October. This rainfall occurred when soil temperatures were lower than the groundwater temperatures. After this rainfall event, the groundwater temperatures at both depths in the borehole, fell sharply by 1°C, to rebound slightly and then decline until another sudden drop in temperatures with the rain in early December.

After the rainfall in October the temperature measured by the shallow Diver became the same, or lower than, the temperature recorded by the deeper Diver.

The close inspection of the subtle changes in the data in Figure 5.39 indicate clearly several important features of the groundwater system affecting borehole SG4, and probably the groundwater system below St Gorman's Well.

The data shows that

1. Warmer than 'normal' groundwater remains in the borehole throughout the summer.
2. The water levels are still oscillating in the borehole with the tides, and therefore water is probably moving in and out of the fractures in the bedrock. As water is being exchanged between the borehole and the bedrock, and the temperatures remain very stable, it is reasonable to assume that the groundwater temperatures in the bedrock are the same as the temperatures in the borehole.
3. Therefore, there is either warmth stored in the rock, or there is still a very slight upward movement of warmer water through both the borehole and the rock during the summer.
4. However, the small but obvious rise in groundwater temperatures during the summer is not a simple reflection of a front of warmer water slightly rising up through the

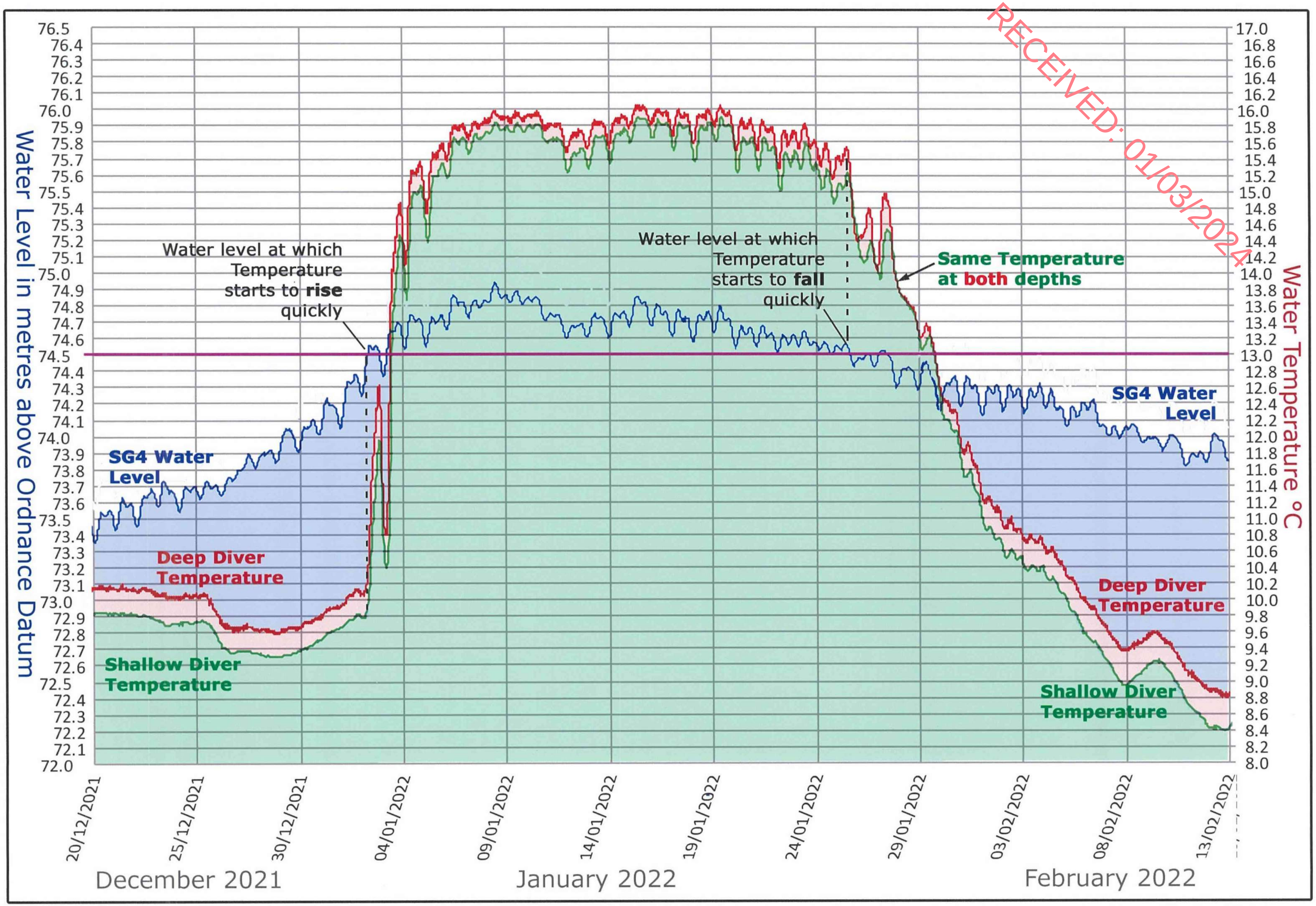


Figure 5.40 Borehole SG4 Water Level and Temperature December 2021 to February 2022

borehole and the rock, but instead, it is complicated by recharge water percolating down through warm soil after significant summer rainfall events.

5. It is evident that the same pattern of summer temperatures occurs in previous years.
6. It is an interesting contrast, that though water temperatures in shallow dug well W3 also rise by over 4°C during the summer months each year, they do not reach the same temperatures as measured by the two Diver instruments in SG4. This can be seen in Figures 5.31 and 4.13. The rise in temperature in both holes is roughly the same but the warm summer recharge at W3 is mixing into much cooler groundwater, starting in spring with temperatures of 7°C. The starting spring and early summer temperatures in SG4 are 10°C.
7. The overall interpretation from the data shown in Figure 5.39 is that the deep groundwater system that drives warmer water up under St Gorman's Well is quiescent or inactive from late winter/spring, through the summer, until the cumulative impact of autumn winter rains raises groundwater levels above a certain trigger level.
8. Finally, it is notable that the same pattern of summer water temperatures in SG4 also occurred during the time that the pumping from boreholes in Rathcore quarry appeared to be lowering water levels in SG4. In other words, the pumping at Rathcore in 2020 did not appear to change the normal pattern of water temperatures that can be observed in the data back to 2014.
9. The water temperatures measured by Sarah Blake's instrument in the late summer of 2013 are higher by about 4°C than the temperatures in SG4 in 2021. Unfortunately, in 2013 there was no corresponding water level data to aid interpretation in the light of the data from 2018-2022. It is possible that the water levels were higher in 2013.

Figure 5.40 shows the water level and water temperatures in the period directly following the data shown in Figure 5.39. The temperature and water levels in Figure 5.40 are at an expanded vertical scale so that, for example, the difference between the temperature from the shallow and deep Diver instruments appears more distinct. Figure 5.40 shows the first significant rise in temperatures in borehole SG4 after the summer of 2021.

The graph extends from the 20th December 2021 to the 13th February 2022. The maximum height of the water level did not reach the top of the casing, nor did water emerge in the base of St Gorman's Well. A later surge in water levels occurred in March 2022 and a small amount of water was seen in the base of the Well depression.

Though the period from August 2021 to the autumn of 2022 was a prolonged drought, the rain at the end of December, particularly on Christmas day, was sufficient to energise the deep groundwater system, and push warm water through the deep conduits and up into borehole SG4.

The purpose of the graph in Figure 5.40 is first to show how, again, the sharp rise in water temperature started in earnest when the water level had risen above 74.50 metres above Ordnance Datum, and second to show the time-lag in temperature rise and fall between the two Diver instruments.

The water level of 74.50 metres above Ordnance Datum has been high lighted by a purple horizontal line across the graph.

It can be seen that in the run up to the sudden rise in temperature, the water level was fluctuating with the tides, but the tidal fluctuation in the temperature was barely noticeable. Then, suddenly, when the water level just reached 74.50 metres the temperature rose by 2.5°C and then fell by 2.0°C.

It can also be seen that the temperature rise deeper in the borehole was 0.6° more than at a shallow depth, and that the temperature peaked at a shallow depth after the the peak at a deeper depth. This clearly shows that the warmer water is moving up the hole from the base.

The next tide cycle brought about an even greater change of temperature.

The water level only rose by 30cms, but the temperatures rose by 4°C. and then only dropped by 0.6°C.

The delay between the top of the water level ‘high tide’ and the peak of the deep Diver water temperature, was about 2 hours. The peak of the temperature in the shallow Diver was about 2.5- 3 hours.

This indicates that the temperature change was not caused by the rush of a column of warmer water entering the borehole at 90 metres, and then being pushed all the way up the borehole, to completely fill the borehole with water of roughly the same temperature.

Instead, the probable transfer of heat is by free convection in the water column in the borehole.

To clarify; convection currents start to take place in a column of water when the thermal gradient exceeds a certain number expressed as °K (Kelvin) or °C per metre. This critical gradient number differs depending on the diameter of the column of water, i.e. the diameter of a borehole. It is much more difficult for warm water to rise, and cool water to sink, if the water column or borehole is a very narrow. For example, if the borehole is only 25mm in diameter, and the general temperature is around 5°C, the critical gradient is 11°C per metre. But if the borehole is 125mm wide, the critical gradient is 0.02°C per metre. When the temperatures are generally around 10°C, then the critical gradient for a 25mm wide hole is 1.26°C per metre and for a 125mm wide hole it is less than 0.01°C.

Borehole SG4 is 200mm in diameter, and the gradient necessary to start convection would be less than 0.01°C. Therefore, to take an example; if a pulse of warm water comes into the bottom of the borehole from the large karst cavity at about 90 metres, and the temperature of this pulse of water is 18°C, and the temperature of the water at the water surface inside the casing is 10°C, the temperature gradient over the 90 metres is 0.088°C/metre. This is more than the critical gradient of 0.01°C/metre, therefore convection currents can initiate, and the warm water will rise through the column of water in the borehole.

Recent research by Russian scientists (Demezhko Khatskevich and Mindubaev 2018) have shown that convection currents in the laboratory equivalents of boreholes, are not necessarily a plumes of warmer less dense water, chaotically pushing its way up through cooler more dense water. Instead they found that convection currents in a long narrow cylinder take the form of a double helix; where the warmer water forms a spiral stream going up, and the cooler water forms a spiral stream coming down. In a rough sided irregular shaped borehole this simple pattern of flow is unlikely to be sustained over long distances. Therefore, the convection flow will be turbulent in some parts of the hole and more organised in others.

However, temperature difference conditions seem to be right for the rise in temperature in the borehole to be the convection of warmer water from the base at 90 metres. It seems to take 2 to 3 hours for the temperature of the water to reach its peak near the top of the borehole, after the 'high tide' in the water levels.

Meanwhile, as convection is taking time to distribute the warmth through the water column, the water column is simultaneously falling on the 'low tide', and cooler water is entering the borehole from the open cracks in the rock around the hole.

With reference to Figure 5.37 and 5.40, it is notable that the first sharp rise in temperature in both 2020 and 2021 is followed by a sharp fall in temperatures at the two Diver positions but, after the next rise in the temperature, the fall in temperature is less. Over subsequent days the amplitude of the rise and fall in temperature appears to decrease, indicating that the water flowing back into the hole from the cracks in the rock is mostly composed of warmer water that had recently flowed out of the hole during the previous 'high tide'.

Convection of warmer water is also taking place in the open interlinked fractures and karst conduits in both the Calp limestone and the Waulsortian limestone. With reference to the openings in the rocks shown in the schematic section in Figure 5.38, it can be seen that the rise of warmer water is likely to be faster in the Waulsortian limestone under St Gorman's Well. The conduits below the Well are likely to be more direct and better developed by karst dissolution processes in the Waulsortian limestone. Therefore, the rise in temperatures seen in borehole SG4 is likely to be simultaneously, but perhaps more slowly, replicated in the karst conduits under the Well. Borehole SG3 may also provide a conduit for convection currents in the upper 13 metres.

A feature, noted before and termed a 'break through', can be seen labelled in Figure 5.40. The water temperature starts to rise sharply at a water level of 74.5 metres above Ordnance Datum, but it also starts to fall rapidly when the water level goes down to 74.5 metres above Ordnance Datum.

Sarah Blake's work, and the earlier work in the 1980s, concluded that the warm water comes up from a deep seated flow system in the limestone associated with the faults. But this interpretation also includes an assumption that flow from the Well and or the boreholes, takes place either immediately, or shortly after the sharp rise in temperature.

The concept was that water from somewhere in the ground water system moves down an isolated karst conduit to a considerable depth (perhaps associated with a Cenozoic strike slip fault), and picks up geothermal heat, and then rises through isolated karst conduits to near the surface below St Gorman's Well. The concept was that this flow only becomes active when the water level in the recharge area at the start of the isolated conduit system reaches, and rises above a certain level. The water at this level then exerts a hydraulic pressure at the inlet of the conduit, that pushes water down, and up through the conduits. In other words the warm water system becomes active when there is a driving force to push water through it. The system is conceptualised as like a very deep 'U' bend shaped pipe. Sarah Blake correctly terms this 'piston flow', and it is a conceptual model commonly used to explain periodic flow in conduits in karst limestones.

Flow down and up a 'U' bend pipe depends upon an input of water at one end, and an opening at the other end. If the other end is closed off, then there will be no flow along the pipe. Therefore, the 74.5 metre level at the St Gorman's end may be indicative of the level of an open end at 74.5 metres at St Gorman's Well.

I have not found a characteristic, or feature at 74.5 metres at the site of St Gorman's Well, except that the invert of the new curved ditch is at 74.4 metres adjacent to the boreholes. Neither I, nor others, have noticed and recorded a sudden flow of water from the ground into the new or old ditch after water levels in the borehole have reached or exceeded 74.5 metres.

In the absence of clear evidence that there is an outlet specifically at 74.5 metres at the St Gorman's end, then the obvious conclusion is that 74.5 metres AOD is a level that is important at the other end of the 'U' bend; i.e. the recharge or input end. In other words there is no flow through the 'U' bend conduit system until the water level at the input end rises above 74.5

metres. As this natural 'U' bend is not a smooth sided pipe, but instead a naturally formed rough karst conduit, there will be friction as water moves along it. Therefore, the critical input level will need to be above 74.5 metres to create a sufficient head of water pressure to start flow through the conduit and overcome friction resistance to flow.

This means that to find a potential input area for the 'U' bend, it is necessary to look for areas where the surface topography, or the level of a lake or river, is above an elevation of say 75-76 metres AOD. There are no lakes or river courses above 75-76 metres elevation close to St Gorman's Well. The nearest stream course shown on the OS Discovery Series maps above the 80 metre contour, is a small stream running from southeast to northwest through the Rathcore Golf Club about 3 kilometres away. This stream is on the edge of gravels above Waulsortian limestone just north of Rathcore Cross Roads.

The nearest land under which there may be an input groundwater level is Ballinakill hill adjacent to the site. Other topographic high areas (see terrain map in Figure 2.1) are the ridge along the road due west of the site, the ridge extending from Rathcore quarry north and east to Rathcore village, and the higher ground across the shallow valley to the north of Ballinakill hill in Cullentry townland. From these potential areas, the foremost would be the adjacent Ballinakill hill.

As John Paul Moore has identified that the Cenozoic strike slip faults with a northwest or north east orientation are more likely lines of weakness along which karst solution conduits will form, it is perhaps significant that a fault appears to run northeast from St Gorman's Well under Ballinakill hill.

In other words, the nearest possible place under which the water level could rise to above 74.5 metres is the hill adjacent to the Well. The EDA pumping test on SG7 in June 2001 also showed that a drawdown was created in two boreholes (7 and 11) along this alignment.

However, when the Well and the boreholes are flowing there is a copious flow of warm water up to the surface. Therefore, a catchment of a reasonable size is necessary to provide the input at the open end of the 'U' bend to sustain the flow over several weeks at present, and over several months in the past.

It is useful to consider the volume discharged by the Well and boreholes in order to obtain a rough estimate of the catchment area. The best records of flow from the spring are the frequent measurements made by Stephen Peel for Minerex in 1981-1983 shown in Figure 5.11.

There was a sustained high flow from the Well from December 1981 to May 1982. The flow rate varied from 200 to over 1,000 cubic metres a day based on Stephen's spot measurements. A very approximate total volume of water from the Well during the six months was 95,000 cubic metres. For the sake of an example to calculate a theoretical catchment area need to provide that flow; if we assume 100,000 cubic metres of water and spread it out in a layer 200mm thick, it would cover an area of roughly 500,000 square metres which is roughly a square with 700 metres by 700 metres sides. This is roughly the area of Ballinakill hill above the 80 metre contour on the O.S. Discovery Series map. During these 6 months the rainfall recorded at Longwood Garda station rain gauges was 380mm. assuming, for the sake of an example, that 50% of this winter rain percolated down through the sandy till and gravels on Ballinakill hill then, to give context, it may not be necessary to look far from St Gorman's Well in order to find a suitable sized recharge area to provide the input at the open end of a hypothetical 'U' bend conduit that emerges under St Gorman's well.

However, the above does not take into account that not all the rainfall recharge will be captured and flow into a single 'U' bend shaped deep conduit system, unless there is a funnel or basin shaped depression with impermeable sides under Ballinakill hill.

The geology of the large field directly to the northeast of St Gorman's Well was investigated by EDA for Roadstone. The thickness of the sandy till and gravel above the bedrock ranges from 2 metres to 15 metres. The Tellus conductivity sections in Figures 2.36 and, in particular, Figure 2.37 show a change in the Waulsortian bedrock under Ballinakill hill that indicates the presence of a very large cavity at a depth of 50 to 90 metres. This cavity was intersected by EDA borehole 7 which was one of the boreholes where the water level was drawn down most when EDA carried out the pumping test on SG7 in June 2001.

EDA did not report that they observed a tidal fluctuation in the boreholes that they drilled on the Roadstone lands. But what EDA interpreted as an anomalous high drawdown in response to pumping may have been a compound of drawdown created by pumping with a coincidental 'low tide'. It is not possible to prove this because EDA only took 7 measurements of water levels on borehole 7 over the 72 hours of the test. Even so, the apparent large cavity system under Ballinakill may form part of the upper, or recharge end of the hypothetical 'U' bend conduit system.

An alternative recharge area for the 'U' bend conduit system could be Rathcore Hill and the quarry. There is no evidence of a direct fault linking the two sites, but they could be linked via the complex mesh of apparent faults picked out from the geophysics sections and plotted on the map in Figure 2.47. Whilst not excluding Rathcore hill and quarry as a potential start of a deep 'U' bend system, there was no evidence of a sudden drop in water levels, or a cessation of the flow of warm water from SG4, when the pumps were turned on at maximum output in the quarry in February 2021. Pumping from the quarry created a drawdown in deep core hole

D3. The water level in D3 outside the quarry was 77 metres above Ordnance Datum in early February 2021 when both borehole SG4 and the Well were flowing. The pumping in the quarry lowered the water level by four metres in D3, but the flow at St Gorman's still continued. This indicated that the effect of the pumping in the quarry extended through the karst conduits outside the quarry, but there was no effect or impact measured at SG4.

In other words if the pumping in the quarry had removed the hydrostatic head of water driving a flow of water through the 'U' bend, then the water level should have gone down in SG4 and the flow of warm water stopped at the other end, in response.

Another fact to consider is that though Rathcore hill is much higher than 74.5 metres above Ordnance Datum, the maximum water level in the limestone at the quarry site is at about, or slightly above the quarry floor level at about 75- 76 metres. Therefore, the head of water in the area of the quarry, and the southern part of the Rathcore Waulsortian limestone ridge, is only slightly higher than the important 74.5 metre level, and probably insufficient to drive water down and up, through a deep 'U' bend conduit system to an outlet about 2km away 'as the crow flies', but much further if the water has to go down 500 to 1000 metres on the way.

There is little evidence on water levels further north under the Rathcore Waulsortian limestone ridge, but the winter water levels monitored in borehole W1, shown in Figure 4.3, have been as high as 91 metres AOD, and in the winter of 2020-2021 when the Well and SG4 were flowing, the levels were about 82 metres. Therefore, the northern part of the ridge could have sufficient head to drive water by gravity through a complex system of cavities to St Gorman's Well. The geophysical sections also indicate a large number of cavities and faults in this area (see Figure 2.49).

A final area, that might have winter water levels sufficiently high to drive water through a 'U' bend cavity system, is on the low hill on the twisty road through Cullentry townland west of Rathcore village. It is a small area of higher ground above 80 metres AOD. EDA measured water levels in two deep boreholes. The table of water level data in Appendix D of the EIS, gives the date as simply '2002'. The EIS text says that water level monitoring took place in September 2001. The water levels were 8.16 and 4.49 metres below the top of the casing. The deeper water level could have been affected by pumping at, or close to the time of the measurements.

If the shallower 4.49 metre measurement represents a static water level at the end of summer in 2001, then it indicates a water level of 75 to 76 above Ordnance Datum. With autumn and winter recharge, the winter water level could rise a further 2-3 metres or more to a level that might provide sufficient hydrostatic head to move water down a 'U' bend deep conduit system.

The Quaternary Sediments map in 2.51 shows that this hill is formed by gravel, probably similar to the gravel shown in Figure 2.52. A study of the air photography from the Google Earth website show that there are two areas on the hill where water ponds in winter. This either indicates a thin layer of clay on the surface that ponds surface water, or that the water table in the gravels has risen to the ground surface at about 80+metres OD in winter. In other words, these could be winter groundwater ponds. Such ponds are not unusual in areas of thick gravels. They can be seen in winter on the Curragh in Kildare.

This area could be considered as a possible recharge area for St Gorman's.

This is an interesting possibility, because the interpretation of the numerous geophysical sections running across the valley between St Gorman's and this area, appear to consistently show faults on the expected Cenozoic northeast-southwest alignment linking the two areas. There also appears to be a major west northwest to east southeast aligned fault, along what is believed to be the late Carboniferous age alignment (roughly parallel to similar age fault running through St Gorman's), crossing these Cenozoic fault lines directly under this hill of gravel. Therefore, the intersection of the faults from the Cenozoic and the Carboniferous makes this is an area with considerable potential for the formation of karst conduits as highlighted by John Paul Moore's research..

A conceptual model could be that rainfall recharge builds up the water level in the gravels above the opening to an isolated vertical karst conduit in the Waulsortian bedrock. Water does not start to flow down into the isolated conduit until the water level in the gravel exceeds a certain threshold level, observed in borehole SG4 at St Gorman's as approximately 74.5metres AOD. There is no flow from the boreholes and no water in the well when this level is reached. All that happens is that warm water moves up into the large cave system at 90 metres below ground level at the base of borehole SG4. Flow only takes place when the water level or pressure at the inlet, and the water level in the shallow Waulsortian limestone conduits and perhaps the gravel at St Gorman's simultaneously exceed the level of the bottom of the Well and the top of the casing at SG4.

The identification, and proof, of the inlet area where water levels are sufficient to drive water down and up a deep 'U' bend karst conduit to St Gorman's, is beyond the scope of the current Rathcore investigation. It would require a large exploration drilling programme on lands not owned by Kilsaran, followed by tracer studies, probably, over several years.

However, the data gathered during the pumping tests in the current investigation has provided evidence that, severely dropping the water level (i.e. water head) in the conduits under the quarry during winter, does not drop the water level at St Gorman's. Nor does it stop the flow of warm water into the Well or from the boreholes. The evidence shows that the inlet area is not below the quarry, or in the immediate vicinity of the quarry where water levels were lowered by the long winter pumping test.

Returning to the characteristics of the sudden rise and fall in water temperatures each year shown in the long graph in Figure 5.19.

It can be seen that at the beginning of 2019, and twice in the winter of 2021 – 2022, there was a rapid rise in water temperature in borehole SG4, that was not accompanied by a flow of water from the borehole or a significant uprising of water in St Gorman's Well.

Therefore, an actual flow of water up and out of the borehole, is not a necessary condition for the temperature to increase. The change in temperature is not determined by actual flow up in the Well or out of the borehole. As discussed above, the temperature can rise at 6.78 and 13.41 metres below the top of the borehole by convection currents bringing warm water up the borehole from depth.

As is often the case, when interpreting data after an event, the interpretation makes it obvious that it would have been useful to collect additional data. In this case, it would have been useful to measure flows within borehole SG4. A sensitive flow meter would have been necessary to detect either convection currents or a slow persistent flow up the hole and out into the rock around the hole. The objective would be to measure vertical movements of water before, during and after the sudden rise in temperatures each autumn or winter. This would have involved frequent visits to the site as the water level rose to near 74.5 metres above Ordnance Datum, Ideally, measurements would be taken at different depths in the borehole, but there is a problem because there is the branch of a tree in the hole that stopped the GSI's video logging of the hole.

My interim conclusion is that the 74.5 metres above Ordnance Datum level is significant in the context of piston flow through the deep conduit system, even though actual water flow does not necessarily take place. The data indicates that at that level a pulse of warmer water is introduced into the large cavern in the Waulsortian limestone at the base of the borehole. In a sense the system is primed ready for warm water flow, but the flow depends upon other factors.

The interpretation of the water level, water temperature and Sarah Blake's EC data in relation to rainfall, shows that rainfall recharge into the overburden and shallow bedrock is the major influence on water levels and hence flow.

It appears that though the deep warm water system is primed, the warm water flow only takes place when the recharge to the shallow groundwater system has raised levels sufficiently for flow to take place from the Well and the boreholes.

It was notable in February 2021 that the temperature in borehole SG4, when it was flowing, was over 17°C but the temperature in the bottom of the pool in the Well was only 10°C. The pool could have been cooled by the 5°C air temperatures, but there was a gentle flow out of the pool and therefore a flow up into the pool The water was not static and the temperature measurement was made at the deepest part of the pool. The 10°C measurement indicates that the water flowing into the pool was predominantly, but not exclusively, cool, recent, shallow aquifer recharge water. Meanwhile, the flow from the boreholes was relatively copious and the temperature of the water increased when the flow was unrestricted.

It appears, in recent years that the potential for warm water flow can exist, but is only realised, or becomes active, when recharge raises the water level at the inlet of the 'U' shaped karst conduit system, and at the same time, cool water recharge raises the local water table level sufficient for the Well and the two boreholes to flow.

In other words, the warm water flow from SG4 SG7 and the Well is not solely dependent on a hydraulic pressure created by recharge elsewhere at the other end of a 'U' shaped conduit system. It is dependent on the level of the local water table which in turn is dependent on local recharge into the shallow groundwater system in the Waulsortian limestone and the gravel and sandy till overburden.

The shallow groundwater system is underpinned by the water pressure in the middle depth karst conduit system, say at below 50 metres. The water level data collected during the long pumping test in the quarry showed that the level in this 'middle section' of the groundwater system was affected by the pumping only in the summer. This effect was negated by the recharge into the local shallow system during the autumn and winter. The variations in local recharge continued to control water levels at St Gorman's, when the long winter pumping test was carried out in the quarry in February and March 2021.

The above interpretations and conclusions are based on an evaluation of the detail in the data collected in recent years from 2014-2022. The detail shows the complexity of the groundwater system affecting primarily borehole SG4, but also the Well at the St Gorman's Well site.

However, standing back from the complex detail, and instead looking at the year on year broad trends illustrated in the long hydrograph in Figure 5.19, it is obvious that the duration of high water levels and flow from the borehole and the Well has decreased. Also it is evident that the temperatures in the borehole, when flow is taking place, are lower than the 21°C in 2014, and

20°C in 2015. The maximum temperatures in 2019, 2020 and 2021 were 17-18°C. There are three years with no data in the winters of 2016, 2017 and 2018, so it is not possible to see if it was a gradual change from 2014 to 2021. It is also made more complex because the Well and boreholes did not flow or fill up in the winters of 2016-2017 and 2021-2022.

It is more difficult to assess trends in the record of the temperature of the water in the Well, as distinct from the boreholes. The Minerex survey in the 1980s showed that the water temperature in the Well was not constant, it was high but it also fell to about 11°C in October 1982 when there was still a small flow. Subsequent spot measurements, in 2003 showed it was 12°C, in 2009 it was 14.4°C, in 2011 it was 10.5°C, and in February 2021 we recorded temperatures as low as 10.5°C and 7.7°C. By contrast in February 2021 the temperature of the water flowing from the borehole was over 17°C. The water source, now, with consistently warmer water is borehole SG4 when it is flowing, rather than St Gorman's Well, where the water can be warm, but is also can be cold.

The earlier records of site visits and tests in 2001, 2002, 2003, 2010, are snapshots of conditions at the St Gorman's Well site, but in combination with the more recent detailed monitoring they give the general impression that the borehole and the Well were flowing for longer. In addition, Nicholas Wilkinson has some records, and he has noticed a marked decline in the duration of flow from the Well and the boreholes, in approximately the last decade.

Several of the wells, boreholes and core holes that have been monitored by Kilsaran since 2006 also show a decline in water levels over the last 15 years, as discussed in Chapter 4.

Overall, it appears that something is changing.

5.4 Changes in Rainfall

Rainfall, and occasionally snow melt, are the initial inputs into the groundwater system. The amount of rainfall that manages to percolate through the soil down into the shallow overburden and the deeper limestone bedrock groundwater systems replenishes the groundwater resource. It creates higher water levels in some areas, and the different water levels in the ground create gradients that allow gravity to move groundwater under the area. The primary driving force behind groundwater flow is rainfall that percolates into the ground.

Rainfall varies from year to year, and also in its distribution and intensity throughout the year. Annual rainfall totals or even monthly totals alone are not a reliable indicator of change or equilibrium. For example, two years may have similar total annual rainfall amounts, but in one year the rain arrived over many days of modest rain, whereas another year received most of the rain on widely separated days of intense rain.

The intensity of rainfall and the time of year matters. A single heavy rainfall event of more than, say, 30mms in a few hours in the middle of summer is likely to cause surface runoff, and any moisture that gets into the soil, is likely to be absorbed by the dry soil and the roots of vigorously growing plants and crops. Whereas, a high proportion of 5-6mm of rain each day over five consecutive days in November is likely to provide a more significant amount of recharge to the groundwater systems.

Kilsaran does not have a rain gauge on the Rathcore site. Therefore, I have relied upon Met Éireann's nearby rain gauges and synoptic weather stations to assess whether the apparent trend or pattern of lower water levels and less prolonged flow at St Gorman's, relates to a natural change in rainfall amounts, or the timing and nature of rainfall events.

The rainfall and climatological information is obtained from the following stations.

These are:-

Dunsany;
There is a Synoptic weather station at the Teagasc research station at Dunsany. The station was changed in 2003. Before 2003 there was a station on the site called Dunsany Grange that operated from 1963 to 2007. Dunsany is 16km from Rathcore quarry.

Enfield;
There is a rain gauge at Newcastle House on the Longwood side of Enfield that started in 2003. There was a previous rain gauge at the Garda station in Enfield that ran from 1942 to 1976. There was another rain gauge called Enfield (Summerhill) that ran from 1894 to 1951. Newcastle House is 2.5km from Rathcore quarry. It is unfortunate that this gauge has a relatively short record, and there are two months with no rainfall data.

Mullingar;
There is a Synoptic station at Mullingar with records starting in 2009 and another rain gauge that started in 2002, but other rainfall records for Mullingar start in 1875 and 1908. Mullingar is a nationally important site for meteorological measurements because of its position and the length of the records. Mullingar is 33km from Rathcore quarry.

Rathwire;
There is rain gauge at Rathwire in Co. Westmeath, with records that start in 1984. Rathwire is 21km from Rathcore quarry. This gauge is closer to the study area than Mullingar.

Longwood;
There was a rain gauge at Longwood Garda station that started in 1943. It ceased in 1986. The advantage of the Longwood record is the proximity of the gauge to the study area and the overlap of rainfall data for the 1980s when Minerex were carrying out their study of St Gorman's Well. Longwood is 4.6km from Rathcore quarry.

There is clear evidence that the world's climate is changing. The observations made at St Gorman's Well span 167 years, and more recent systematic measurements span the period from 1981 to 2022.

The early observations by Du Noyer and Conwell were made before the impact of the increased emissions of greenhouse gases had any significant impact on the world's climate. Yet their observations were made at either end of a prolonged, and significant drought in the 1850s, that affected the level and flow from St Gorman's Well. Their observations are evidence that the Well already has been affected by 'natural' changes in Ireland's weather and climate.

Identifying the onset of changes in Ireland's climate brought about by humankind's emission of greenhouse gases depends upon data. There is a considerable effort and wealth of new analysis taking place in Ireland on climate change, because the relatively straight forward, and immediately available record of air temperatures show that Ireland is warming in line with the increase in European and world temperatures. Provisional data for 2022 shows that it will be the warmest year in Ireland since 1900 and the 12th consecutive year with above 'normal' temperatures. It is difficult to distinguish the effects of artificially created changes in temperature on weather patterns and climate, whilst the change is actually happening. It is necessary to have data over a period of time in order to look back and detect where and when an unusual pattern or trend started to become apparent and have an impact.

Global warming is happening, but understanding the effects and implications in terms of rainfall, evapotranspiration and recharge to the groundwater system is more complex. Met Éireann, the EPA and numerous research teams in universities, are analysing how the climate has been changing, and are modelling how they expect rising temperatures to affect the climate and rainfall patterns in Ireland in the future.

The results of this work are mostly reported through the time frame of calendar years or calendar seasons; such as annual rainfall, winter rainfall, spring rainfall etc..

Hydrology and hydrogeology are applied sciences, and use a different timescale to look at rainfall and other factors affecting recharge. These sciences use a hydrological year timescale, where the year starts with the onset of autumn rains in September or October, and extends through the winter and early spring recharge period when water levels rise, to the summer when soil moisture deficits increase, recharge decreases and groundwater and surface water levels recede. The hydrological year ends in either August or September.

For this report, I have analysed the available Met Éireann data from the standpoint of a hydrological year from September in one year through to August the following calendar year.

However, the work of others using the calendar year and calendar seasons is still informative and useful. For example, Ciara Ryan, Mary Curley, Seamus Walsh and Conor Murphy in the Irish Climate and Analysis Research Unit in Maynooth University published a paper titled 'Long-term trends in extreme precipitation indices in Ireland' in the International Journal of Climatology in June 2022. The paper was submitted in 2021 and they used data up until 2020. Therefore, the drought in the 2021-2022 hydrological year is not included.

One of the important factors in relation to rainfall recharging the groundwater system is the intensity of the rainfall. The above research uses long term data from 36 stations throughout the country, including Dunsany and Mullingar. The researchers rescued, digitised, quality controlled and homogenised daily data from before 1940 to observe the trends starting in the 19^{th} century. Most previous work had analysed post 1940 data, and found a trend of increasing rainfall in the west of the country. The above paper confirms that there is not a uniform pattern of change across the whole island, but found that there was a trend of increasing frequency of intense rainfall in the east and southeast of Ireland.

They state that

> 'The overall tendency of increasing trends observed here suggest that heavy or extreme precipitation events are contributing significantly more to annual totals in Ireland, while precipitation is becoming more intense, particularly in the east and southeast of the country.'

They go on to state that this trend may not persist in the future because

> 'potential changes in the North Atlantic atmospheric circulation patterns, will also have a direct impact on future precipitation, with changes in the frequency and intensity of Atlantic depressions and their associated weather fronts and convective activity (being) important factors for extreme precipitation.'

The latest observations and predictions from the Climate Change Research section in the EPA, along with the Met Éireann, currently are stating that:

> 'Ireland has seen an increase in annual national rainfall of approximately 60mm or 5% in the period from 1981-2010. Compared to the 30year period from 1961-1990.'
>
> 'Significant reductions are expected in annual, spring, summer and autumn rainfall.
>
> Projections indicate a substantial increase in the frequency of heavy precipitation events in winter and autumn of approximately 20%.'

The above projections have significant implications for any groundwater investigation in Ireland, that would normally have used past long term averages to quantify the available sustainable groundwater resources in an area, and then assess the impact of any proposed development. The most significant statements above are the expectation of less total annual rainfall, and less total rainfall in the autumn. The projection of a 20% increase in the frequency of intense rainfall events in autumn and winter might seem to ameliorate or mitigate the impact of less total rainfall in autumn on groundwater recharge. However, rainwater has to get through the soil surface in order to reach the groundwater system. Soils vary, but each has a limited capacity to allow water to pass through it. A large amount of rainwater in a short period of time will usually exceed the capacity of the surface of the soil to permit it to percolate into the subsurface. A large proportion will run-off the land into the surface water drainage system.

Therefore, Met Éireann and the climate scientists are warning hydrogeologists that there will be less water available in total, and the speed with which this water is presented in the critical autumn and winter periods will increasingly exceed the soil's capacity to allow the water through it into the subsurface to recharge the groundwater resources. In other words, recharge will be rejected, not because there is insufficient space in the sub surface to accept it and store it, but because it arrives too quickly to get through the soil surface.

In essence, the climate scientists are predicting that groundwater resources are going to be relatively starved of recharge. As a result, groundwater levels are going to be lower, and hence the hydraulic heads necessary to drive water through the system to springs, and provide base flow into rivers, are going to be less. The level of water and duration of water in the depression and the volume of flow from St Gorman's Well is entirely dependent on recharge creating and sustaining these hydraulic heads. Therefore, the implications of the climate projections for St Gorman's well are obvious.

Ireland is not unique in an anticipation of change. Water resource specialists around the world are acutely aware that there is a change taking place, but the picture of the 'new normal' is not clear. The change may be happening quickly, but it is difficult to measure the speed and nature of the change, because identifying change usually relies on the analysis and comparison of trends in long term average data sets of 30 years or more. Global warming is creating instability, and an increased frequency of extreme weather events. Therefore, it is now appropriate to be looking at much shorter data sets in order to understand the characteristics of the 'new normal'.

The climate change science consensus has observed from long term averages that annual rainfall has increased, but the models are predicting that there will come a time of flux and a change to a different pattern of rainfall.

The expectation of a change has implications for the study of Rathcore quarry and, in particular, any potential effect it may have on St Gorman's Well.

I list below, for background context, a series of average annual rainfall for different time periods for stations near Rathcore and St Gorman's Well.

Overall the data shows that average annual rainfall is between 800 and 1000mm each year.

Mean Annual Rainfall for different time periods

Mullingar	1961-1990 934.3	1971-2000 886.4	1979-2008 941.3	1992-2021 990.4	2010-2021 1009.2
Dunsany	1964-1993 831.6	1971-2000 843.1	1979-2008 865.6	1992-2021 879.5	2010-2021 864.5
Rathwire	1992-2021 1001.6	2010-2021 999.5			
Enfield	2003 -2022 894.8	2010-2021 899.0			
Longwood	Jan 81 to May 83 902.7				

The data shows that Mullingar and Rathwire, to the west of the area, have a mean annual rainfall that is 100mm higher than Enfield and Dunsany.

Though the latter two stations are more representative of the rainfall in the study area, the information from the former stations provide a useful secondary data set for the analysis of trends.

It can be seen that the observed trend for increased annual average rainfall is clear in the 30 year long term averages for Mullingar, and even evident in the 10 year average from 2010-2021. Dunsany's 30 year averages show the same trend but the 2010-2021 average shows a decrease in rainfall. The records for Rathwire and Enfield are too short for comparison.

I have included the annual mean rainfall measured at Longwood Garda station for reference during the two and a half years in the early 1980s when Minerex were monitoring St. Gorman's Well. The data from Longwood Garda station is very similar to the more recent average rainfall measured at Enfield. This indicates that rainfall during this time, when St Gorman's Well was comprehensively recorded as flowing for many months, was not unusually high. At first glance, this indicates that the early 1980s was not unusually wet, and any change in the characteristics of flow and temperature between the 1980s and the 2000s is not related to a change in rainfall. This, prima facia, interpretation will be discussed in more detail below.

The Mullingar and Dunsany long term data show a fall in the mean annual rainfall during the 30 years from 1971 to 2000, because the mid 1970s were a period of reduced rainfall. There was the prolonged drought in 1976.

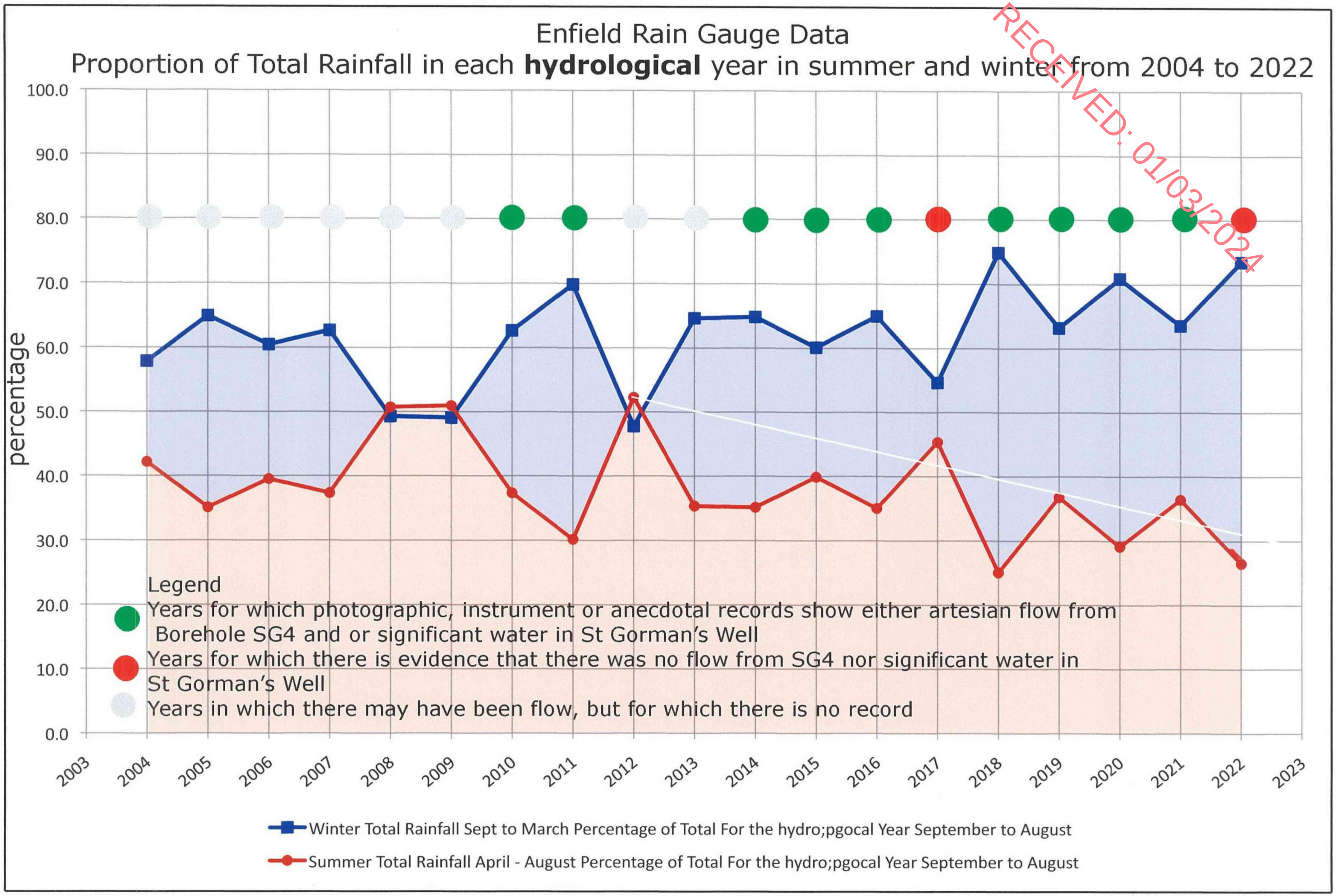


Figure 5.41 Enfield proportion of Winter and Summer rainfall (hydrological years 2004-2022)

The rainfall for the 30 years from 1992 to 2021 confirms the observation by the EPA and Met Éireann, above, that rainfall in Ireland increased between 1961-1990 and 1981-2010 though the increase at Dunsany was less than 60mm per year.

I have included, above, calculations of mean annual rainfall for shorter recent time periods in order to see whether recent annual rainfall continues the long term trend, or whether the predicted change to lower annual rainfall has already begun.

The data from Mullingar for 2010-2021 indicates that the pattern of increasing rainfall is continuing to the west of the study area, but the data from Dunsany to the northeast of the area indicates a fall in annual rainfall over the same time period. There appears to be no change at Enfield and Rathwire.

I have compiled additional average annual rainfall for two different and shorter time periods below:-

Mullingar September 2013 to August 2022 = 1022.0mm

Mullingar September 2016 to August 2022 = 937.0mm

Dunsany September 2013 to August 2022 = 858.1mm

Dunsany September 2016 to August 2022 = 819.98mm

Enfield September 2013 to August 2022 = 889.9mm

Enfield September 2016 to August 2022 = 815.6mm

The first time period from 2013 to 2022, is a period of nine years that covers all the period of for data collected by instruments on water levels in borehole SG4 at St Gorman's Well. The second period covers the last six years, including the two years (winters) when the Well did not contain significant water or flow.

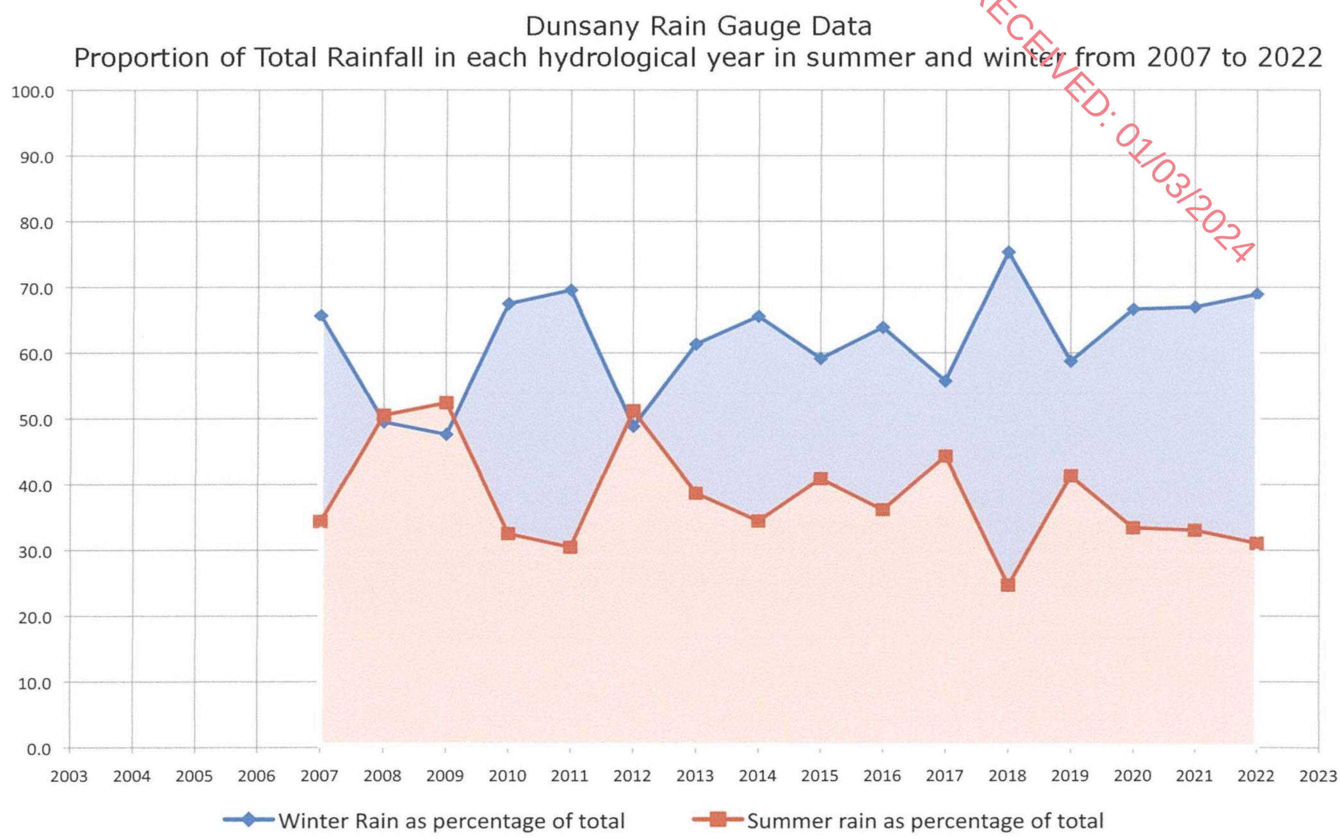
It can be seen that the average for the last six years is 85mm less at Mullingar; 38mm less at Dunsany and 74mm less at Enfield.

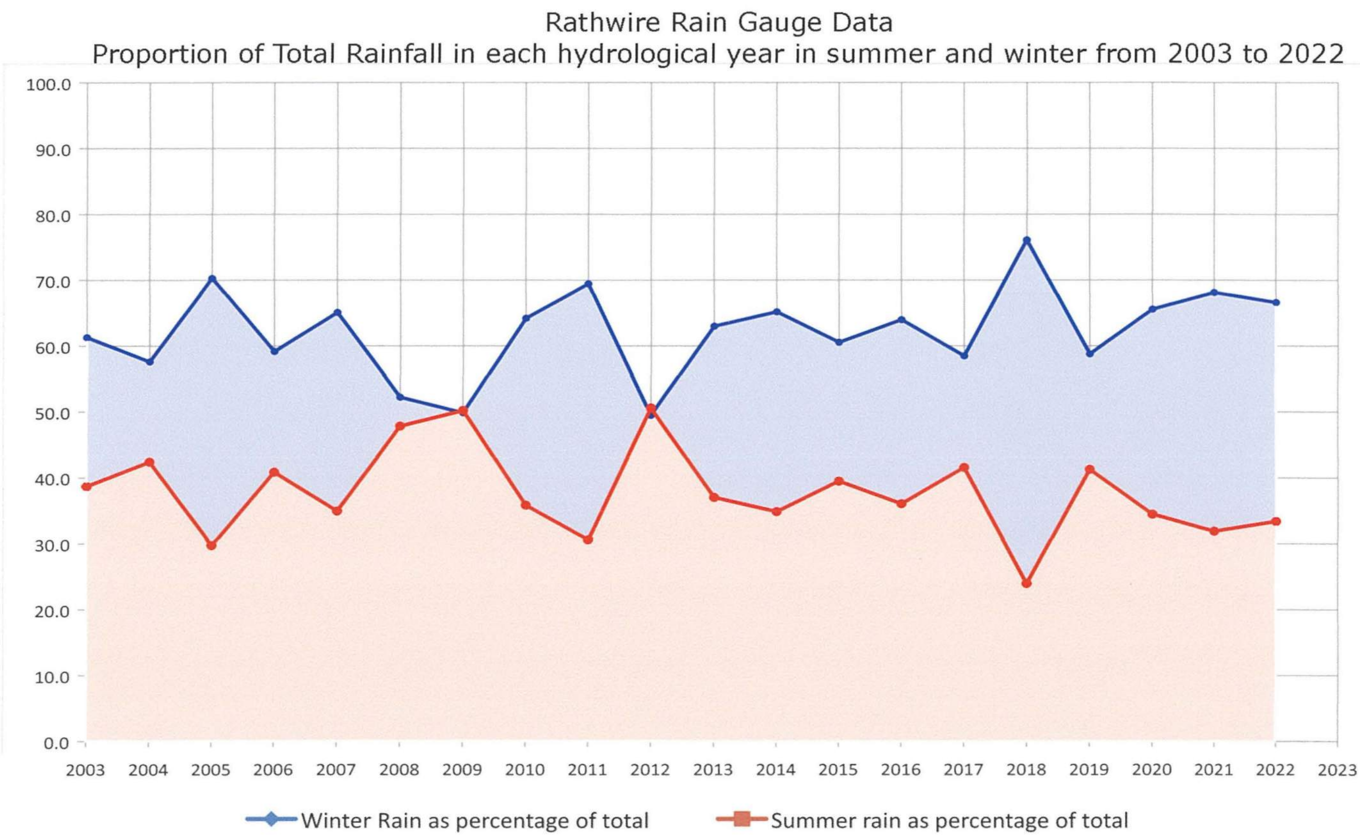
These differences over a short space of time are large changes. they may suggest that the EPA, Met Éireann predictions of a significant reduction in rainfall at some point in the future, actually may be taking place now.

To explore this further, I have compiled a graph showing the proportion of the rain falling during two parts of each hydrological year.

I have taken a hydrological year starting on the 1st of September and ending on 31st August the following year. Having assessed the rainfall data in tandem with the water level monitoring data, I have divided the year into two unequal periods. The first is the main recharge period of seven months that runs from September to the end of March. The second is the remaining

Figure 5.42 Dunsany and Rathwire proportion of Winter and Summer rainfall





period of five months from April to the end of August. I have calculated the percentage or proportion of the total rainfall that fell in each period, for each hydrological year.

Figure 5.41 shows these percentages for the hydrological years from 2004 to 2022. The Enfield rain gauge started operation at the beginning of the hydrological year that ends on 31st August 2004.

To clarify, for ease of reference, the year date on the horizontal axis of the graph is the date at the end of the hydrological year. For example, "2019" marks the end of the hydrological year extending from 1st September 2018 to 31st August 2019. '2017' marks the end of the hydrological year extending from 1st September 2016 to 31st August 2017, This is the year in which Nicholas Wilkinson recorded that neither the boreholes nor the Well flowed. Though there may have been a small amount of water in the base of the Well at some point in the winter.

Figure 5.41 shows a trend for a lesser proportion of the rainfall in summer and a greater proportion in winter, seemingly in line with Met Éireann's climate model predictions for the future, The diverging lines on the graph since 2012 seem to illustrate a change of distribution of rainfall that already has been taking place in the last 6 years, at a time when the average annual rainfall Dunsany has decreased.

The near 50:50 balance of winter and summer rainfall amounts in years 2008 and 2009, and 2012 may have been the end of an old trend of increasing annual rain and the start of a change that appears persistent since the dry year of 2017.

Rainfall in summer can consist of well separated but large convection rainfall events that might miss one rain gauge, and yet be recorded by another. A large summer storm in an otherwise low rainfall year could distort the record, but Figure 5.42 shows the same pattern of the proportions of winter and summer rainfall at Rathwire and Dunsany, as was recorded at Enfield. Therefore, the pattern of changing proportions of summer and winter rainfall seems to be occurring elsewhere, and not confined to Enfield.

Below is a table showing the total rainfall for the last three hydrological years for Dunsany, and the number of days in each year with daily rainfall above 15, 10 and 5mm.

Hydrological Year (1st Sept – 31st Aug)	**2021-2022**	**2020-2021**	**2019-2020**
Hydrological Year Total Rainfall mm	681.9	849.1	1017.5
Number of Days with >15mm	5	9	13
Total rain (mm) on days with >15mm	106.4	192.5	267.4
Percentage of hydrological year total	15.6%	22.7%	26.3%
Number of Days with >10mm	15	24	30
Total rain (mm) on days with >10mm	241.9	381.6	464.4
Percentage of hydrological year total	35.5%	44.9%	45.6%

Number of Days with >5mm	46	49	71
Total rain (mm) on days with >5mm	442.8	566.9	753.1
Percentage of hydrological year total	64.9%	66.8%	74.0%

Tabulating the data for hydrological years provides a sharp illustration of the scale of the drought in 2021-2022 by comparison with 2019-2020. The total rainfall in the last hydrological year was less than 70% of the rainfall in 2019-2020. There was also less heavy rainfall in terms of the number of events and the quantity. The data above provides a simple explanation for the low water levels in Borehole SG4 and the absence of water and flow from St Gorman's Well.

For many years agronomists, hydrologists and hydrogeologists have been wanting to find a standard way of rapidly analysing rainfall to provide an early assessment of droughts as they develop, or the imminence of flooding.

Various methods and indicators were in use until the World Meteorological Organisation held an international workshop in 2009, which recommended that a Standardised Precipitation Index (SPI) should be adopted and used worldwide by all National Meteorological and Hydrological Services.

Met Éireann, the Geological Survey and other agencies in Ireland have followed this recommendation.

The Standardised Precipitation Index is a statistical method for measuring rainfall anomalies at a location. It is based on a comparison of the observed rainfall amounts during an accumulation period of interest, (for example, 1 month, 3 months, 6 months or much longer) with the long term historic record, for the same period (1, 3, 6 months or longer) at that site.

The statistical calculations establish a normal curve distribution for the historical record so that the mean for that accumulation period is zero. The deviation of the observed rainfall for the accumulation period is then compared with the normal distribution, and this deviation is expressed as either positive or negative numbers. These are standard deviations from the long term mean for the chosen accumulation period.

A positive number represents rainfall that is greater than the mean. A negative number represents rainfall that is less than the mean. The larger the number, the greater the deviation from the mean.

A negative number of -1, or more, is commonly regarded as a meteorological drought anomaly. Numbers more negative than -1.5 are often characterised as an extreme droughts. The converse is used to characterise wetter periods.

Standardised Precipitation Indices are calculated from rainfall data collected over many years; ideally a minimum of 20-30 years, and often for a 50-60 years period. But, in the absence of a long high quality data set within or close to an area of interest, SPIs can be calculated from shorter records, and still provide a useful method for seeing a trend in the data from one rain gauge, and comparing the data from other rain gauges in a standardised way.

Therefore, agencies can observe a trend at one site or observe the spatial variation in a trend. The Standardised Precipitation Index may indicate that a drought, or imminent flood conditions are developing rapidly in one area, but is only beginning in an adjacent area.

The term drought or flood means different things to different scientists. A drought for an agronomist relates to the soil moisture conditions affecting plant growth. These conditions may be less than a month long, but could have serious consequences for a crop growth cycle of just a few months. Agronomists would want to calculate SPI's for one or two month accumulation periods.

A drought for a surface water hydrologist, or an engineer using a river as a source for a public water supply, might look at a longer SPI of 2 months to 8 months depending upon the nature of a river catchment, and the size of water storage reservoirs on the river system.

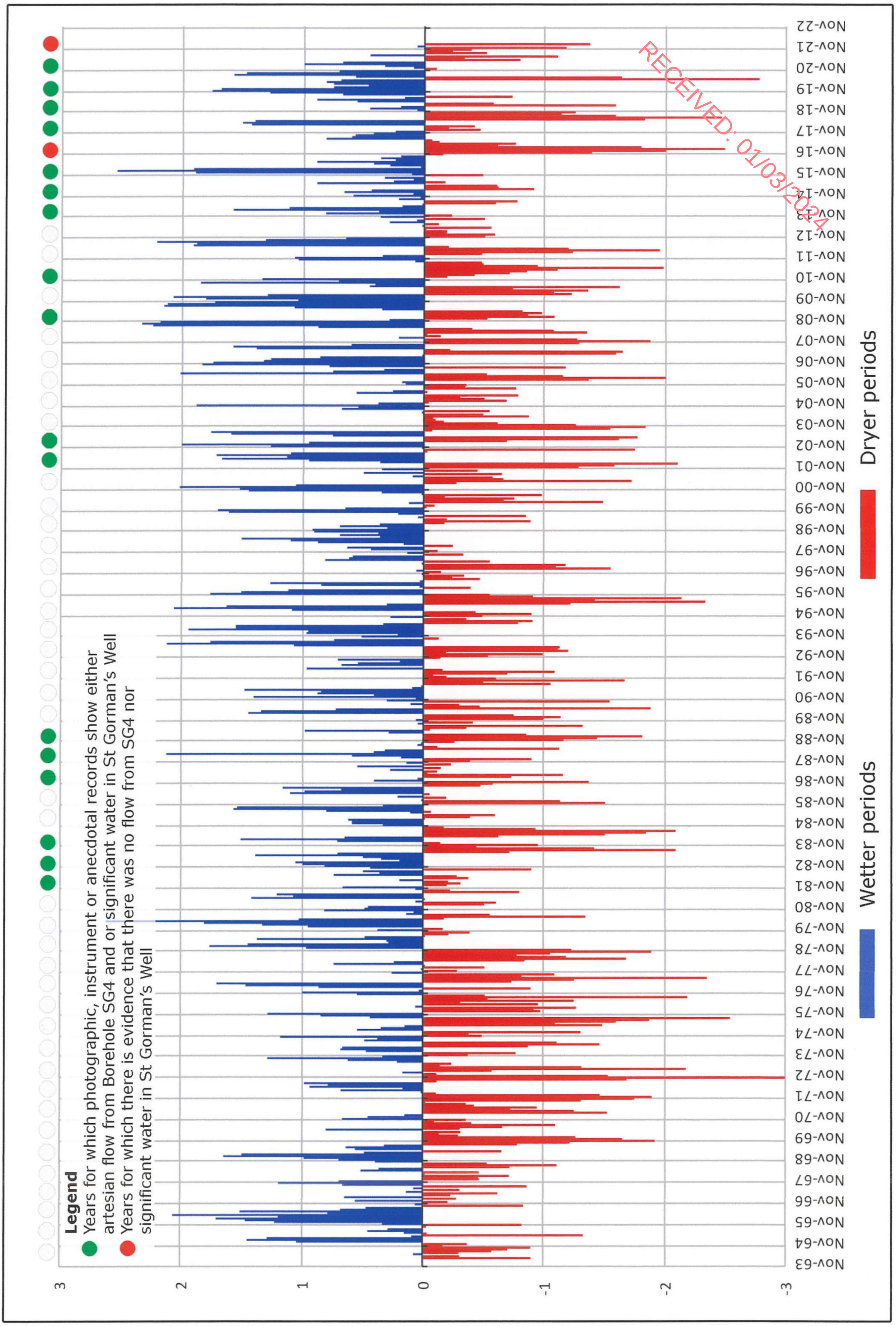
A hydrogeologist looking at a large groundwater system with a large storage capacity may look for even longer, possibly multi-annual, SPIs, because such large storage systems contain more water and will drain more slowly.

Simon Noone in his PhD, referred to above, calculated SPI's for numerous long term rainfall data sets and compared the pattern of wetter periods and drier periods with flows in different river catchments. He found that short SPI's of one or two months matched measured values of river flows in small 'flashy' river catchments, where the catchment land surface had steeper slopes and low permeability soils.

He investigated the Boyne catchment and there he found that longer SPIs of 3-4 months were more appropriate for the Boyne catchment, because the river base flow was influenced by the large contribution of water released into the river from groundwater storage. In other words, the flow in the River Boyne doesn't drop suddenly if there is just a month of dry weather. Dry weather has to persist for a longer period for there to be a significant impact on the River Boyne.

Groundwater moves slowly, and as water levels fall in an aquifer the gradient driving the flow decreases, and the drainage of the groundwater into the river system also decreases.. The water level in an aquifer will never fall below the base level to which the groundwater system is flowing. For example, the water level in the rocks and sands and gravels will never fall below the level of water in the River Blackwater and the Boyne in the area of Rathcore or St Gorman's

Figure 5.43 Dunsany 3 month SPI (Standardised Precipitation Index)



Well. Just as the level of groundwater in an aquifer next to the coast will never fall below sea level, which is the ultimate base level for all groundwater and surface water flow.

Groundwater systems or aquifers will usually be fully or partially replenished when the next period of recharge takes place. However, it can take time for a groundwater system to recover after a long dry period. Sometimes it takes several years. Therefore, long term climatic cycles can affect groundwater systems. To give a time context; I developed a new water supply north of Navan, and I got the Atomic Energy Research Station at Harwell in the UK to analyse the stable and radioactive environmental isotopes in the groundwater. We found that the groundwater was 33,000 years old. Work that I carried out in Arabia for four years early in my career showed that some waters were more than 48,000 years old, and in the large groundwater flow systems, under what is now a desert, there were still relic groundwater gradients representing the wet conditions during the last ice age,. In short, hydrogeologists consider both short and long accumulation periods for calculating Standardised Precipitation Indices.

I want to acknowledge my sincere gratitude to Shane Carey in the Geological Survey of Ireland. I do not have the algorithm, or skill, to calculate Standardised Precipitation Indices. Shane voluntarily took monthly rainfall data sets that I downloaded from Met Éireann's records, and calculated SPI's for several rain gauges and for several time periods. He provided graphs, but also gave me the calculated SPI data so that I could plot my own graphs at appropriate scales for this report.

The following text describes these graphs

Shane calculated Standardised Precipitation Indices for 3 month, 6 month, 12 month, 36 month, 72 month and 120 month accumulation periods, using the data from several rain gauges. The most useful and relevant appear to be the SPIs for the long record from the old and new Dunsany rain gauges going back to the 1960s, and the shorter record of nearly 20 years for the Enfield (Newcastle House) gauge because it is the closest gauge providing up to date information.

Shane calculated the SPIs on data that I gave him in February 2022. The Dunsany data is up to January 2022. Enfield data was only available up to December 2021. Therefore, the SPIs were calculated using data that showed just the beginning of the drought that took place during the hydrological year from September 2021 to August 2022.

Figure 5.43 shows the Standardised Precipitation Indices for Dunsany for a 3month period. The dry period negative values are shown as red columns and the wetter period positive values are shown as blue columns.

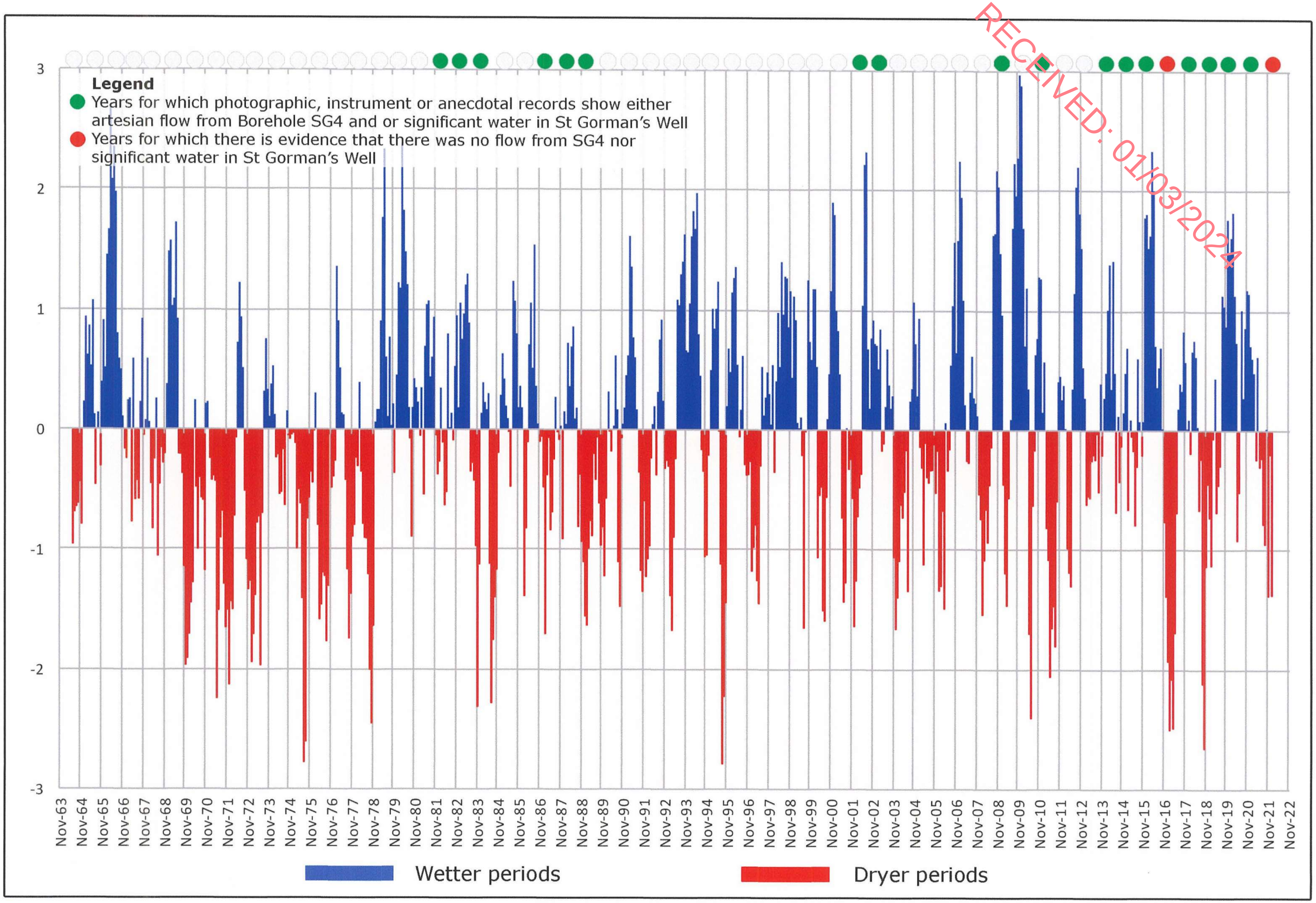
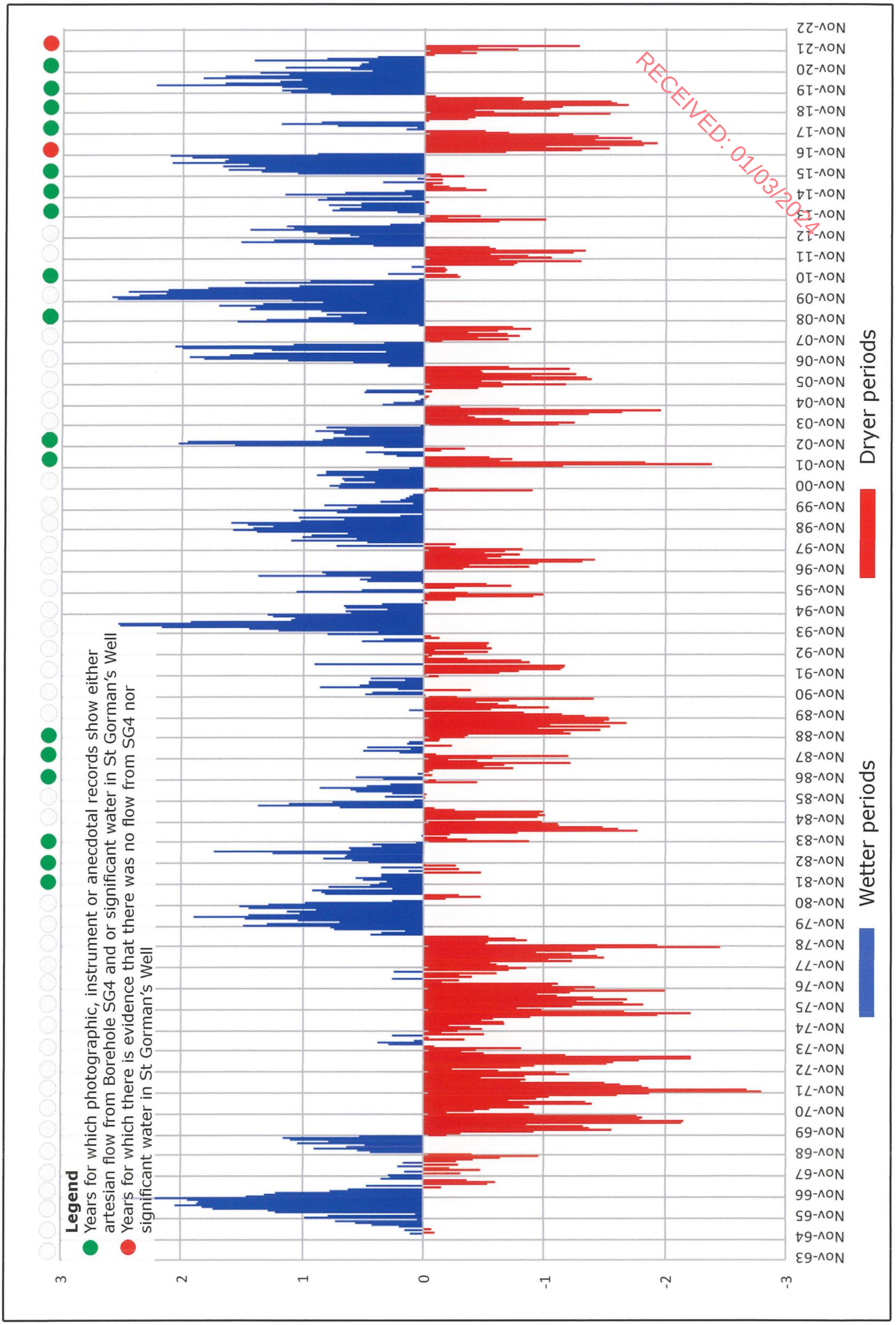


Figure 5.44 Dunsany 6 month SPI

Figure 5.45 Dunsany 12 month SPI



It can be seen that the 3 month SPI picks up numerous dry periods and wetter periods throughout the 60 year record. There are a great preponderance of dry periods from the late 1960s though to 1978, including the long period with no rainfall in the summer of 1976.

It can also be seen that there was a greater preponderance of wetter periods from 1978 through to the end of 1982 which was the year that Stephen Peel in Minerex regularly monitored the flow from St Gorman's Well.

I have put green and red dot symbols along the top of the graph to roughly represent hydrological years for which there is a record of St Gorman's Well flowing in winter. The three green dots in the early 1980s represent Minerex observations. I am less certain of the observations made in the mid-late 1980s by Hydro Research and Frank Murphy. The two green dots in the early 2000s represent the EDA and EcoServe observations. And the later two green dots are the observations by Tobin and Richard Langford.

The red and green dots in recent years are a combination of observations and instrument measurements made by Sarah Blake and this study, combined with observations recorded by Nicholas Wilkinson. The red dots show the two years for which there are records that the Well and the boreholes did not flow.

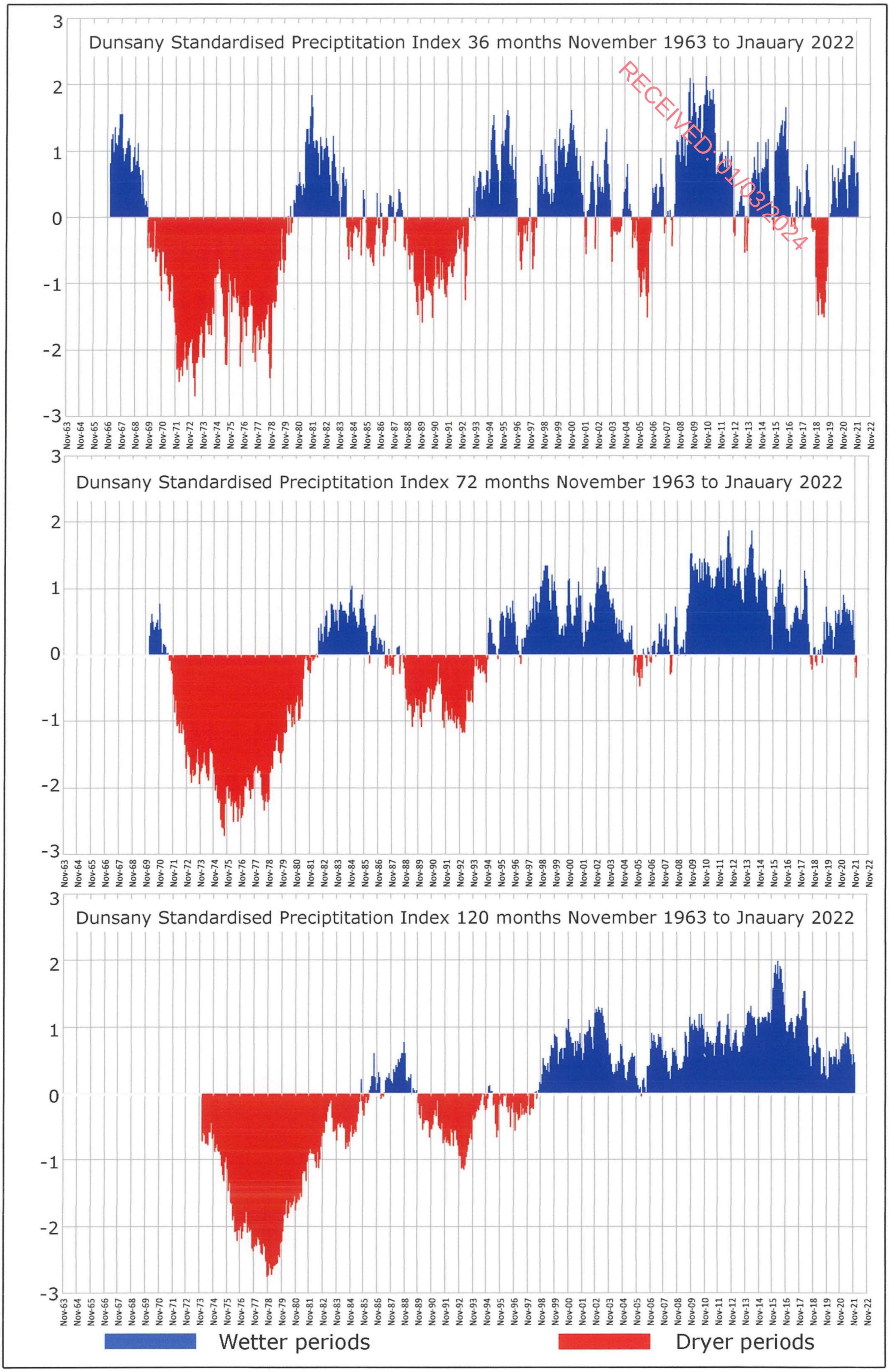
It can be seen that the 3 month SPI shows the very dry period that lead to the absence of flow in the winter of 2016-17, and the beginning of the drought that lead to no flow in the winter of 2021-2022. But the 3 month SPI also shows a very dry period in mid 2018 that appears to be sufficiently intense and prolonged to suggest a similar lack of flow in the winter of 2018-2019. It can be seen in the long hydrograph in Figure 2.19 that there was flow for about two weeks at the end of March 2018, seemingly in response to prolonged and heavy rain in early March 2018. Therefore, though the 3 month SPI shows that there was a drought and correctly predicted that the flows from the Well would be small and short-lived, the groundwater system and levels responded in a few days to a short period of significant rainfall.

In other words, several red negative columns shown together on the 3 month SPI graph do not necessarily mean that the Well will not flow in that year, or that water levels will not recover shortly after the end of the drought.

Looking at the positive (blue) SPI columns, the graph shows that the years when Sarah Blake was monitoring water levels were more wet than dry, and similarly during our measurements in 2019. 2020, 2021.

Overall, since 2014 there have been two prolonged wet periods and three drought periods. This is seen more clearly in Figure 5.44 and 5.45, which are the running average SPIs for 6 month and 12 month periods

Figure 5.46 Dunsany Rainfall 36 month 72 month and 120 month SPIs



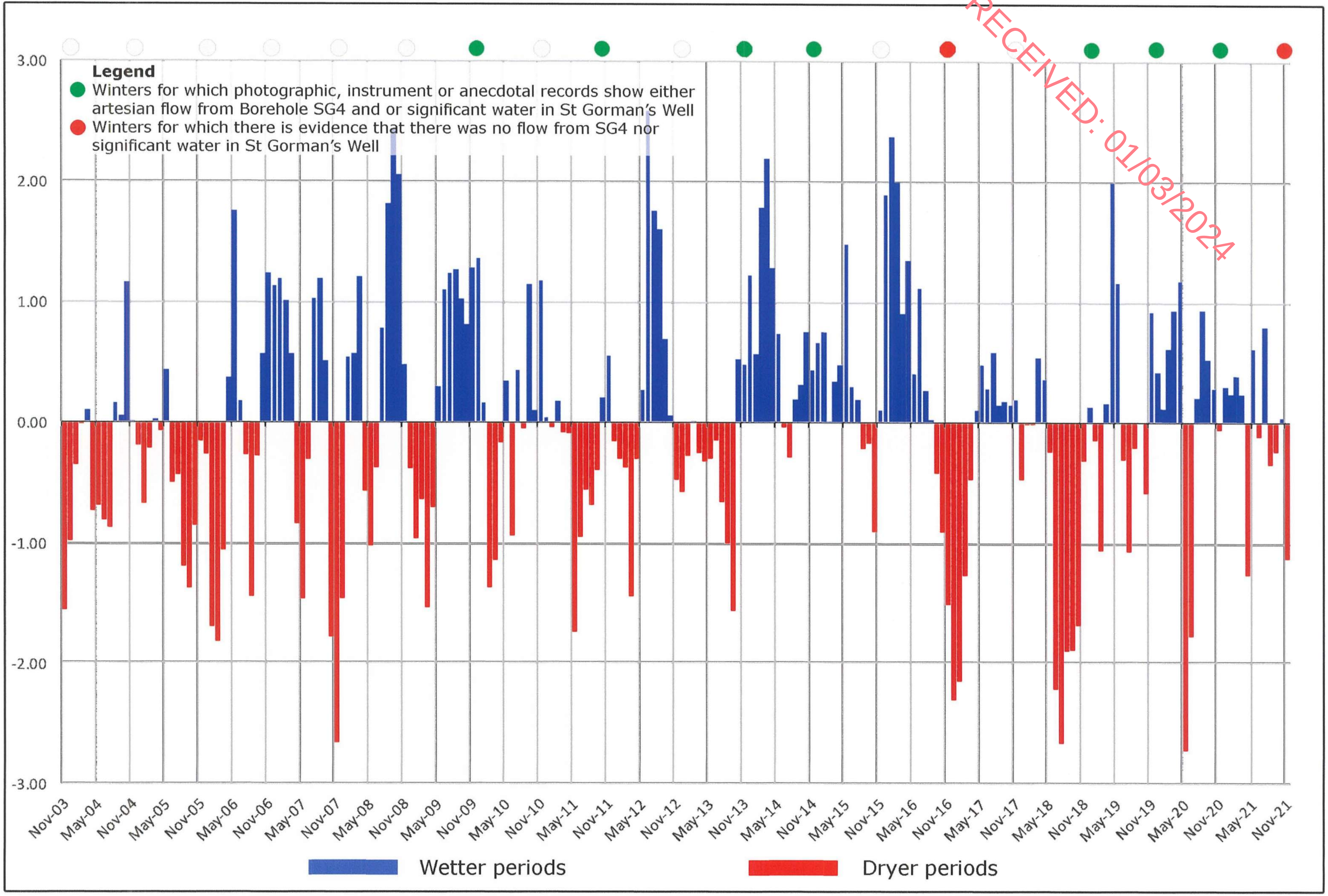


Figure 5.47 Enfield 3 month SPI (Standardised Precipitation Index)

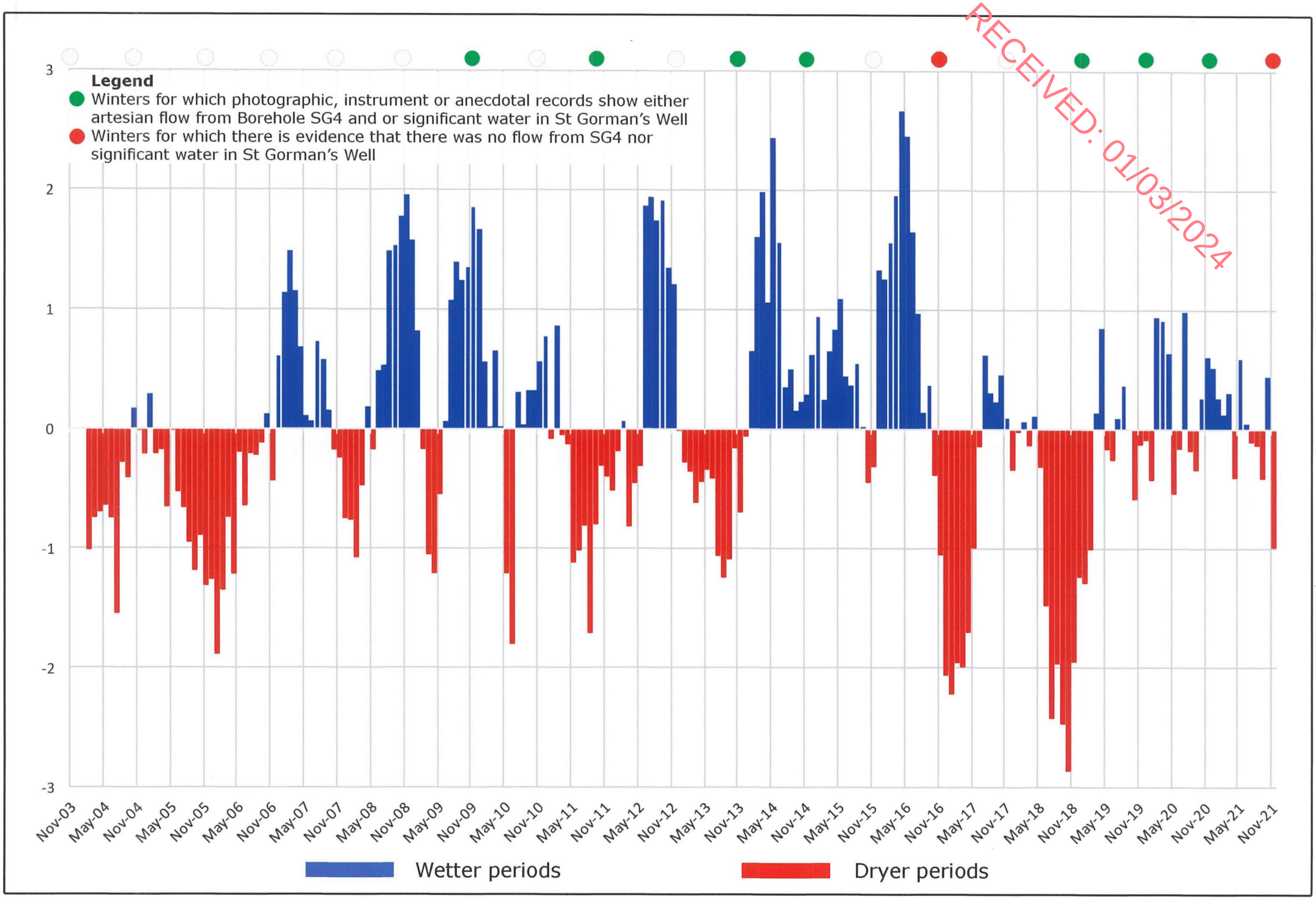


Figure 5.48 Enfield 6 month SPI

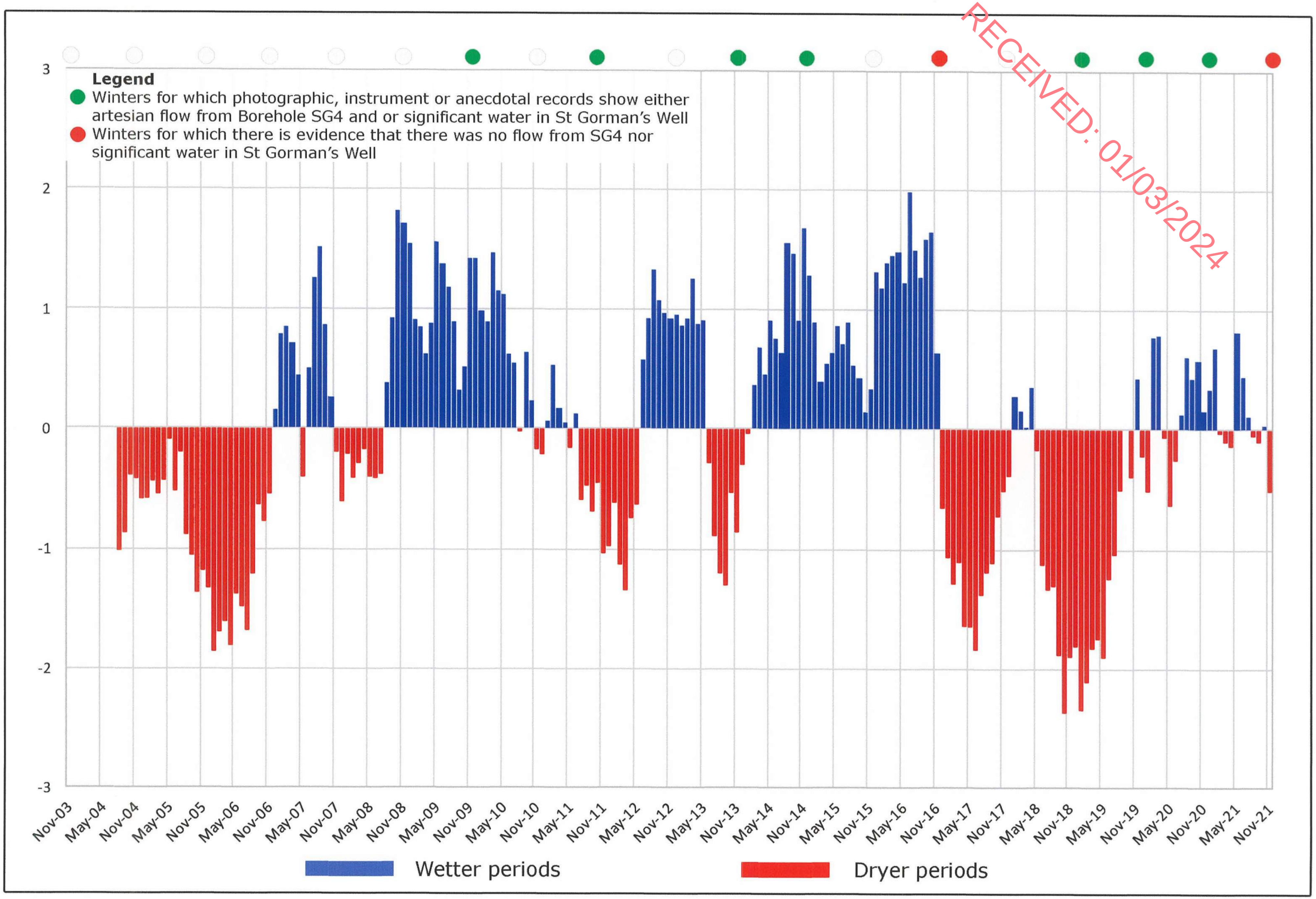


Figure 5.49 Enfield 12 month SPI

The 12 month SPI clearly picks out the long term drought in the 1970s and contrasts it with the much wetter period in the early 1980s during the Minerex study. It shows the much drier period in the late 1980s when Frank Murphy was doing his thesis. It shows the very wet period in 2008-2010 whilst Tobin were studying the Longwood water supply borehole. November 2009 was a memorable month of flooding across the country when it rained nearly everyday through out the month. This unusual rainfall is clearly shown in the SPI for 12 months.

There was one significant wetter period and one significant drought period in the three years between the end of Sarah Blake's early instrument monitoring of SG4 and Sarah's later monitoring, that started in August 2018.

On a 12 month running average, in the last six years there have two pronounced wetter periods and, including 2021-2022, three very pronounced drought periods.

Figure 5.46 shows three Standardised Precipitation Indices on a single page, to illustrate how the big shifts in rainfall pattern can emerge with longer time intervals. All three SPis show the same pattern, but it is most clear in the 120 month or 10 year SPI. This graph shows the overall dryness developing in the late 1960's and carrying on through the 1970s. Notice that the first SPI is for 1973 and illustrates the overall dryness of the previous 10 years. At the other end of the graph the last SPI shows that the 10 years 2012-2022 was wetter.

All three SPI graphs in Figure 5.46 show that it was becoming less dry by the mid to late 1990s and since then the long term averages of 3, 6 and 10 years show predominantly wetter periods. These three graphs are another way of illustrating the trend of increasing rainfall observed by Met Éireann, and which, with further global warming, their models predict is going to reverse. The first signs of this may be seen in decrease in wetness in the last 10 years in the 120 month period SPIs.

Standardised Precipitation Indices are based on the length of the record at a particular station or rain gauge. I include three SPIs for the 19 year rainfall record from Enfield (Newcastle house).

As the Enfield record does not include the dry late 1960s and 1970s, recorded at Dunsany, the zero deviation line in the Enfield data is different and, in combination with the compressed horizontal scale, the wetter 3 month periods in recent years appear less frequent and pronounced. However, the Enfield data shows a pattern very similar to the Dunsany data.

The predominantly wet period from the winter of 2013 to the summer of 2015 when Sarah Blake was collecting instrument data from borehole SG4 can be seen more clearly in the 3 month and 6 month SPI graphs for Enfield in Figures 5.47 and 5.48, than the corresponding graphs for Dunsany.

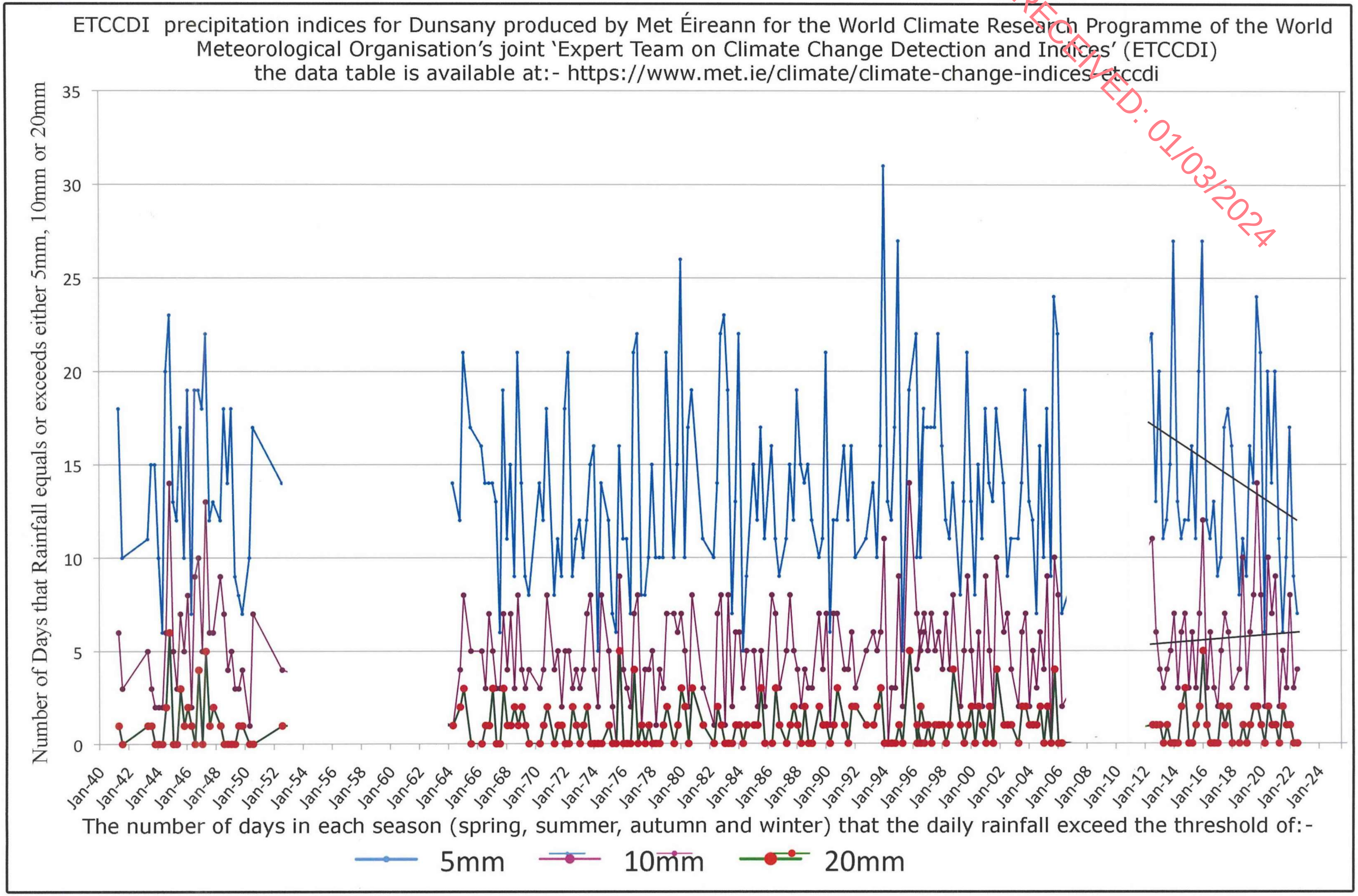


Figure 5.50 Met Éireann ETCCDI Dunsany Precipitation Indices 1940 - 2022

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The contrast between these years, and 2016, of overall wetness, and the overall dryness and droughts in subsequent years is further reinforced by the 12 month SPI graph for Enfield in Figure 5.49. The comparison of 12 month periods shows that the last six years have been dominated by two periods of relative drought.

There are other indices being used to detect the impact of climate change on precipitation. Met Éireann has produced a large table of core climate indices for the World Climate Research Programme of the World Meteorological Organisation (WMO). The WMO set up an Expert Team on Climate Change Detection and Indices (ETCCDI), who set out 27 indices for characterising climate change and climate variability. The data is based on daily values from met stations with long records, but in the table the results are given for the three month seasons Spring, Summer, Autumn and Winter. Dunsany is one of the stations given in the table. It can be accessed at https://www.met.ie/climate/climate-change-indices-etccdi.

I reproduce three indices used to assess the rainfall data from Dunsany.

Figure 5.50 is a graph showing the rainfall back to 1964 that has been used above in the SPIs, but it also includes earlier data from the 1940s and early 1950s. There is also a six year gap in the data between 2006-2012, presumably excluded by Met Éireann through some quality assurance protocol.

The graph shows the number of days that rainfall at Dunsany exceeded three different amounts in each season. The upper blue line in the graph is the number of days that the rainfall exceeded 5mm. The middle mauve line shows the days when rainfall exceeded 10mm and the green line with red dots shows the number of days with more than 20mm of rain.

The trend in the early and middle blocks of data appears to be relatively uniform though there are some seasons, such as in 1994 when there was a large amount of low intensity rainfall >5mm.

In the block of data from 2012, there appears to be a change. A trend line through the >5mm data shows a marked decrease in frequency of these rainfall events >5mm. A trend line through the >10mm rainfall events appears to show a slight increase in >10mm rainfall events. The number of >20mm rainfall events reached a high of 5 events in the winter of 2015-16, but thereafter never exceeded 2 in any season.

Figure 5.51 shows the data from 2012 up to the end of August 2022. The significant downward trend in the number of days where the rainfall exceeded 5mm is clearly evident, suggesting a change in the nature of rainfall events over the last 10 years. As noted before, there appears to be a progressive change taking place in the rainfall pattern observed at Dunsany.

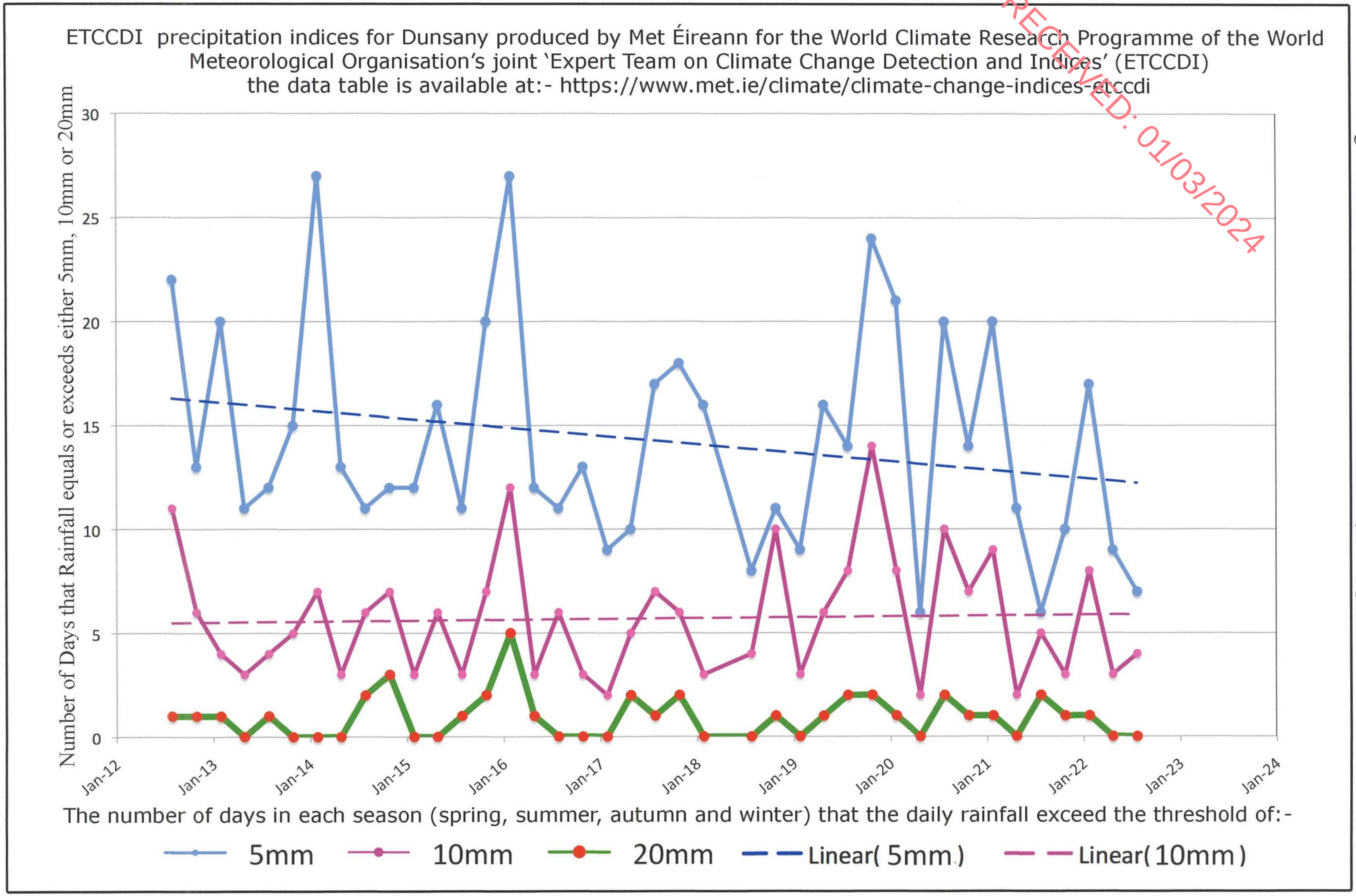


Figure 5.51 Met Éireann ETCCDI Dunsany Precipitation Indices 2012 - 2022

The rainfall amounts and their distribution provide the starting point for recharge to the groundwater system below the soil layer. The soil layer is subject to the removal of moisture by both evaporation, and water taken up by plants and transpired through the leaves into the atmosphere. The two combined are referred to as evapotranspiration. If the soil is at field capacity, rainfall can pass through the soil and percolate down into the subsoil and the rock below, but if there has been insufficient rain to meet the potential evapotranspiration from the soil and plants, a moisture deficit can build up in the soil. When it next rains part, or all, of the rain is absorbed by the soil to make up up the soil moisture deficit. Therefore, the soil moisture deficit is a way of estimating the potential for rainfall to percolate through the soil and recharge the groundwater system in the overburden and the bedrock. The soil moisture deficit is calculated by Met Éireann for three soil types at each Synoptic Weather Station. It is the difference between the rainfall and the evapotranspiration. The three soil types are well drained soil, moderately drained soil and poorly drained soil.

Figure 5.52 shows the soil moisture deficit data for Dunsany from 2011 to August 2022 for a well drained soil. Dunsany started calculating soil moisture deficits in 2011. The data for a well drained soil was chosen for the simplicity of a single illustration, and because recharge into the groundwater system is most likely to take place through the well drained soils in the area.

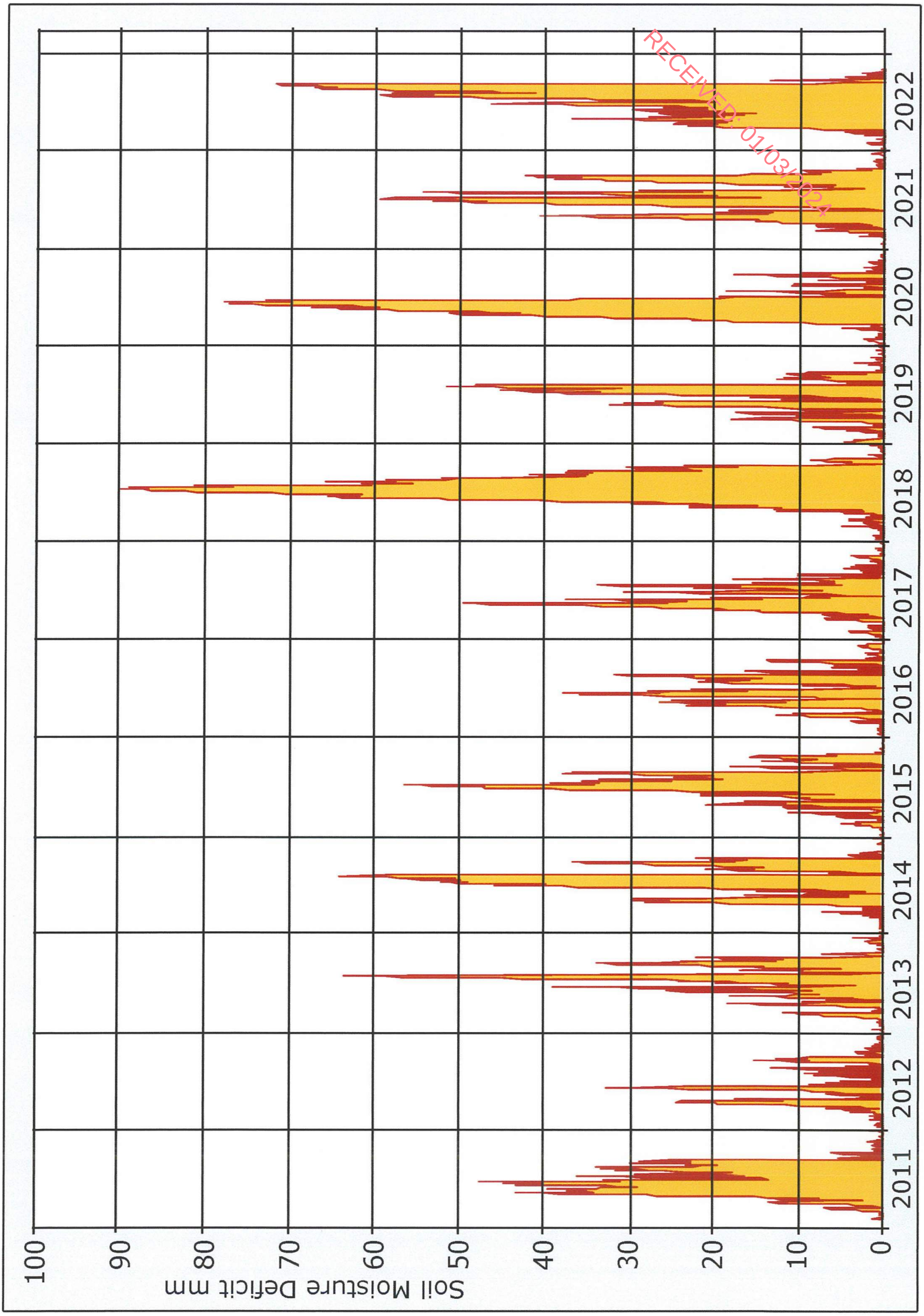
Figure 5.52 shows that there is usually no soil moisture deficit in late autumn and winter months. A soil moisture deficit usually starts to develop in late spring and rises to a peak deficit in summer.

The interesting feature of the soil moisture deficits, shown in the figure, are the relatively small peaks in the deficit in the first seven years of the record, and then in 2018 a major peak followed by two more years of high peaks in the following four years. The high peak in 2018 started with prolonged dry weather in early summer and though there was adequate rainfall in late summer and autumn to recharge the groundwater system, this rainfall first had to replenish the moisture deficit in the soil. This is why the recharge to the groundwater system was low in the hydrological year 2018-2019 and St Gorman's Well and borehole SG4 only flowed for a two weeks at the end of March in 2019.

The years shown in the graph in Figure 5.52 correspond to most of the 12 consecutive years when Ireland has had higher than 'normal temperatures'.

The pattern of soil moisture deficits over the last 11 years adds to the impression that Met Éireann's models predicting that Ireland's future climate will have less rainfall, in particular in spring, summer, and autumn is beginning to take place.

Figure 5.52 Dunsany Daily Soil Moisture Deficit in Well Drained Soils



A simple way of assessing this is to calculate and plot the accumulated rainfall over the course of each rainfall record. Met Éireann, and other researchers into long term rainfall trends, have observed that rainfall is increasing across the island, but this is not uniform. They have found a trend that towards the east and south east the increase is less or very slight. In other words there appears to be an east west difference in response to the early phase of climate change that has been observed over the last 20 years. The predictions are that the next phase is going to see a larger difference and the decrease in rainfall in the east and south east is going to be more marked than in the west.

Figure 5.53 shows the accumulated rainfall for Mullingar since 1973. If rainfall does not change significantly then over a long period the minor changes should be evened out and the line of the data will be a straight line. A straight line shown in red can easily be drawn through the Mullingar data, particularly the middle section between the mid 1980s and 2004.

When the line is projected back to the origin in 1973 it is noticeable that the dry years of the mid 1970s cause the blue line of the actual data to dip below the red line.

It can be seen that at the other end of the graph the blue line of actual rainfall slowly diverges upwards from the red line, reflecting an incremental increase in rainfall. It can be seen that by 2022 the difference between the accumulated actual rainfall, and the predicted rainfall if the historic rainfall had continued, is about 1,250 mm.

This graph is another way of showing how the average rainfall at Mullingar has increased by about 80 mm per year in the last 20 years, but the advantage of this graph is that it shows when the increase in rainfall started to happen. It appears to have started in 2006-2008. In other words, it seems to be a recent change.

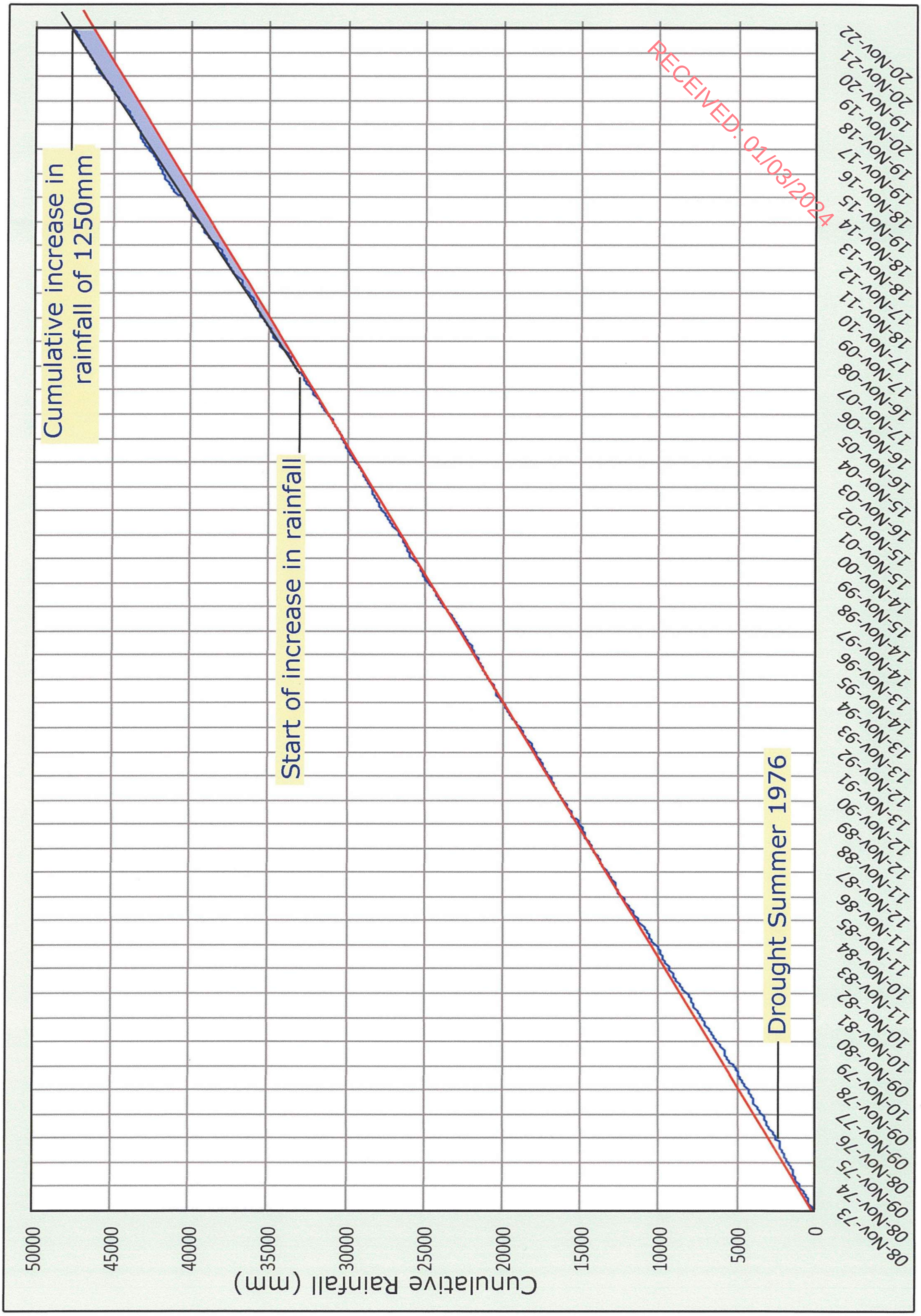
Figure 5.54 shows a different trend. It shows the accumulated rainfall for the new synoptic weather station at Dunsany that started recording in 2006, along with the accumulated rainfall for Enfield. The Enfield gauge that started recording in 2003, but the accumulated rainfall has been calculated from the same starting point as Dunsany in 2006.

The length of the rainfall record is shorter than the Mullingar record, and therefore there are more irregularities in the actual data line, and it is more difficult to draw a straight trend line through these data.

The divergence of the two lines of actual data shows how Enfield has a slightly higher average rainfall than Dunsany.

Drawing a red trend line though the early data, it is possible that the slope of this line represents the equivalent of the increasing rainfall seen after 2006-2008, in the Mullingar record in Figure 5.54. However, it is notable that after the autumn of 2016 both rainfall data blue lines diverge

Figure 5.53 Mullingar - Cumulative Monthly Rainfall from 1973 to 2022



from the red trend line, and show that the rainfall is starting to decrease. By mid-summer in 2022, the difference in cumulative rainfall at Enfield seems to be a reduction, or deficit, of about 800mm over 6 years. This is about 130mm per year or about 14%. The corresponding deficit for Dunsany is smaller; about 500mm over 6 years or about 80mm per year or 9%.

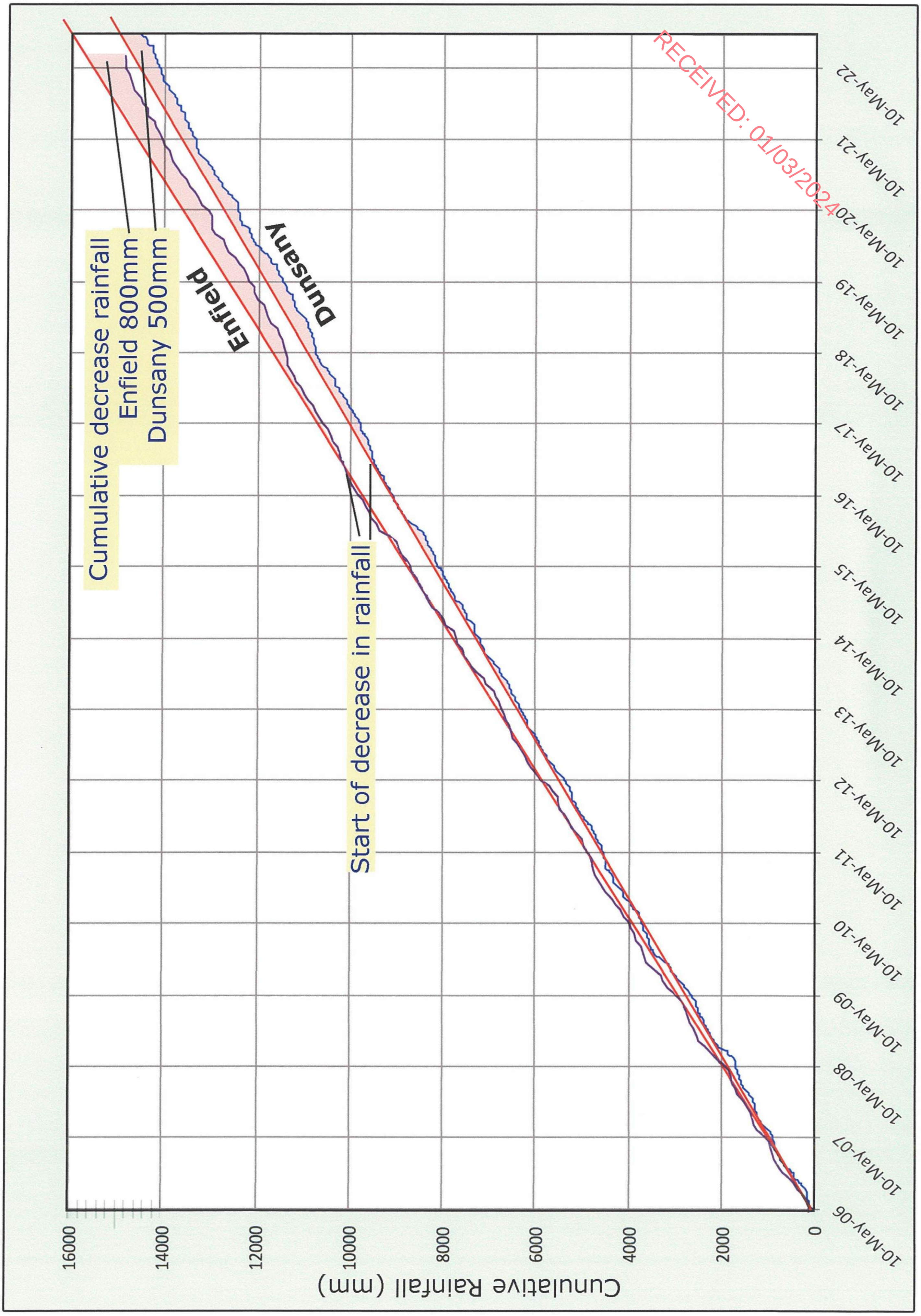
I have plotted similar cumulative rainfall graphs for stations further east, such as Phoenix Park, Casement and Dublin Airport, and there is either no significant deviation from the long term trend line or a slight increase. Therefore, it appears that this area of south Meath is unusual in that the predicted effects of climate change on rainfall appear to have started in advance of other areas. (On a lighter note: a local farmer in Rathcore told me two years ago, that in recent years, he had noticed that when he was waiting for much needed rain in summer, he could see it raining elsewhere, but the heavy rain clouds always seemed to avoid his land and the general Rathcore area. The data suggest there may be truth in his observation.)

I have looked in detail at rainfall because it is the source of recharge for the groundwater system. I focussed on the rainfall because the data strongly indicates that the volume and timing of rainfall is changing. It appears to be a rapid change and a significant change. The data looked at in different ways indicates that the last 6-10 years are part of a change-over period, or a major period of flux. There has always been variability in rainfall, even in Ireland, which has hitherto been known for a stable cool temperate moist climate, but the contrast between the rainfall total in the hydrological year 2019-2020 at Dunsany (1017mm), and the year 2021-2022 (681mm) is perhaps a measure of a change that is taking place now.

When trying to find an answer for the reduced water levels and flows from St Gorman's Well and SG4 in recent years, it is apparent that changes in timing and a reduction in the rainfall amounts would have had a significant effect on the recharge getting into the groundwater system. The data is showing that the vital input of rainfall is diminishing. The quantities when described in millimetres of rain may appear small, but when these amounts are translated into volumes over a modest area of say 10 square kilometres, the volumes are large. For example, 100mm of rain over 10 square kilometres is the equivalent of 1million cubic metres of water or, if spread out evenly throughout the year, the equivalent of 2,740 cubic metres per day. This volume, for context, is the equivalent of the water supply demand from a town of 10,000 to 15,000 people.

Whilst the change in rainfall input to the groundwater system appears to be a factor that could account for the reduction in flow from St Gorman's Well in recent years, it is just one side of a water balance. It is important to consider the abstractions and losses from the groundwater system on the other side.

Figure 5.54 Enfield & Dunsany - Cumulative Monthly Rainfall from 2006 to 2022



5. 5 Abstraction of Groundwater

Groundwater is found in the overburden tills and sand and gravel deposits, the thick weathered limestone zones above the hard bedrock, and in the underlying different limestone bedrocks and the karst solution weathered conduit systems within them.

All the houses and farms along the roads surrounding the low valley extending north east from Rathcore quarry to the river Blackwater have groundwater supplies. There is no public piped distribution system to the houses and farms. They each have one or more shallow dug wells or boreholes. New houses have been built in recent years, and they and the older houses and farm houses probably use more water than in previous years. There are more than 90 houses and farms along the roads surrounding the valley. If on average each house and farm house uses 1,000 litres per day, the total annual abstraction of groundwater would be 32,850 cubic metres a year. This total is an estimate to provide an example of the order of magnitude of the domestic water abstractions for comparison with the other larger abstractions described below. The increase in the volume of water abstracted in recent years is probably not significant in the context of falling water levels

The abstraction of water for agriculture and livestock is probably small because a large proportion of the land is used for tillage. The cattle on the fields of pasture gain much of their water from the grass, water troughs and access to streams or drains. Though agriculture uses water for spraying, and for cattle in dry periods and over winter in barns the volume has probably not increased significantly in recent years, sufficient to cause a fall in groundwater levels with an impact on flows at St Gorman's Well.

Gordon Elliott Racing at Cullentra House Stables has expanded considerably in recent years. The water supply appears to come from three low yielding boreholes and two wide diameter dug wells. Water is used for watering the horses and for hosing them down after they have been exercised. There is also a large in-door swimming pool for the horses. No record is kept of the total amount of water used, and the number of horses and their water requirements vary during the year. During a site visit, I estimated that the enterprise uses in the region of 30 cubic metres of water a day (approximately 11,000 cubic metres a year). Though the use of water has increased in line with the expansion of the enterprise, the amount of water abstracted is unlikely, by itself, to have lead to a significant reduction in groundwater levels.

The Longwood public water supply comes from two boreholes at the north western end of the low valley, as described earlier. The caretaker's recollection, and the records at the pump house, show that the demand for water from Longwood has not increased substantially during the last 10-15 years. The only change, as described earlier, is that the second borehole was drilled and completed in 2011. This borehole draws water from the Waulsortian limestone. The original borehole is believed to obtain most of its water from the gravels above the Lucan limestone. Both boreholes overflow in both summer and winter when they are not being pumped. I estimated that the combined pumping and overflow volume in the middle of summer in 2021 was about 500 cubic metres per day. In winter the artesian overflow will be much greater, but taking the minimum summer estimate as a base, it would seem that the Longwood boreholes are taking, or letting flow about 182,500 cubic metres of water a year. During winter the artesian overflow could be an additional 500 cubic metres a day or more. The pipework and concrete channels installed by the County Council to take the overflow from the wellheads of the two boreholes appear to have been designed to take even larger flows.

The first borehole was pumped to meet the varying demand from Longwood town over a 24 hour period. It was probably pumping continuously during the day and at times of peak demand in the evenings and only off for brief periods. This pumping would have drawn down water levels below the top of the casing, and there would be no artesian flow. Water levels in the borehole recover very quickly after pumping. Therefore, artesian flow could could take place at times during the night when demand was low.

The commissioning of the second borehole has made a significant difference. The two boreholes are now operated alternately. The pumps in each hole are on for 12 hours and off for 12 hours. This means that each borehole is releasing water by artesian overflow into the ditch for 12 hours a day.

In addition, each borehole is releasing artesian flow when demand is low and the pump is off during the 12 hour duty cycle.

It would be thought that pumping from either borehole would lower the water level or artesian pressure in the non-pumping borehole, and prevent artesian flow from the non-pumping borehole. However, my observations at the time of drilling and in July 2021 found that the 'interference effect' between the two holes was not noticeable. The boreholes are sufficiently far apart, and are drawing water from two separate systems.

The second borehole drilled in 2011, has a deep cement grouted pump chamber casing that prevents the borehole from drawing water from the upper confined gravel aquifer. The second borehole draws water primarily from the Waulsortian limestone karst conduits.

The first borehole is drawing water primarily from the gravel aquifer and and a smaller amount from the Lucan dark grey limestones and shales. Therefore, it appears that by a combination of borehole construction and distance of separation, the interference between the two holes is small.

The unintentional impact of the second borehole has been to at least double the artesian flow to waste from the site. Therefore, together the two holes are draining artesian water from two parts of the groundwater flow system down gradient of St Gorman's Well.

The pumping and artesian flow from the second borehole may have had greater impact, because the flow is coming directly from the Waulsortian limestone groundwater system that sustains St Gorman's Well.

It is notable that St Gorman's Well only flows for brief periods in winter, whereas the evidence from July 2021 is that both Longwood boreholes have artesian flow throughout the summer as well as the winter.

The development of the second Longwood borehole may have had a significant impact on water levels (artesian pressure) in the Waulsortian limestone groundwater system in the last 11 years.

Rathcore quarry has a shallow sump at the south western corner of the quarry that is used to collect water if it starts to pond on the floor of the quarry. A pump lifts water from the sump up over the lip of the quarry, and down into a large settlement pond. The water flows from this pond through a hydrocarbon trap into a large constructed wetland or reed bed.

The system works well, and clear good quality water flows out of the reed bed into a 'V' notch weir chamber. After the weir, the water flows through a pipe north under the road and under the field on the other side of the road. The water flows into a ditch, and then on into the system of drains maintained in part by the Boyne Arterial Drainage section of the Office of Public Works.

There is an Ott pressure transducer in the 'V' notch weir chamber that automatically records the water pressure on the instrument's sensor in the chamber, upstream of the 'V' notch. The Ott instrument has been measuring the water pressures every 15 minutes since 2014.

The Ott instrument's memory is downloaded at monthly intervals by Kilsaran. Kilsaran use an algorithm, compiled by an outside contractor, to take the water pressure readings and convert them first into water levels, and then into water flow over the weir. The instrument and the system appeared to work satisfactorily.

During the long pumping test in 2020, we used flow meters on each borehole to provide immediate flow information, with which to monitor and as necessary, adjust the pumping rates. Initially, we were pumping onto the quarry floor, but when we connected the boreholes direct to the settlement pond, we noticed that the borehole flow meter rates appeared to exceed the flow rates being measured by the Ott instrument in the 'V' notch weir chamber.

We guessed that there might be an error in either the calibration of the Ott instrument or the algorithm for converting pressures into flow rates. We could not stop the pumping test for long enough to let the settlement pond and the reed bed drain fully in order to get a flat water level behind the 'V' notch weir, and then down load the corresponding Ott data. Eventually, during dry weather in the spring of 2021 we got conditions where we could check all parts of the 'V' notch set up.

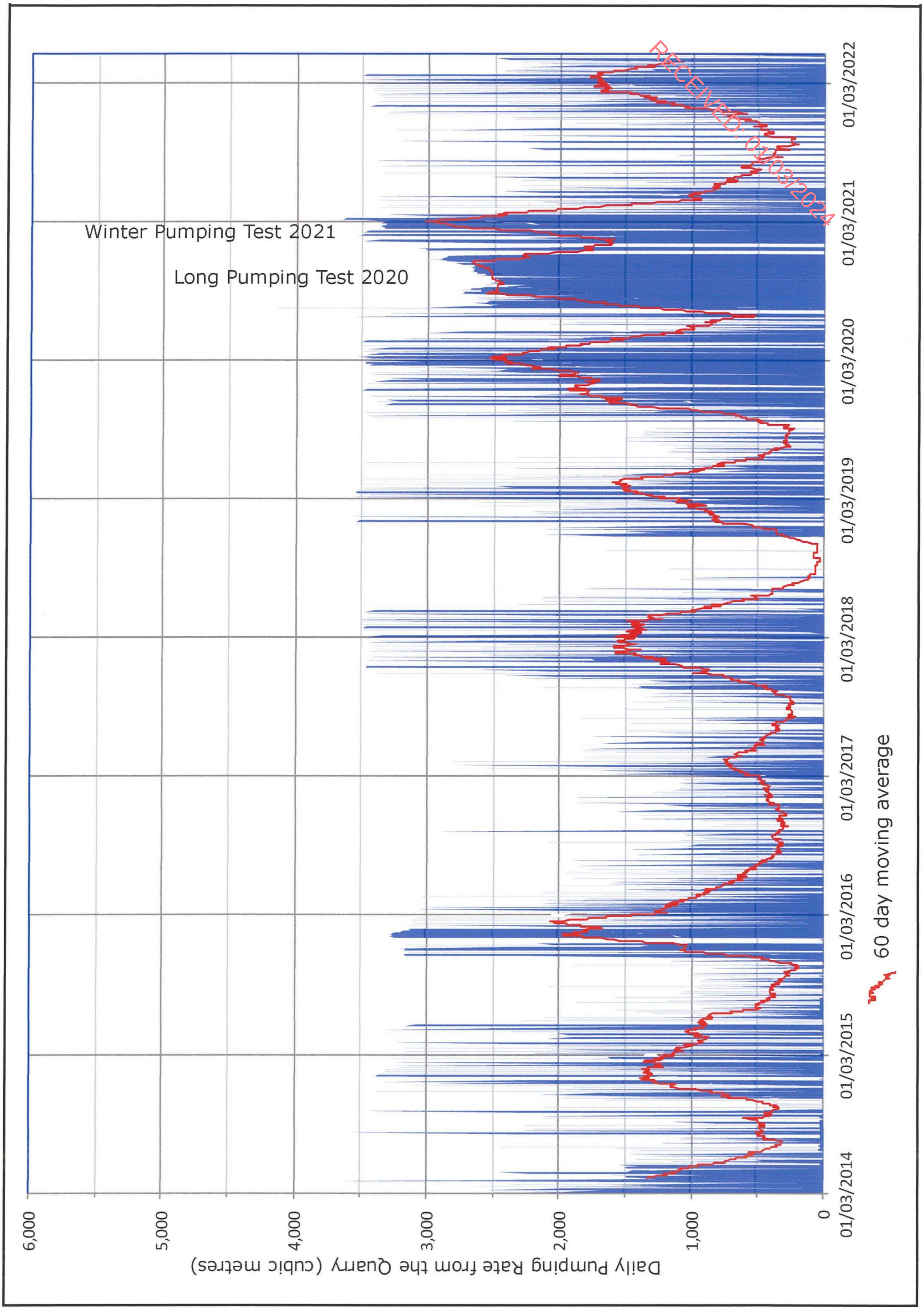
We found that either the instrument position relative to the base of the 'V' notch had been incorrectly measured, or that when the instrument had been taken out for servicing, it had not been put back in the original place. For whatever reason, we found that the instrument was higher above the floor of the chamber, and higher relative to the bottom of the 'V' notch, with the result that the constant in the algorithm for calculating the flow was incorrect by 4.5 centimetres. The instrument was producing accurate raw data, but an incorrect value in the algorithm meant that the flow was being miscalculated. The actual flows were greater than had been recorded.

When we measured the position of the instrument and used the revised constant in the algorithm to recalculate the flows during the pumping test, we found that the recalculated flows in the 'V' notch weir matched the flow rates that we had recorded from the flow meters at the borehole wellheads.

Kilsaran do not know whether the error occurred at set up, or whether it occurred when the instrument was re-installed on one of the several occasions when the instrument was serviced. Kilsaran has taken a conservative approach, and assumed that the error was at the original set up in 2014, and hence they have re-calculated all the historical flows back to 2014. 4.5 centimetres is a small amount, but a 4.5 centimetre difference in the level of water flowing over a 'V' notch weir makes a big difference in the calculated flow rate. As examples; a level of 5cms over the weir equates to a daily flow of 67 cubic metres per day. Whereas a level of 9.5cm equates to 336 cubic metres per day. 15cm equates to 1,043, whereas 19.5cm equates to 2,006 cubic metres per day.

The pump in the sump in the quarry is only operated when needed. The pump is powered by a stand-alone generator. Because generators can be unreliable, the pump is usually operated during working hours on week days, but sometimes it is left on overnight. Sometimes it is operated when the quarry floor is dry, but heavy rain is forecast for the coming days. In these circumstances the quarry staff are pumping levels down in order to make space for the anticipated rainfall.

Figure 5.55 Daily Flows over the Rathcore Quarry 'V' Notch Weir



The floor of the quarry is made up of a layer of loose shattered and crushed rock. Rain falling onto this layer immediately flows into the large pore spaces between the pieces of rock. It then flows slowly towards the sump through the layer of broken rock on top of the solid rock, if the water level in the sump is lower than the water level in the broken rock. Therefore, the pump in the sump is used to create a gradient to make water flow towards it through the broken rock.

During the summer the quarry is usually dry and there is little or no water in the sump. The quarry floor is above the level of the summer water table. However, the sump and the zone of shattered rock is sometimes full in summer after a heavy rainfall event.

For example, a 20mm fall of rain directly onto a 10 hectare quarry floor is the equivalent of 2,000,000 litres of water. This can make working conditions on the quarry floor difficult.

Over the last five years, there has been a concerted effort by the quarry staff to try to drain water towards the quarry floor from the hard surfaces and stock piles of overburden around the quarry excavation. They have dug drains and built small dams and berms, in order prevent run off leaving the site, in particular, to prevent water flowing out onto the public road. This conscientious work to bring all rainfall runoff into the quarry floor has meant that the volume of rainwater pumped from the sump, and through to the 'V' notch weir has progressively increased.

In winter the water table rises above the quarry floor. The water level monitoring data from core hole D3 (a monitoring point that is well connected to the cave system under the northern end of the quarry) indicates that the winter water levels can rise briefly to 2.5-3.0 metres above the quarry floor.

Therefore, in winter the sump pump is removing groundwater as well as rainfall.

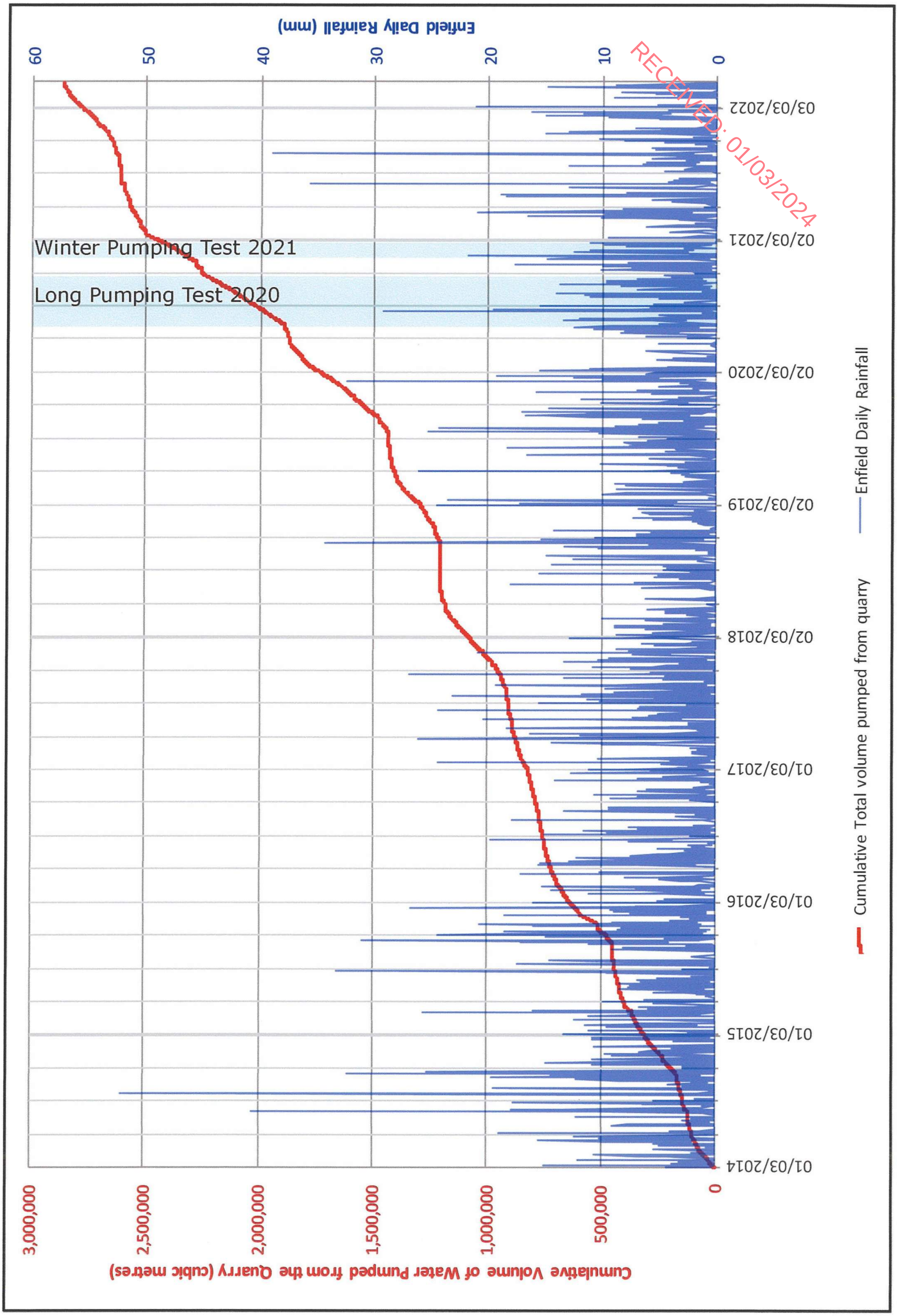
Figure 5.55 shows the corrected daily flow rates over the 'V' notch weir from 2014 to May 2022. It shows how the flow varies and that pumping, and hence flow, does not take place every day.

In summer the pumping is generally less frequent and the flows are much less. In some winters there is a lot of pumping and in others less.

In 2020 and the early part of 2021, there were borehole pumping tests when flows from the quarry were at a high rate and continuous. In the later part of 2021 the sump pump was used much less frequently, but after January 2022, there was a staff change in the quarry and the pump appears to have been operated more frequently.

The graph also shows a 60 day moving average (in red) for the flows from the quarry. This moving average shows that in all summers the average volume is roughly 50 to 400 cubic

Figure 5.56 Cumulative Daily Flows over the Quarry 'V' Notch Weir and Enfield Daily Rainfall



metres per day. In winters (excluding the periods of borehole pumping tests), it ranges on average from 1,000 to 2,000 cubic metres a day.

Figure 5.56 shows the daily rainfall recorded at Enfield, and the cumulative quantities of water flowing from the quarry. The time periods for the two major pumping tests are also shown on the graph.

It can be seen that the cumulative volume pumped rises after the main concentration of winter rainfall events, but also how the volume increased after 2018-2019 when many site works were carried out to try to bring all the rainfall runoff onto the quarry floor. The average daily total discharge from the quarry in the four years from March 2014 to March 2018 was 750 cubic metres a day which is close to the discharge licence volume. The steepest cumulative rise took place with the constant pumping during the long pumping test, and the heavy rain during the late summer and autumn of 2020. The average daily total discharge from the quarry in the four years from March 2018 to March 2022 was 1,130 cubic metres a day (including the water pumped during the two long pumping tests). Since July 2020 the discharge licence for testing has been 6,000 cubic metres per day.

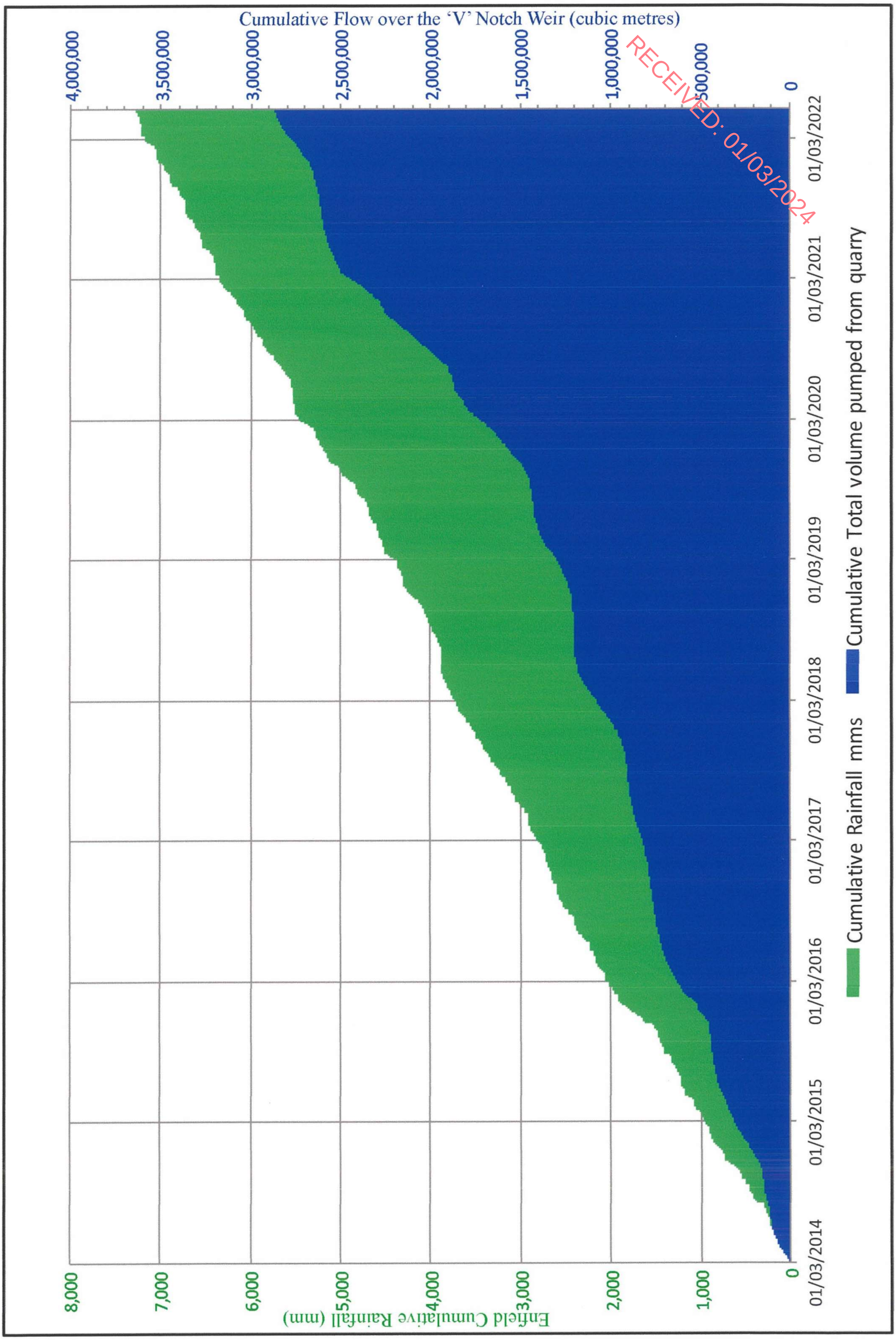
Figure 5.57 shows the cumulative daily rainfall from Enfield and the cumulative volume of flow from the quarry.

It is important to note the different vertical scales on the graph. The scale for the flow is in cubic metres and the scale for the rainfall is in millimetres.

The objective of the graph is to show how the increased gradients in rainfall volume and volume of flow from the quarry follow a similar pattern but after 2018-2019 the slope of the cumulative flow from the quarry steepens, for the reasons described above.

Placing the two cumulative parameters on the same graph makes it easy to make rough calculations of the proportions of rainfall and groundwater pumped from the quarry, assuming that all rainfall onto the quarry is captured and pumped out of the quarry. This assumption is incorrect, but it is useful for the purpose of trying to give an idea of the amount of groundwater pumped from the quarry. The cumulative total amount of water pumped from the quarry reached 1 million cubic metres around the 1st March 2019. By the same date the cumulative rainfall total was about 3,800 mm. Assuming an open bare quarry area of about 10 hectares, this depth of rain would create a volume of 380,000 cubic metres of water. There is no allowance for evaporation of rainfall from the quarry, Therefore this example indicates that as a minimum, roughly two thirds of the water pumped from the quarry is likely to be groundwater.

Figure 5.57 Cumulative Rainfall and Flow over the Quarry ‘V’ Notch Weir 2014-2022



The proportion increases by March 2021. By this date 2.5 million cubic metres had been pumped from the quarry and the rainfall had been about 6,200 mm. The volume of rainfall on a 10 hectare quarry floor would have been 620,000 cubic metres, indicating that roughly 25% of the water leaving the quarry was rainfall and 75% was groundwater. If the quarry staff's efforts to direct water onto the quarry floor from the yard and stockpiles around the excavation are taken into account then the catchment area would increase and the volume of rainfall runoff would increase, perhaps bringing it back closer to 30%.

The purpose of these crude calculations is to show that the quarry is, and has been, removing groundwater for several years, and therefore would be affecting groundwater levels.

The removal of water from the quarry floor will affect the groundwater system in two ways. First, it is intercepting rainwater that would otherwise, under natural circumstances, have recharged the groundwater system. It is difficult to quantify how much recharge would have percolated down into the limestones if Rathcore hill was in a natural state with no quarry, because the slopes of the unexcavated hill were steep, and, as described in Chapter 2, there are yellow and chocolate brown clays lying above the limestone and below the sandy till. It is likely that if there was no quarry the amount of heavy rain getting into the ground and down through the low permeability clays would have been small.

It is interesting to reflect that the early part of the quarry operations consisted of stripping the overburden whilst at the same time the floor level of the quarry was 10 metres above the winter water table level. So, in the early part of the quarry's life the quarry floor was permanently dry, there was no need to pump groundwater, and exposing the bare rock made it easier for rainfall recharge to get into the karst cavities and directly down into bedrock groundwater system. In other words, in the early history of the quarry, the removal of the overburden and exposure of rock containing fractures and conduits, actually enhanced the recharge into the bedrock groundwater system, whilst perhaps reducing the recharge into the shallow overburden sandy till and gravel aquifer.

Another factor is that recharge into Rathcore Hill would have created a recharge mound of relatively high groundwater levels under the hill. This would have created the potential for groundwater to flow away from under the hill to the west and north west, but also to the east and south into the Lucan formation limestone. In other words, not all the rain that fell would have contributed recharge to the groundwater resources in the Waulsortian limestone in the direction of St Gorman's Well.

As can be seen, assessing the impact of keeping the quarry dry is complicated. However, it remains evident that since the quarry floor reached about 75 metres above Ordnance Datum the pumping from the sump has intercepted and removed rainfall that would have recharged the bedrock groundwater system. More so, pumping has kept the water level in the quarry below the winter water level in the limestone groundwater system. This has meant that when rainfall recharge has raised water levels in the system adjacent to the quarry, the water has drained towards, and into, the quarry. Therefore, the quarry pumping has been skimming off rainfall recharge from elsewhere when the water levels were higher than the level of the floor of the quarry. The water has not been lost from the Blackwater-Boyne catchment. It has been removed from the groundwater system and placed in the surface water system.

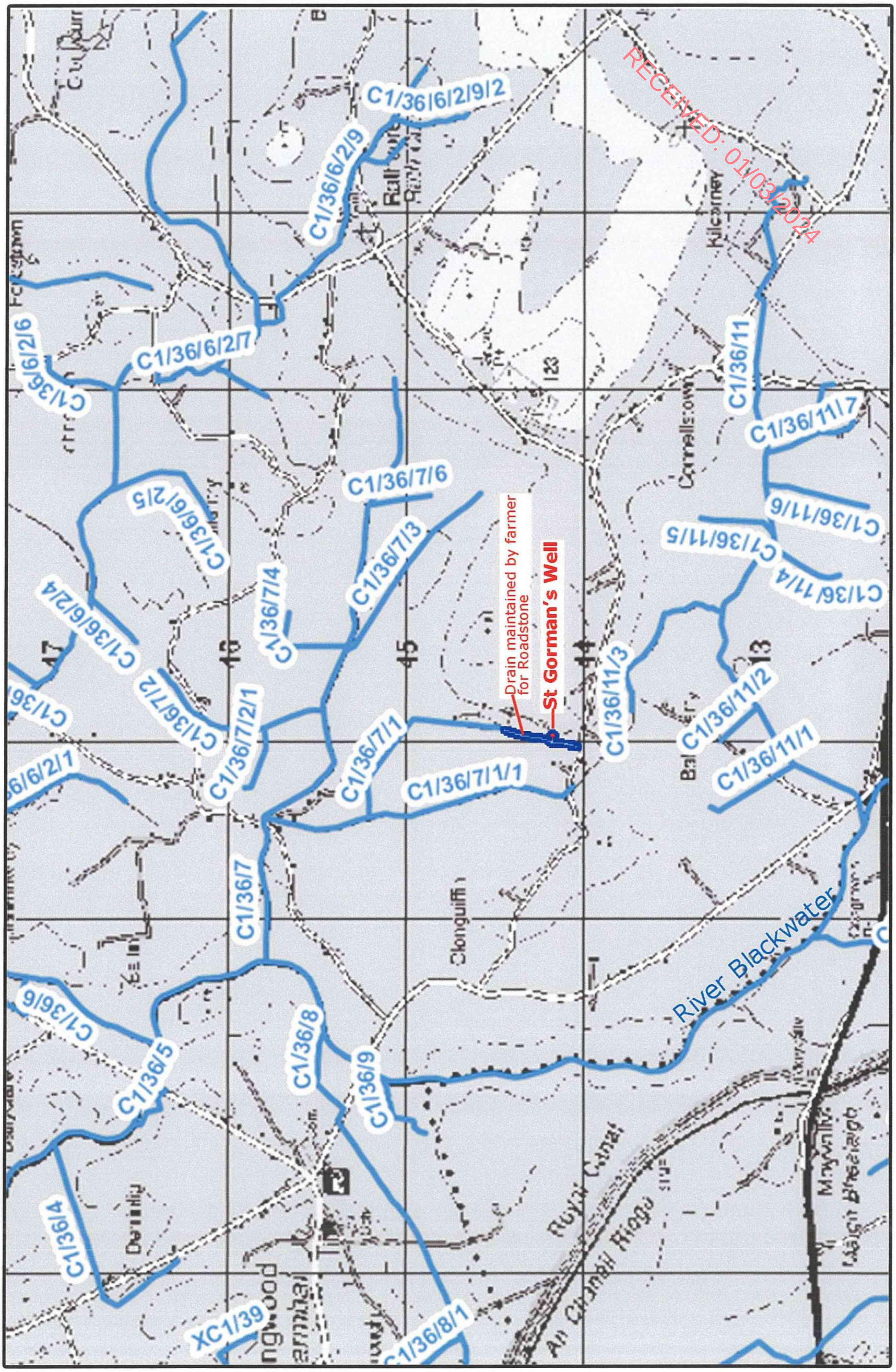
Overall, the pumping from the quarry has intercepted recharge that would have helped maintain groundwater levels and pressures in the karst conduit system in the area. This removal of recharge water is on average of the order of 1,000 cubic metres a day. The amount of groundwater removed by pumping or inadvertent loss of artesian water by the Longwood Water Supply boreholes is roughly 500 cubic metres a day in summer, and though it is yet to be established could be of the order of 1,000 cubic metres a day when artesian heads are higher in winter.

Therefore, there are two obvious abstractions at either end of the valley. One is intercepting water before it can flow through the system, the other is draining water away and lowering water pressures at the other end of the system. Both are likely to be contributory factors in the apparent reduction in water levels. However, it is important to keep in mind that the evidence from the water level monitoring started in 2006, indicates that water levels were already falling before the second borehole was commissioned at Longwood, and before the quarry started pumping.

Finally, there may be a small scale factor influencing water levels locally at St Gorman's Well. Groundwater rises to the surface and forms a spring when it cannot flow more easily through the ground. Therefore, when water levels rise in both the bedrock and the overburden, water emerges in the small depression that forms the Well and flows out of the Well through the grass, because it is easier to flow on the surface than through the sandy till above the limestone. All water flow is opportunistic. It will not take a difficult path when an easier pathway is available. Groundwater flow, like surface water flow only occurs when there is a gradient. The steeper the gradient the more pressure is exerted on the water in front by the weight of water behind. Water flow is driven by gradients and gravity.

The local factor that may have a bearing is that the immediate local base level for surface and shallow groundwater is the drainage ditch adjacent to the boreholes and the Well. This ditch,

Figure 5.58 River Boyne Arterial Drainage Scheme Drains



further to the north, was deepened by the OPW ("Board of Works") as a part of the Boyne Arterial Drainage Scheme. The Scheme was completed in 1986 after the Minerex survey of the Well, and after David Wilkinson had constructed the duck pond next to the Well. The drainage ditch adjacent to the Well is an extension of the Board of Works drain, and it has been excavated and maintained by contractors working for the tenant farmer who leases the lands from Roadstone.

The drains maintained by the Board of Works are shown in Figure 5.58. The drain linked to St Gorman's Well is "C1/36/7/1". I have drawn the drain extension up to St Gorman's Well on the map. The southern end of C1/36/7/1 is 70.7 metres above Malin Ordnance Datum (Personal communication from Robert Duncan, Boyne Drainage Division, Trim).

There are two main purposes for the drains. First, to make it easier for surface water to flow to the river Blackwater and then into the river Boyne. Second, to drain the land by creating a lower local base level and increase the gradient in the subsoil, to induce shallow groundwater to flow out of the ground, and into the drain, in doing so, to make the land around more workable and productive for agriculture.

The relative elevation of St Gorman's Well and the drain can be seen in Figure 5.38. The deepening of the drains has increased the groundwater gradient. The increased gradient has created the potential to increase the rate of flow from the shallow groundwater system into the drain. We know from our recent work and the work of Richard Langford and Tobins that warmer water is getting into the drain.

In other words, it is possible that as shallow groundwater levels build up in the overburden and upper limestone karst under and around the Well, there is now the potential for a faster flow into the drain than there had been in the past. Therefore, because the lateral drainage can be more rapid, the groundwater level may not rise as high in the Well as it had in the past.

This local factor is probably not a major contributing factor, but it may add to the impact of other more significant factors in the context of reduced levels and flow from St Gorman's Well.

Chapter 6. Conclusions and Recommendations

The previous sections of this report contain a large amount of information and interpretation. While they contain assessments of the specific information, they do not integrate the specific assessment into a broader set of findings.

The objective in the final section of this report is to bring together these findings within the context of questions that will be asked by various parties who may read this report.

Kilsaran will want to assess whether it is technically feasible to deepen the quarry. Groundwater is just one aspect of that assessment. If they decide that it is technically feasible then they will need to make a second decision on whether it is economically feasible. Finally, they will need to decide whether to prepare and submit a planning application.

If a planning application is submitted, then the planning authority and local residents will want answers for their questions on groundwater, and other matters. Finally, if and when a decision is made by the planning authority, the decision may be appealed to An Bord Pleanála. The Board may also want answers to various questions.

In the following text I will use the findings from the work to provide succinct conclusions that will try to answer the most obvious and potential questions.

Questions that need answering:-

1. Can the deeper quarry be dewatered, or will there be uncontrollable inflows of groundwater that will flood the quarry?

Yes the quarry can be deepened and dewatered. The evidence from the drilling and pumping tests showed that groundwater is primarily found in an ancient karst conduit system, with the conduit size ranging from small slightly widened fractures to much larger caves.

The conduits containing water are not everywhere, and they are not well connected to each other. The rock between the conduits is solid and does not contain conduits. All of the small and large conduits are partly or wholly clogged with yellow clay. The flow of water along the conduits is restricted by the shape and size of the conduit itself, and the proportion of the cross section of the conduit clogged with clay. The constriction controlling the flow can occur some distance away, and not just where the conduit is encountered by the excavation. Therefore, when the proposed deeper excavation encounters a water bearing conduit there would be a large initial flow of water and clay, but the rate of flow will be controlled by the groundwater gradient into the excavation, and the diameter of the smallest constriction in the shape of the conduit, perhaps some distance from the excavation. The evidence from pumping borehole 3 (the most productive borehole) showed that water levels could be drawn down in a matter of days at the appropriate pumping rate and the level held down and steady.

2. How much water will flow into the quarry?

The long pumping test in 2020 extended through a wet late summer, the autumn rains and into winter. The later winter pumping test was carried out at the time of the highest water levels in the winter of 2021. The highest pumping rate of 3,500 cubic metres a day achieved a drawdown of water levels to about 25 metres. I consider it probable that this is close to the maximum pumping rate necessary to cope with the inflow of groundwater, unless there is another completely separate karst conduit system that was not located during the drilling of the 52 exploration boreholes.

On the basis of the results obtained I would project that the pumping rate during the operation of a deeper quarry, including incident rainfall, will be of the order of 5,000-6,000 cubic metres of water a day or less.

3. Can the whole footprint of the quarry be excavated, or should work focus on one area first?

The evidence from the exploration boreholes, and the non uniform response of water levels in monitoring boreholes, during the pumping tests, indicate that the southern and eastern part of the quarry contains few, and less well developed, karst conduits than the north and north west part of the quarry. I think it would be logical to start quarrying in the southern part of the quarry and incrementally work northwards. Existing test boreholes 1 and 3 can be pumped to drawdown water levels in the north of the quarry in advance of the quarry operations extending into the northern part of the quarry.

4. Will the groundwater entering the quarry contain a large clay content?

Yes. When the quarry operations encounter a new water filled conduit, the initial flow will contain a large content of clay and sand, but our findings during the borehole development tests proved that the initial load of clay and sand in the water decreases significantly with time, and a near sediment free water can be obtained under constant pumping conditions. The large karst conduits contain clay and sand deposits, probably laid down during and after the last ice age. Though there is some soft easily disturbed clay and a minor amount of sand on the top of the layers of clay in the conduit, most of the clay deposits in the conduits seem to be tough, competent and stable. We had to violently airlift surge boreholes to create turbulent groundwater flow to break up the clay sediments into the large lumps of clay shown in the photograph in Figure 2.28.

5. Can the existing settlement pond cope with the dewatering flow?

No, an additional settlement pond is necessary. This had been planned already, and the land is available.

6. Can the stream or drain cope with the flow of sediment free water from the quarry?

Yes. A hydrological evaluation carried out by SLR in 2016 showed that the drains maintained by the Board of Works and the farmers have ample capacity to take the extra flow. This drainage system already has been shown to cope with similar flows from the pumping tests during the summer and winter of 2020-2021,

7. Will the dewatering of the quarry affect local shallow wells?

No - the shallow wells draw upon water perched in a sand, gravel and sandy till aquifer lying above the limestone bedrock, and separated from this bedrock by glacial clays. The monitoring of water levels during the pumping tests showed that there was no impact on the water levels in this perched overburden aquifer.

8. Will the dewatering during the operation of a deeper quarry affect the productivity of local deep boreholes?

Probably No. Unlike a shallow dug well, which draws upon perhaps just a metre of saturated aquifer, the yield of a deep borehole is rarely affected by a relatively small fall of the static water level. The yield of deep boreholes depends upon the characteristics and position or depth of the water filled cracks or conduits in the bedrock that are contributing water to the hole. If these water yielding fractures and conduits are located at depths of, say 20-30-40-60 or more metres below the static water level, then a drop in the water level by 5-10 metres, usually will have no effect on the yield of the borehole. The deeper fractures and conduits will still remain productive to sustain the borehole yield. If, on the other hand, the the open saturated water yielding fractures and conduits are confined to just the top of the bedrock, then there might be an impact.

The water level monitoring evidence in the hydrographs from 2006-2022 in Figures 4.3 – 4.10 showed a drop in water levels during the pumping tests in some nearby boreholes tapping the Waulsortian or Calp limestones. Borehole W1 due north of the quarry in the Waulsortian showed a rise in water levels during the test. Borehole W10 showed a drop of 2.5 metres during the test. The biggest drop to the south was seen in boreholes W12 and W13. There was a decline in the water level of about 2-5 metres during the late summer, but this was the same as in some previous summers, even before any water was discharged from the quarry.

9. Will the dewatering of the quarry affect the water resources of the wider area?

Yes, but not evenly across the area, or in every year. The quarry will intercept and remove a proportion of the rainfall that would otherwise recharge the Waulsortian groundwater system via conduits under the quarry. This happens already, The quarry dewatering also will withdraw groundwater resources from the conduit system and discharge this water into the surface water system; which is where the groundwater naturally flows.

However, though the borehole pumps were removing over 3 million litres a day during the long test in early winter, and the 43 day test in late winter, the recharge entering the limestone groundwater system from elsewhere more than compensated for this withdrawal. The recharge elsewhere was sufficient for St Gorman's Well and borehole SG4 to flow, and water levels rose in line with the normal winter patterns in boreholes and core holes adjacent to the quarry.

The amount of water pumped from the quarry will depend upon the amount of rainfall on the quarry area, and the amount of rainfall recharge to other parts of the karst conduit system. The recharge elsewhere will determine the groundwater level elsewhere and the gradient to the quarry, and hence the flow rate to the quarry. As recent data has shown, the rainfall varies from year to year, but there appears to be a change taking place in the rainfall amount and distribution, which adds further uncertainty.

10. Will the dewatering of the quarry affect the flow of water from St Gorman's Well?

The answer is both No and Yes.

Water flows from St Gorman's Well when the water table level in the immediate vicinity of the Well is sufficiently high. This now usually happens in winter. A long, high pumping rate test, approximately simulating dewatering of the quarry was carried out in the quarry in the winter of 2021 when the Well contained water and was overflowing.

The water level monitoring data showed that the pumping from the quarry had no effect on the water levels at St Gorman's Well. The well and the boreholes continued to flow whilst at the same time the boreholes in the quarry were being pumped at the maximum rate possible. The data showed that there was no direct effect of pumping on the flow from St Gorman's Well when the Well was flowing.

The earlier long pumping test in the summer, autumn and early winter of 2020 showed that pumping from the quarry will lower groundwater levels just in the summer when there is little recharge, water table levels are low in the St Gorman's boreholes and there is no water in the Well depression. In other words the pumping had an effect on water levels at the site at a time when water levels were low and there was no water in the Well and hence no flow from the Well.

However, pumping from the quarry will indirectly affect the groundwater level at St Gorman's Well. It will do this by intercepting, and hence reducing the recharge through the quarry floor into the middle depth limestone conduit groundwater system, and also by removing groundwater from this system.

The evidence from this investigation has showed that this removal of water at Rathcore was partially or fully compensated in autumn and winter of 2020-21 by the local recharge closer to St Gorman's Well, particularly the recharge into the overburden aquifer and karst limestone system under Ballinakill hill up gradient of the Well.

11. Where does the warm water come from?

It is groundwater that has gone down a deep karst conduit associated with a Cenozoic age fault to a sufficient depth to be warmed to about 20 degrees.

12. Where is the start of the karst conduit?

I don't know – but I expect that it is to the northeast or east northeast of St Gorman's well. It is probably local and therefore could be under Ballinakill hill but the catchment area under Ballinakill was probably insufficient to sustain large flows of warmer water in the past. The other prime potential source is across the valley where the Cullentry block of Waulsortian limestone is overlain by sufficiently elevated gravels. When the water levels rise sufficiently in these gravels then the hydraulic head may be sufficient to push water down a vertical conduit in the limestone and bring it to the surface at St Gorman's Well.

13. Could the origin of the warm water conduit system be at Rathcore quarry?

Hypothetically it could, because there are karst conduits under the quarry. However, there needs to be a water level difference between Rathcore and the Well to create a head of water to drive warm water down to great depth and then push it up to the surface. The groundwater levels at Rathcore quarry are naturally just above the level of the Well. So theoretically there could have been sufficient head in the past to drive the water. We pumped the water levels down in the quarry to 20 metres below the level of St Gorman's Well during the winter test in 2021, yet during this 42 day test the water levels in SG4 and the Well remained high, and the flow of warm water did not stop. This evidence shows that there is no direct link between lowering water levels in the quarry and a separate system that is driving warm water up to the surface at SG4. The pumping in the quarry did affect water levels in SG4 during the summer but this did not affect the temperature of the water in SG4.

14. What causes the spring at the Well to flow?

In detail it is very complicated, as described in Chapter 5, but in broad terms, the spring flows because rainfall recharge locally into Ballinakill hill raises the 'water table' in the upper limestone and the overburden aquifer. The Well does not flow if these water levels are low. Below the upper limestone conduit system there is a pressurised karst conduit system probably in the depth range 30-100 metres. This palaeo-karst system passes under the areas with very deeply weathered karst as is found in the shoulder or valley between Rathcore quarry and Ballinakill hill and under the shallow valley between Ballinakill and Cullentry. The clays and decomposed limestone in these weathered layers create a confining layer that pressurises the groundwater below and separates it from the phreatic or water table conditions in the sands gravels in the overburden. Finally, there is the third component which is the 'U' shaped deep conduit system that brings warm water to the surface when the head is sufficient. It appears that the recharge that raises the water levels in the cool shallow aquifer at St Gorman's Well, elsewhere raises the water levels at the start of the deep 'U' shaped conduit that brings up the warm water from depth. It is probable that the same rainfall recharge events in two separate places combine to make the Well fill and flow with warm water.

15. Does warm water come up elsewhere?

Yes - it may come up elsewhere. There is strong evidence from the pumping tests carried out on the two Longwood Water supply boreholes that the water there is above the normal level of 9.5-10.5 degrees. The temperature is above 12 degrees. Robbie Meehan's measurements of small springs along the Clonguiffin drain also show water with temperatures above 12 degrees. Therefore, the warm water coming to the surface may not be limited to just a 'U' shaped conduit feeding St Gorman's Well. There maybe other seepages coming up along the fault as it crosses the valley from northeast to southwest. The other explanation for the above average temperatures elsewhere is that warm water is coming up at St Gorman's and flowing out into the shallow limestone and the sand, and gravels, mixing with cooler water and then migrating down gradient through both the shallow limestone conduits and the over burden gravels towards the Longwood boreholes and the small springs along the drains in between.

16. Is the conduit system containing warm water active throughout the year?

It may be, but when there is no flow out over the surface, the upward flow, if it exists at all, is very small. It's as if the process of water moving down to depth and then rising in the area of St Gorman's Well goes into hibernation (albeit in summer). It becomes quiescent when there is not a head to drive it. The warm water appears to be lurking deep in the conduit system, when there is insufficient hydraulic head to push it up to the surface.

17. Does the sudden spike in temperatures found in SG4 mean that warm water is flowing up towards the Well, even if the well and the boreholes are not flowing?

I don't think so. I think that water levels at the other end of the 'U' shaped conduit rise to a certain level sufficient to move an initial pulse of warm water into deep caves. The warm water enters the very large cave system found at 90 metres in SG4 and 7, and most probably connected by vertical caves up to the Well. This warm water does not move upwards as a constant flow immediately from the cave at 90 metres, but instead, the pulse of warmth into the cave, rises by convection currents up the borehole and vertical caves under the spring. If there was persistent continuous upward flow of warm water, then the temperatures recorded by the Divers would remain the same regardless of the tides, but until flow takes place out of the borehole, the temperatures rise and fall with the tides; indicating that cooler water comes into the borehole from the surrounding rock and overburden with the low tides.

18. Is the site of St Gorman's Well a site of special scientific importance?

Yes – it is very important, but not necessarily for all the perceived reasons.

The investigation described in this report built upon the work carried out in previous investigations over the past 40 years. It has been found that the combination of the seasonal St Gorman's Well/spring, and the boreholes drilled adjacent to the spring, provide unique access to the inter-relationship of three groundwater flow systems at a single site.

First, there is the shallow, overburden-upper karst/epikarst local groundwater system that responds rapidly to local rainfall recharge and local groundwater flow gradients.

Second, below this, there is a more regional, major conduit karst system in the Waulsortian limestone that is confined and water levels respond to several tidal influences.

Third, there is a very deep conduit system, conceptually akin to a 'U' bend pipe, that brings warmer water from 500 – 1000m depth up to the surface. Water appears to flow down, along and up this 'U' bend conduit when rainfall recharge, at the inlet end of the conduit, raises water levels to a level that is higher than the water level at the St Gorman's Well outlet.

The source or inlet of the system is not known. but may be related to an apparent northeast to southwest aligned strike-slip fault that runs from the Cullentra side of the valley to the north, under the valley and under Ballinakill hill to St Gorman's Well.

I do not know of another single site in the country where the interplay of three such systems can be measured and investigated. Nor do I know of any such complex site that has been studied in such detail, and yet still will yield important information in the future.

For these geological and hydrogeological reasons, I would endorse the Geological Survey of Ireland's proposal that the infrastructure and site of St Gorman's well is eventually designated a proposed NHA (pNHA) or full NHA by the National Parks and Wildlife Service (NPWS).

19. Is the St Gorman's Well site formally listed as a geological NHA or pNHA ?

No – but the process of designation and listing a pNHA (proposed Natural Heritage Area) requires clarification.

pNHA is currently only a designation used by the NPWS to identify an area, or site, that the NPWS is aware may be an ecological site of scientific interest. The site may be well studied and currently of significant interest, or it may be an site identified as interesting during a survey in the past (often in the 1960s or 70s), and its condition has not been re-assessed. The designation pNHA is a form of 'holding' designation. The designation pNHA for a site indicates that the site may be put forward at some future date as an NHA if the site is surveyed and the results show that it warrants the NHA status.

The NPWS last drew up and published a list of only ecological pNHAs in 1995. The list has not been updated since 1995. The designation pNHA provides no legal protection.

St Gorman's Well is not on the list.

Since 1995 the Geological Survey has put forward sites of geological importance to the NPWS for listing as geological NHAs and pNHAs. The NPWS has not listed these geological sites because the list only contains ecological sites.

The Geological Survey has also carried out County Geological Heritage Audits, usually in conjunction with the Local Authority and the Heritage Council. The audits were carried out using 16 themes.

The thematic process involved a commissioned desktop study report on sites selected by an expert panel. Though not formally on the expert panel, I, and other hydrogeologists have been asked to propose sites of hydrogeological interest in different counties.

The audit process normally did not involve a site visit. It is anticipated that site visits would later be carried out by the Geological Survey, and the results would ultimately form part of the NHA designation process.

A County Geological Heritage Audit of Meath was carried out by Aaron Clarke, Matthew Parkes and Sarah Gatley and published first in 2007 and revised in 2009. St Gorman's Spring or Well was selected as a site. There was no site visit by the authors but the site report contains two photographs taken in February (year unstated), when the Well contained water. The site report reproduced information on the maximum temperature of 25°C taken from Brian Beckett's measurement in the summer of 2003 that was discussed above in Chapter 5. This appears to have been an anomalous measurement.

The report states that the site is to be proposed as an NHA, and should be listed as a County Geological Site in Meath.

Therefore, though St Gorman's Well is not formally listed as a pNHA by the NPWS, it has been proposed as a pNHA by the Geological Survey, and it is recognised by Meath County Council as a County Geological Site.

20. Is St Gorman's Well listed as an NHA or pNHA for ecological or biological reasons?

Though the simple answer is No, the question requires a much longer explanatory answer. The site was not included in the NPWS listing of pNHA sites in 1995. I have contacted Neil Lockhart, Wildlife Inspector and Project Officer for NHA designations in NPWS, who confirmed that St Gorman's Well was not a proposed NHA in the NPWS biological re-survey of the Areas of Scientific Interest (ASI) in 1992-1994. The NPWS does have a site code for St Gorman's Well (2901) in its database, but this is for correspondence concerning the sites geological interest, and not its ecology.

Currently the Well is a shallow depression with a vegetation on its base and sides dominated by grass species, as shown in the photographs in Figure 5.17 and the upper photograph in Figure 5.4.. In recent years the Well depression has not contained water except for a brief period in winter. There appears to be no evidence of a special permanent plant or animal ecology relating to water in the depression. When there was water in the Well in February 2021, we observed smooth newts in the water. The smooth newt is common and widespread in Ireland, and its usual habitat is terrestrial. The newt only ventures into available water in the breeding season starting usually in February.

Though St Gorman's Well is not listed as a pNHA, Brian Beckett's site description in the Ecoserve report in 2003 was the source of a desk study database entry in the NPWS Map of Irish Wetlands, produced as a joint project between the consultants Wetland Surveys Ireland and Foss Environmental Consulting.

I have discussed the database entry with Patrick Crushell of Wetland Surveys Ireland who confirmed that there was no ecological assessment of the site or visit before the site was entered into their database, and depicted on the NPWS map.

The information in the database is a very brief summary of Brian Beckett's site report from 2003. I explained to Patrick that the location for St Gorman's Well on the Map of Irish Wetlands was misplaced. and gave Patrick the true position. He has since corrected the NPWS map.

The site was summarised as Calcareous spring, reed swamp, lake, scrub, and with a temperature between 12 and 25 degrees, presumably taken from Brian Beckett's original report.

The terms 'lake' and 'reed swamp' give the impression that the site consists of a much larger water or wetland area than has existed. The site description does not refer to the intermittent nature of the spring.

The 'reed swamp' is a probably a reference to the duck pond artificially created in the 1980's, and largely overgrown by the early 2000s.

The term 'lake' is a misunderstanding of either the size of the small spring depression when it contains water, or refers again to the artificial duck pond.

The Map of Irish Wetlands data base entry from a desk study might give the impression that the site is a significant permanent wetland. Whereas several site visits by hydrogeologists in the last 20 years have shown that it is not. Whilst it is correct that the spring is calcareous, this would be a normal characteristic of all springs where groundwater emerges from limestone bedrock or limestone gravels.

St Gorman's Well is entered in the database as a cNHA, with a site evaluation listed as a 'C+ rating: County Conservation value'. A cNHA is a candidate NHA, described by Neil Lockhart as a pre-pNHA designation; meaning that the site could be considered for a site survey and assessment, and, if the biological evidence is sufficient, then proposed as an NHA.

The Wetland Survey of Meath was started in 2009, but Patrick Crushell confirmed that the site has not been visited or re-surveyed.

A tufa spring was marked with a symbol on the OPW Boyne Arterial Drainage map to the north of St Gorman's Well, in the position originally used to depict the position of St Gorman's Well on the Map of Irish Wetlands. This symbol may represent a seepage in the OPW drain, or it may be a representation of the misplaced position of St Gorman's Well on the uncorrected NPWS Wetlands map.

In the past the Well depression was different. With only shorter periods when it was dry (usually in the late summer and autumn) plants remained in the depression until the water level rose again. The ecological survey carried out by Brian Beckett for EcoServe in spring and summer 2003 when there was some water in the Well, identified several species of plants and animals. However, by cross-checking these species with the National Biodiversity Database in Waterford, it appears that all the species are common and well distributed in Ireland. There is no record of tufa forming in the Well, even though the Boyne Arterial Drainage map appears to have marked it as a tufa spring and the Map of Irish Wetlands refers to light tufa deposits on flora within the spring. The entries in these databases are secondary data, and not based on primary site visits. The reference to tufa is an interpretation by compilers of the secondary data bases of a comment by Brian Beckett that "a light tufa deposition was noted on some spring basin submerged flora and substratum".

The description "a light tufa deposition" can be interpreted from experience of tufa springs, as the appearance of a slight white patina on the leaves of some plants under the water. This can be a very fine deposit of calcium carbonate, or it can be a deposit of fine clay that has settled out of the water, or even, when viewed from the edge of a pool, an impression of a layer of white, which is created by micro bubbles produced by photosynthesis, caught in the hairs and creases on the surface of plant leaves.

There is no current evidence of the typical 'crunchy' amorphous calcium carbonate deposits typically found making up the substrate around the base of plants in perennial tufa springs found elsewhere. A fine layer of calcium carbonate may be deposited on the leaves of plants when there is water in the depression and when there is flow, but calcium carbonate is easily dissolved by the carbonic acid in rainwater. Therefore, a patina of calcium carbonate on leaves when there is water in the Well would probably be dissolved by summer rainfall when there is no water in the Well.

Sarah Blake noticed that a calcium carbonate precipitate was forming below the overflow holes in the steel casing of borehole SG4 in 2013 (see Figure 5.16). Green algae appear to have grown on this deposit whilst there was a flow of water from the borehole. Subsequently, the casing was cut down to a level below these holes in 2018, and a steel lid bolted onto the casing. There is no evidence of a calcium carbonate deposit currently on the casing or on the ground around the hole.

In summary, the St Gorman's Well site has not been designated as a pNHA on biological grounds. The only ecology survey took place in 2003. It appears that there were no rare species amongst the identified plants and animals at the site in 2003. Currently, there appears to be no evidence of solid tufa in the Well depression or in the overflow channel and adjacent drains that could form a habitat for rare bryophytes that require protection.
I agree with the recommendations that the site should be a cNHA or a pNHA, but for hydrogeological rather than ecological reasons.

21. What are the reasons for the decline in the frequency of flow from St Gorman's Well?
An overview of observations by scientists who have visited and or monitored the site in the past, and the notes and family photographs of the current owners of Hotwell House all show that the duration of flow, or the duration of water remaining in the Well to create a semi permanent pond, and the maximum temperature of the water in the Well, has decreased in the last 10 to 12 years. It has not been a consistent decrease, but over the past 6 years there have been two winters when the Well has not filled and there has been no flow. These have been years with low rainfall. I have assessed the information in some detail in the previous section of this report. It is also important to keep in mind that the flow of water from the Well depends upon the local rise in the water table in the overburden, whereas the flow of warm water depends upon the recharge to a separate deep conduit system, the location of the origin of which has not been found. My conclusion is that the decrease is not linear or with a single cause. It results from a combination of factors. The removal of rainfall and groundwater from the quarry is a factor. Of probably equal magnitude is a reduction of rainfall (and hence groundwater recharge) as the changes in weather and climate predicted by models appear to be taking place. The increased use of groundwater by the increasing number of one-off houses in the area, and loss of groundwater by pumping and unrestrained artesian flow from the Longwood boreholes have also contributed to a depletion of the bedrock groundwater resource and consequent lowering of water levels. The deepening of drains may also have made a secondary local impact at the site. Whether or not the quarry is deepened, the trend observed in recent years is likely to continue. It is difficult to predict how much the rainfall is going to decrease because the climate and weather appears to have just started to change in the last 5-10 years, and a clear pattern or trend is yet to emerge. Models are just models and not reality. They can provide a guide for expectations but what happens from year to year cannot be predicted accurately. The Well is not going to never fill or flow. There will be years when there is

sufficient rainfall recharge, and others like the winter of 2021-2022 when it is insufficient to bring the water table in the overburden up to the surface.

Whilst the effect of climate change from year to year will be uncertain over the long term, the effect of the quarry is predictable.

When quarrying ceases, the excavation will fill up with groundwater and rainfall in a very short time. Rainfall within the quarry area will be fully captured, and though some of it will evaporate from the open surface of the lake, the effect will be positive. The water level in the quarry will create a local groundwater level 'high', or what is called a 'recharge mound'. It will be more of a recharge mound than it was before quarrying started. Before excavations began, heavy rainfall ran off the relatively steep slopes of Rathcore hill and flowed into the surface water drainage system. In the future all rainfall will be collected into the flooded excavation, from which it can easily enter the groundwater system through the karst conduits. Therefore, the extension of the existing quarry would have a temporary effect, as distinct from climate change which seems destined to have a long term effect. Whether the closure of the quarry now or in 10-15 years will compensate for the effect of climate change is uncertain or unlikely because Rathcore hill is not the only source of recharge for the groundwater resource.

22. Are there any mitigation measures?

Yes

1. The obvious measure would be to seal the tops of both Longwood production boreholes to prevent the artesian flow from one or both boreholes into the drain and out into the river Blackwater.

2. Kilsaran are, I know, willing to pay for the drilling of extra boreholes. if any local resident finds that the yield from their existing borehole has decreased as a result of the quarry.

3. It is possible to consider pumping water from a borehole such as SG4, SG7 or SG3 next to St Gorman's Well in order to perennially fill the Well, and create a permanent pond. Technically, it would be easy to run in a power supply and install a small pump to do this, but whether the water would be warm is not certain.

We know that Hydro Research in the 1980's invested a significant amount of money in drilling large diameter boreholes around St Gorman's Well. The records of this work are not available, but it is likely that they carried out pumping tests at different times of the year in order to determine whether warm water could be obtained throughout the year from boreholes. Recent personal communication with Stephen Peel revealed that Hydro Research were assessing the feasibility of using a perennial warm water supply to breed and farm eels. Eels, grow faster in warm water. Farming eels requires a constant warm water temperature preferably above 23 degrees. There could be many reasons why this plan did not progress, but one reason could be that when they pumped the boreholes in summer, the water was not as warm as in winter. In other words, the warm water flow is dependent on the height of the water level at the inlet of the 'U' bend conduit, and in summer if this level is too low, then the driving force for the warm water is not present. Trying to, in effect, suck the water from the conduit, without direct access to the conduit may have failed, and only cooler water with more normal temperatures was abstracted from their pumping boreholes.

So, though the Well depression could be filled with water by Kilsaran offering to pump water into it, it may just create a small cool water pond. Nicholas Wilkinson has already created an aesthetically attractive, cool water pond surrounded by trees adjacent to the Well by lining a large shallow landscaped depression that roughly occupies the site of the duck pond created by David Wilkinson in the 1980s. Therefore, pumping water into the Well to create a small, perennial unlined leaking pond may not be a significant enhancement of the amenity.

I hope that my attempts to provide direct answers to these questions has been of help to a reader who found it unrewarding to read the dense details in the other chapters.

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Summary of Recommendations for further practical measures and investigations by the Geological Survey and others

It has been suggested by a member of the Geological Survey of Ireland that it would be useful for them if I provide a summary of recommendations for further practical measures and investigations at the end of this report.

No investigation of groundwater resources is ever complete, particularly in areas as complex as this, because unlike flow in a river, groundwater flow is in a three dimensional network of linked and isolated conduits of varying sizes that cannot be seen or directly measured.

The practical measures or further investigations that I would recommend are as follows:-

1. With the permission of the owner of St Gorman's Well, the tree branch stuck in borehole SG4 should be removed, a video camera survey then carried out to the borehole's full depth, and a log made of each open fracture, changes in apparent lithology, zones of calcite veining and karst conduits.
2. With the permission of the owner of St Gorman's Well, a similar video camera survey and log should be carried out of the recently re-discovered borehole SG3, if it is not lined to full depth with solid casing.
3. With the permission of the owner of St Gorman's Well, borehole SG3 should be capped in line with the closures installed on SG4 and SG7.
4. The Tellus team in the Geological Survey of Ireland could use the processing techniques used for this report, and described in Duygu Kiyan's paper published in 2022, to create conductivity sections across other lowland areas in the Irish Midlands underlain by Waulsortian limestone and other clean oolitic limestones, as well as dark grey shaley limestone, such as the Lucan and Ballysteen formations. Suitable target areas would be the due south and southwest of Portarlington in Laois, north of Robertstown and east of Derrinturn in Kildare, and east and southeast of Two-Mile-Borris in in Tipperary. The objective would be to find out whether elsewhere, in other parts of the Irish Midlands, there is a thick high conductivity layers in the deep overburden and upper bedrock above the unweathered low conductivity bedrock elsewhere.
5. With the permission of the relevant landowners, I recommend that the Geological Survey of Ireland drills several exploration boreholes in both the valley between Ballynakill Hill and the Cullentry area, and also to the south of Ballynakill Hill, in order to precisely determine the nature of the materials creating the high conductivity layers

found in the Tellus sections shown in this report. The objective would be to determine the original lithology and the nature and age of the weathering.

6. With the permission of the landowners, the Geological Survey drills two exploration and future water level monitoring boreholes at Easting 675283.67, Northing 745765.61 on the low ridge of ground above 80mAOD, northeast of the road, in Cullentry townland. The objectives would be to explore and define the overburden and bedrock geology, and to monitor separately the water levels in both the overburden gravels and the karst Waulsortian bedrock. One borehole would penetrate only the presumed gravel deposits. It would have a slotted well screen placed in the saturated gravel section. The second borehole would case and grout off the gravels, and be only 'open-hole' in the presumed underlying Waulsortian limestone. Water level monitoring, using pressure transducers, would be carried out in tandem with the planned continued water level monitoring in borehole SG4 at St Gorman's Well by the Geological Survey.
7. A final practical measure: the two artesian Longwood Water Supply boreholes are allowed to overflow to waste when not being pumped. When they are pumped alternately, it means that water is being continually lost from the Waulsortian limestone groundwater system through the well drainage system of the non-pumping borehole.
   A flange bolted steel lid with a slightly modified rising main and sealed ports for the power cable and water level sensors, could be installed on the steel conductor casing in each borehole to prevent this loss of water. I, or another hydrogeologist, could draw up the simple designs for the lid and pipework, as used elsewhere in the world, to assist Meath County Council control this inadvertent depletion of the groundwater resource.
8. A future detailed research project could use the infrastructure of boreholes SG3, SG4 and SG7 at St Gorman's Well to determine and monitor the hydrochemical and environmental isotope signatures of the water in the main three groundwater systems.