Figure 5.9 The Well Head of Borehole SG 7 and the proximity of SG4, SG8 and SG7

It can be seen from the above description of the site, the infrastructure on the site, and the changes to the site over time, that the site is complicated, and that the detail is important.

It is also important to keep in mind that the Well and the borehole infrastructure are different. The Well is essentially a natural feature created by natural processes. The boreholes are artificial features, and though they both can give information on the complex groundwater flow systems in the subsurface, they are not providing information on the same thing. The boreholes provide access to shallow and deep processes. The spring is just a shallow feature and represents just the surface expression of the culmination of shallow and deep processes.

It is easy to think that measurements in the boreholes represent conditions in St Gorman's Well, but they do not, because conditions in the boreholes reflect both deep conditions and shallow conditions depending upon their depth and construction.

Therefore, the next section of the report focuses on history and observations on St Gorman's Well. The subsequent sections focus on the information from the boreholes (mostly information from SG4) and their response to rainfall, and then the final sections describe and correlate water levels in Rathcore and St Gorman's Well boreholes.

5.2. Historical Observations at the site of St Gorman's Well

St Gorman's Well is an interesting paradox, because it is known as a spring, yet it is a spring that does not flow all the time.

It is a micro-sized enclosed depression in a karst limestone environment, that contains water when the local water table is high, and contains no water when the water table falls sufficiently. In some respects, it is like a turlough or seasonal lake fed from below and the sides by groundwater..

There is no stream flowing into the depression. Currently, water can be found in the Well depression for a variable period of time in winter, but in the winter of 2016-2017, and again in the winter of 2021-2022, there was either no water, or no significant water, in the depression. At the time of writing this report (December 2022) the Well has been essentially dry for the last 21 months.

5.2.1 Du Noyer

It is disappointing to visit St Gorman's Well when there is no flow.

This is not just a modern disappointment.

There have been several visits and studies of the Well and its unusual hydrogeology, but the first record that I have found is notable for its blunt yet careful description.

George Victor Du Noyer was a remarkable person. He was a very talented, precise draughtsman and watercolour artist, but he was also a surveyor with the Ordnance Survey and eventually, before his untimely death from scarlet fever, a District Surveyor for the Geological Survey of Ireland. He mapped large areas of the country and his work is still highly regarded.

Du Noyer mapped south Meath and he visited St Gorman's Well.

I found his careful, hand written comments on his coloured 6" field sheet, Meath 48a-1. His Victorian style handwriting is neat, but it is not easy to read in its entirety. It can be seen on the map in Figure 2.2 and have reproduced the text again in Figure 5.10.

Du Noyer starts his note

> ***"This spring was not the least warm when I visited it on the 21st July 1859, and to me, it appeared in every respect a delusion."***

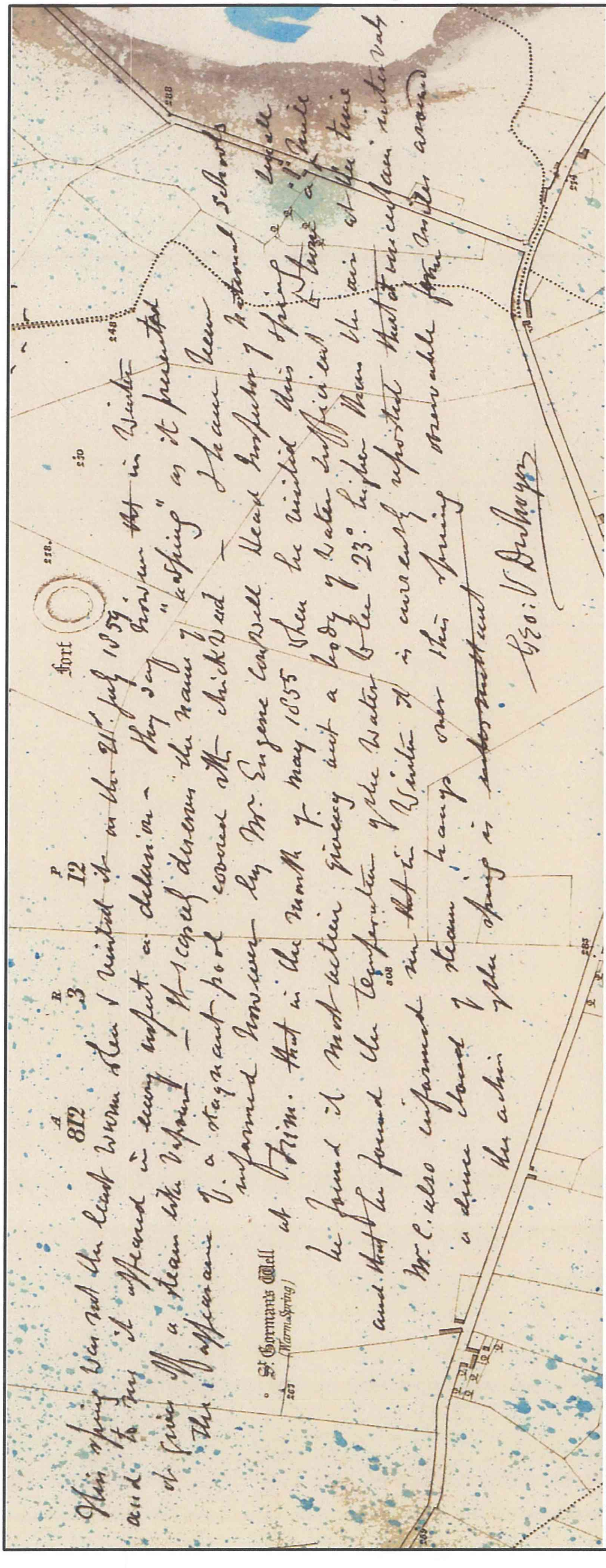
He then balanced this blunt observation with the comment

> ***"They say however that in winter it gives off a steam like vapour."***

He then returned to his disappointment by writing

> ***"It scarcely deserves the name of "a spring", as it presented the appearance of a stagnant pool covered in chickweed*"***
>
> ** I guess that he meant 'duckweed'*

Figure 5.10 George V. Du Noyer's handwritten description of St Gorman's Well in July 1859 with reference to Eugene Alfred Conwell's observations made in May 1855




G.V.Du Noyer


E.A. Conwell

However, Du Noyer was puzzled by his findings, and he must have discussed his visit and observations with others, because he writes

> ***"I have been informed however by Mr Eugene Conwell, Head Inspector of National Schools at Trim, that in the month of May 1855, when he visited this spring, he found it most active giving out a body of water sufficient to turn a small mill, and that he found the temperature of the water to be 23° higher than the air at the time.***
>
> ***Mr C. also informed me that in winter it is currently reported that at uncertain intervals a dense cloud of steam hangs over this spring observable for miles around."***

The name of Mr Conwell was not easy to decipher in Du Noyer's hand writing, but I tried various spellings of a name beginning with 'C' and ending in 'well', in order to discover whether a verbal report by a 'Head Inspector of Schools for Trim' was likely to be reliable.

When eventually I tried "Conwell", I found that Mr Eugene Alfred Conwell was much more than just an Inspector of National Schools. He was an important archaeologist and author, and a Member of the Royal Irish Academy.

I found that he was of sufficient standing in the mid 19th century, that the National Portrait Gallery in London has an albumen photograph portrait of him taken in 1862, in their collection. I have obtained permission to reproduce the photograph. It is shown, along with Du Noyer's photograph in Figure 5.10.

Given the credentials of the two men, it seems reasonable to accept that the dates are correct, and that Mr Conwell's temperature measurement was accurate with the thermometer that he possessed.

Met Eireann have published historical daily temperature records for the Phoenix Park back to 1831. Unfortunately, we don't have the exact day in May 1855 when Mr Conwell took his measurement of the water in the Well, but May 1855 was relatively cool.

In the early part of the month the minimum temperatures were below freezing and the maximum temperature was 7°C. Later in the month the temperatures rose to a maximum of 15°C. Mr Conwell's measurement of 23° was presumably in the Fahrenheit scale. It converts to 12.78°C.

Therefore, if Mr Conwell visited the spring at the warmest part of the coldest day in early May, his temperature for the flowing Well would have been 19.78°C. If he took it on the warmest day it would have been 27.78°C. These calculations prove nothing, but they show that the water flowing from the Well was definitely warmer than would be expected for shallow groundwater (which is about 9.5-10.5°C), and that the temperature was in a similar range to temperatures measured in the Well later in the 20th century. Mr Conwell's measurement also indicates that St Gorman's Well would not be classified as a 'hot spring', with temperatures above, say, 35°C. Du Noyer concludes his comments on the map with

"The action of the spring is intermittent" and it's signed *"Geo: V Du Noyer"*

Du Noyer's note on the map is important because it establishes that flow from St Gorman's Well was intermittent 160 years ago. The present intermittent nature of the spring is not just a modern phenomenon.

The contrast between Du Noyer's observation of a **'stagnant pool'** in July, and Conwell's observation of a spring **'most active'** in May, has the logical explanation that the flow from the spring declines and stops in the summer during the natural recession of shallow groundwater levels. The flow from most springs, in Ireland, decreases in this way in summer and may even stop in the dry months, when the rate of rainfall recharge into the groundwater system, is exceeded by the rate of underground drainage out of the groundwater system.

However, there was a long-term trend taking place, that also may explain the difference between their observations four years apart.

Simon Noone in his PhD thesis ('Development and analysis of a homogeneous long-term precipitation network (1850-2015) and assessment of historic droughts for the island of Ireland') for Maynooth University in 2016, and Met Eireann, have published tables of homogenised rainfall data from 1850 to 2015 for 25 rainfall stations in Ireland.

Simon also used the data to assess droughts in this period and the effect on river flows. It was a massive piece of research.

Simon Noone's analysis of rainfall data and contemporary meta-data, such as, newspaper articles about crop failures and shortage of water supplies, found that one of the most prolonged meteorological and hydrological droughts in Ireland extended from 1854/55 to 1859/60.

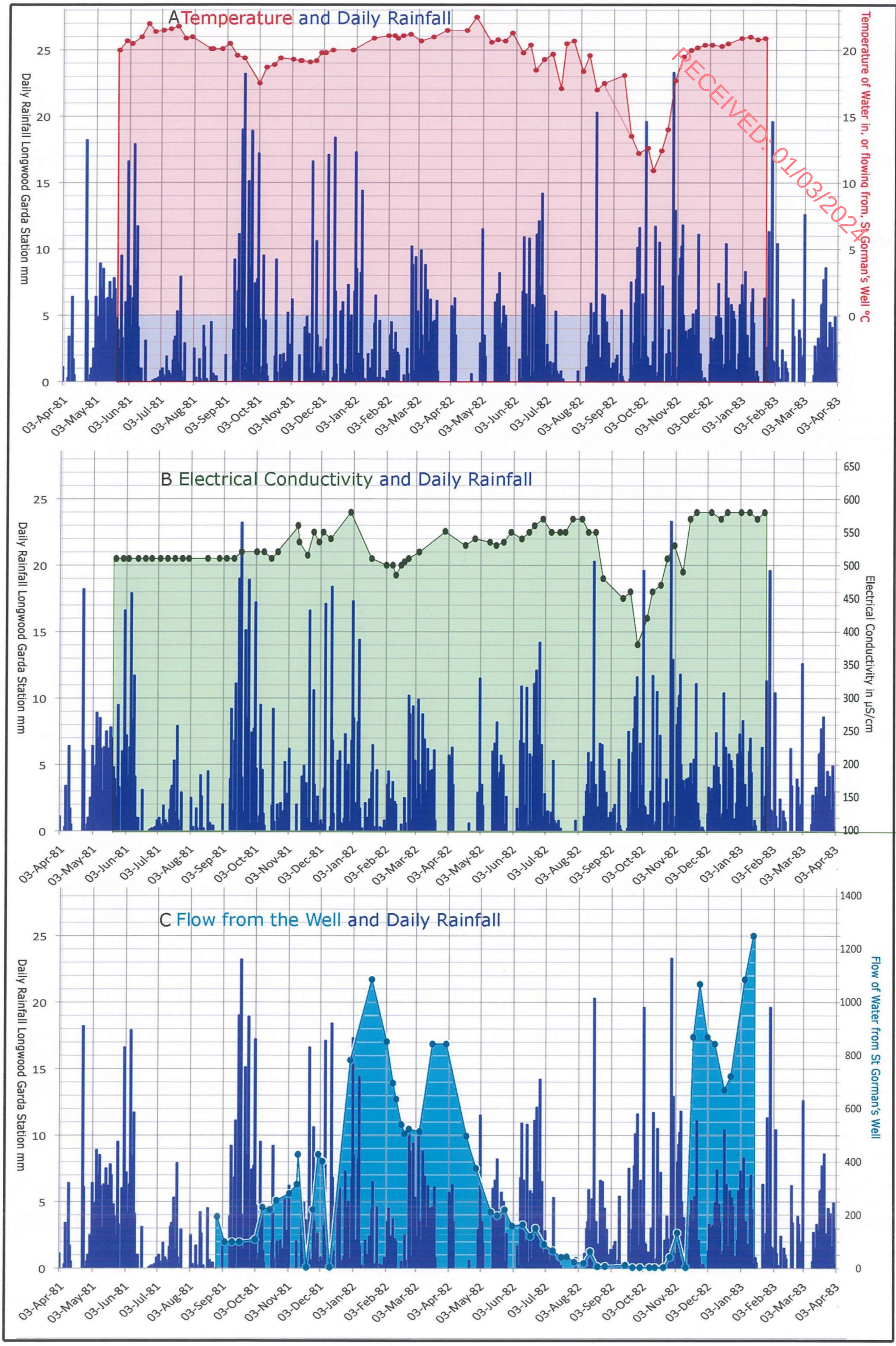
Therefore, Mr. Conwell's observation in May 1855 was at the start of this drought, and Mr. Du Noyer's observation in July 1859 was near the end of the drought.

Overall, the short comments, handwritten on a map in 1859, are important as they indicate that the water level and flow from St Gorman's Well was affected by the amount and distribution of rainfall in the mid 19th century.

5.2.2 Aldwell

The next report on the temperature of the water in St Gorman's Well is a personal communication from Bob Aldwell to Edward Fahy, in An Foras Forbatha, referred to in Fahy's paper titled 'The biology of a thermal spring at Enfield, Co Meath, with some observations on

Figure 5.11 St Gorman's Well Manual Measurements 1981 to 1983



other Irish thermal springs' published in 1975. The "spring at Enfield " in the title of the paper is now called Kilbrook Spring, which was also investigated by Sarah Blake for her thesis. Table 4.1 in Fahy's paper gives a temperature for the St Gorman's Well of 15.8 – 19.8°C. However, Fahy did not investigate St Gorman's Well. He reported data and other characteristics given to him by Bob Aldwell.

5.2.3 Minerex

The next scientific report on St Gorman's Well was the ground breaking geothermal investigation carried out by Minerex (David Burdon and Stephen Peel) in association with Bob Aldwell from the Geological Survey of Ireland, in the early 1980s. It was an EEC research programme. Stephen Peel in Minerex manually measured the temperature of the water either flowing from the Well, or in the Well depression when there was no flow. They also measured or estimated the flow and measured the electrical conductivity of the water either in the flow, or in the Well when there was no flow.

In Bob Aldwell and David Burdon's paper in 1986 they provide a monthly list of the measured flows. Their table of data is given below, with the addition of flow rates converted into litres per second.

Month	Longwood Monthly Rainfall (mm)	Discharge from the Well (m^3/d)	litres/second
January	84	1,017.6	11.8
February	58	616.8	7.1
March	80	746.4	8.6
April	25	549.6	6.4
May	67	177.6	2.1
June	120	81.6	0.9
July	19	26.4	0.3
August	81	4.8	0.05
September	77	0.0	0.00
October	106	4.8	0.05
November	119	768.0	8.9
December	87	780.0	9.0

In the same paper they give a temperature for the Well water as 22.5°C on the 27th April 1982. However, the Geological Survey of Ireland has the raw data collected by Stephen Peel that was used to compile the table in this paper. Sometimes, Stephen was visiting the site to taking manual measurements three times a week. The monitoring did not just take place in 1982, but started in April 1981 and continued until January 1983.

I have compiled the raw data into three separate graphs on one page in Figure 5.11.

The daily rainfall measured at Longwood Garda Station is on each graph. The years 1981-1983 were generally a time of above average rainfall with sodden ground and difficult farming conditions in the autumn and winters. The number of days with rain can be clearly seen on the graphs.

The data on the graphs is much more informative than the table of monthly data for 1982 in the Aldwell-Burdon paper.

Starting with the bottom graph on Figure 5.11.

The flow measurements did not start until August 1981. There was a small flow out of the Well in August that decreased in September to about 1 litre a second, even though it rained every day from early September to the beginning of October in 1981.

It can be seen that it took nearly a month of heavy rain before the Well responded, and flow started to increase. The rain in September did not significantly change the Electrical Conductivity readings, but there was a 2 degree drop in the temperature of the water. This indicates that a proportion of the increased flow from the Well was recent cool rainwater that had percolated into the shallow overburden and upper bedrock groundwater system and raised the 'water table' at the Well. It is unfortunate that there were no boreholes on the site at the time to measure the rise in groundwater levels, but an increase in flow can be used as a proxy for a rise in groundwater levels.

October and November were relatively dry, but with the heavy rain in early December the flow suddenly increased dramatically to 1,100cubic metres a day (12 litres per second) in mid January 1982.

The temperature did not rise suddenly. It was already high at over 20°C.

The conductivity that had risen erratically from 520 to 580 µS/cm, rapidly dropped back to 500µS/cm when the flow from the well rapidly increased. This suggests that an increased proportion of the water flowing from the Well was recent recharge containing less dissolved minerals.

The middle and end of January and the beginning of February 1982 were relatively dry and the discharge from the Well fell by 50% from mid January to the beginning of March 1982.

The numerous days of rain from late February to mid March created another increase in flow from the Well. The temperature remained constant but the conductivity increased, suggesting that the shallow and deep groundwater systems were all active, and that the proportion of more mineralised water had increased.

The flow from the Well rapidly decreased from the end of March 1982, and there was a long decline in flow until the middle of October. Water remained in the Well and Stephen Peel was able to measure the temperature and the conductivity.

During the summer and autumn decline in flow from the Well, the temperature readings show an erratic pattern. This indicates that the temperature in the decreasing flow from the pool was being affected by the variation in sunlight on the water and air temperatures. The highest recorded temperature is 22.5°C, and this is the temperature quoted in the Aldwell and Burdon paper.

This measurement was made on the 27th April when the air temperature at Mullingar was 18.6°C in the shade. It is likely that this unusually high temperature was not a representative groundwater temperature. Depending on the time of day and the place where the measurement was made, it is possible that the thermometer or temperature probe was recording in full sunlight on a warm day the temperature of shallow water at the edge of the pool. Unfortunately, this temperature is often reported as if it is the definitive temperature for groundwater emerging at St Gorman's Well.

From mid August to mid September the conductivity decreased by 100μS/cm after a day with 20mm of rain, and it fell further with many days of rain at the end of September.

The temperature also appears from the data to have fallen significantly from mid September to early October. But this may be incorrect. It is probable that the temperature reading of 18.1 degrees on the 14th September was another anomalous high reading. The air temperature was also 18.5 degrees in Mullingar on that day and the shallow water level in the Well pool was again probably warmed by the air and direct sunlight. The conductivity and temperature both started to decline rapidly in August after very heavy rain. Then, both the conductivity and the temperature began to rise in mid October even though the flow from the Well had barely increased.

This pattern of a fall in temperature in autumn, followed by a sudden rise in temperature before the 'water table' has risen sufficiently for the Well to flow at a high rate, is a characteristic that is seen in the monitoring of water levels and temperatures in borehole SG4 from 2014 to 2021/22.

By the middle of November, after two months of near daily rain, the flow from the Well had increased to over 1,000m^3/d, the conductivity had risen to 575μS/cm and the temperature was back above 20°C.

The end of November saw a reduction in rainfall and the flow from the Well reduced to about 650m^3/d by mid December, at the same time as the rain increased in frequency. There appears to be a one to two week lag between rain stopping and flow decreasing, and rain starting and flow increasing.

The rain in December and January caused the flow from the Well to increase to 1250 m^3/d.

Stephen Peel's monitoring stopped in mid January 1983.

The data collected manually by Stephen Peel acts as a benchmark for all later observations. It showed that the flow from the Well varies in response to rainfall recharge.

It showed that the late summer/early autumn rain brings about a fall in water temperatures in the water in the Well.

It showed that late summer/early autumn rainfall brings about a fall in conductivity that starts before the fall in temperature.

It showed that the conductivity and temperature both rise in advance of the water level rising suddenly and the Well flowing profusely.

The relationship between rainfall, water levels and flow will be explored and discussed in detail later in this Chapter.

5.2.4 Hydro Research and Frank Murphy.

Hydro Research in the mid 1980's measured the temperature in the water from boreholes at an unspecified date. SG4 was 21°C and SG7 was 22.3°C. These data were given in Frank Murphy's report in 1989. Hydro Research drilled these boreholes around 1985-6 as described in Chapter 2.

Frank Murphy also measured the temperature in his new very deep core hole, SG8, with a logging tool 60 hours after it was drilled. The temperature reached a maximum of 21.7°C at a depth of 60 - 74 metres below ground level, but it declined thereafter to 18.5°C at a depth of 250 metres. Frank was not able to log below 250 metres, and the upper hole subsequently collapsed and became blocked shortly after the drillers removed the NQ sized drill rods, that had been acting as a casing to stabilise the hole. He was not able to measure a flow of water from SG8.

5.2.5 Eugene Daly and Associates for Roadstone

Eugene Daly and Associates (EDA) were working for John Barnett and Associates on an EIS for Roadstone Dublin in 2001-2002 in the large field northeast of St Gorman's Well. As a part of their work they tested St Gorman's Well boreholes SG4 and SG7.

In particular, EDA carried out a short three day pumping test on SG7, from the 5th to the 8th June 2001. They reported that the static water level in SG7 was 0.76 metres below the top of the casing. The top of the casing is at 76.27metres above Ordnance Datum. Therefore, the water level in the borehole was at 75.51 metres above Ordnance Datum, The base of St Gorman's Well is at 75.34 metres above Ordnance Datum. Therefore, it seems probable that there was about 17cm depth of water in St Gorman's Well. In other words, on the 5th June 2001, there was a little water in the small depression of the Well, but no flow out of the Well. EDA pumped SG7 at a high rate of 4,300 gallons per hour (19.5 m^3/h, or close to half a million litres per day), The pumping from SG7 created a final drawdown in SG4, 2.5 metres away, of just 0.56 metres, but created a drawdown in EDA's exploration borehole 11 of 1.04 metres. Exploration borehole 11 is 708 metres away to the northeast along a line of breccia observed in EDA's geophysics, and along a northeast alignment that I interpreted as a fault from the airborne conductivity maps and sections. A second EDA borehole (7) also responded to the pumping from borehole SG7.

The EDA data showed that SG7 and SG4 are connected to a preferential flow path in the bedrock extending under Ballynakill hill to the northeast of SG7 and SG4.

EDA drilled a new wider diameter pumping borehole in the large field to the northeast of St Gorman's Well, and carried out a second pumping test in February 2002. They report that both SG4 and SG7 were flowing throughout this test. EDA did not measure the flow or artesian head in SG4 or SG7, or comment on the level or flow from St Gorman's Well.

The EDA work in 2001-2 gives information that in June 2001 there may have been water in St Gorman's Well, and that in February 2002 SG4 and SG7 were flowing. It can be assumed that St. Gorman's Well contained water in February 2002.

5.2.6 EcoServe

The next recorded observation of the Well, and measurement of temperature was by Ecoserve Consultancy, who carried out an ecological survey of seven warm springs for a report in 2003 for the Heritage Council. The report on the work was attributed to Chris Emblow, and the report is titled 'Development of a baseline ecological data set for selected warm springs in Ireland'.

I have talked with Chris Emblow, and he believes the survey and measurements were made by Brian Beckett. I have talked with Brian and he believes that he visited St Gorman's Well in 2003. He visited the Well in spring, summer and autumn. The Well was dry in autumn. The Well water was 12°C in the spring with an electrical conductivity of 413µS/cm. In summer it was 25°C with a conductivity of 464µS/cm. On both occasions the pH was 7.8. He says that when the Well was overflowing strongly, the water flowed into an adjacent 'swamped area'. Interpreting this comment, it is assumed that the 'swamped area' is the remains of the 'duck pond' created in the 1980s by David Wilkinson.

Unfortunately, neither Brian nor Chris can find the records that would give the exact date of the measurements. However, Brian confirmed that that he used the thermistor incorporated in the Electrical Conductivity probe to measure the temperature. This probe is attached by a short

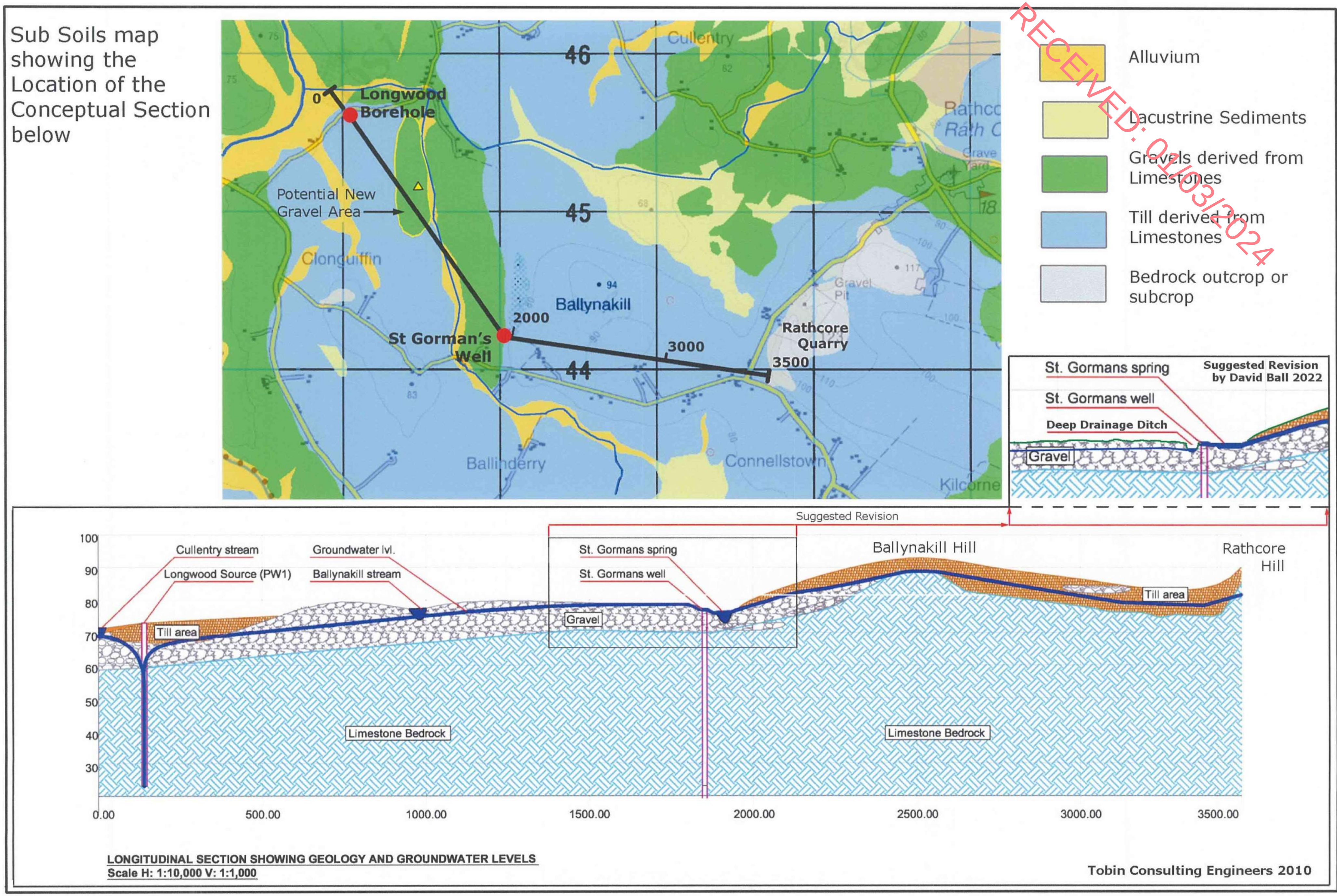


Figure 5.12 Tobin 2010 - Conceptual Section from Longwood Borehole to St Gorman's & Rathcore

cable length to the hand held conductivity meter. Brian also confirmed that he would have made his measurements in the shallows at the edge of the pool. He did not wade into the centre of the pool and to measure the temperature and conductivity at the bottom of the pool. He, and I, concluded that sunlight and warm air in summer would have warmed the shallow, stagnant open water in the depression.

Therefore, we concluded that his recorded temperature of 25°C was not a true groundwater temperature, but the temperature of the shallow water at the edge of the pool in summer.

The conductivity readings are unusually low.

The 12°C and 25°C temperatures from Ecoserve's survey have been re-quoted in part, or in full, in many subsequent, easily accessible, authoritative on-line publications, such as the National Parks and Wildlife 'Map of Irish Wetlands', and 'The Geological Heritage of Meath, An audit of County Geological Sites in Meath' by Meath County Council in 2007. These organisations, or their consultants, also stated in their on-line site entries, that they had neither visited, nor made observations or measurements at St Gorman's Well.

In other words, each on-line source repeats the Ecoserve water temperature, without checks.

5.2.7 Tobin Consulting Engineers

The next investigation that looked at St. Gorman's Well was carried out by a team from Tobin Consulting Engineers in September and November 2009. The team consisted of Coran Kelly and John Dillon, with assistance from Robert Meehan and Jenny Deakin. Robert Meehan is an authority on the soils and sub soils of Ireland and, in particular, of Co. Meath. This team produced a comprehensive report on the Longwood Water Supply titled "Establishment of Groundwater Source Protection Zones Longwood Water Supply Scheme" for the EPA in 2010. This report was written before the second Longwood water supply borehole was drilled in 2011.

The first Longwood borehole in 2001 had encountered productive gravels below a layer of low permeability clay. The gravels lay above the Lucan formation limestone which was only significantly productive in the upper few metres. The water in the gravels and upper bedrock was confined, and the borehole was free flowing when the pump was not in operation.

Because the main yield of water from the borehole came from the gravels, the Tobin team sought to better understand the distribution of the gravels to the south and east of the borehole in order to define the zone of contribution for the water supply. They identified from the Teagasc Sub Soils map that there appeared to be ribbon of limestone gravels and alluvium just to the east of the Longwood water supply borehole, that ran roughly north to south along the shallow valley of what they named the Ballynakill Stream (known locally as the 'Hotwell

Stream'). The Tobin team also found evidence in drain exposures and an old shallow gravel pit, that there is a potential area of gravels in an area previously mapped in the Sub Soils map as Till.

As the original and modified gravel deposit extends south to St Gorman's Well, the team included St Gorman's Well as a part of their assessment of the Longwood Water Supply. They visited the Well and took photographs and measurements. They worked on the basis that the gravel was the main groundwater resource supporting the Longwood Water Supply borehole, and needed to define the zone of contribution. The team were aware of the groundwater work carried out by Eugene Daly and Associates (EDA) for the Ballynakill EIS produced by JBA in 2002 and 2006. They were also aware of the BHP core hole drilling in 1998 referred to in Chapter 2.

The Tobin team integrated their findings, and produced a conceptual cross section as Figure 3 in their Source Protection Report.

I have reproduced this section in Figure 5.12. I have used the GSI's Sub Soils map on a Discovery Series base as a map to locate the position of the section. I have included on the GSI map the potential new area of gravels shown in Figure 4 in Tobin's Source Protection Report.

The conceptual section starts at the Longwood water supply borehole and extends south east under a low flat valley to St Gorman's Well, and then turns in a more easterly direction to the base of Rathcore hill.

They have shown that the gravel aquifer extends to the slopes of Ballynakill hill. The names on the section are slightly confusing. St Gorman's Well is labelled as 'St Gorman's spring', and one of the deep boreholes is labelled as 'St Gorman's well'.

The section shows a gravel aquifer underlain by undifferentiated limestone bedrock.

The second Longwood boreholes was drilled the year after the Tobin's Source Protection report was published. Therefore, Tobins could not have been aware that within 100 metres to the southeast of Longwood Borehole 1, the bedrock changes from the Lucan formation limestone to karstified Waulsortian limestone.

The Tobin section shows a blue line, representing a conceptual water table in the gravel and the till. The water table is shown above the bedrock. The highest level of the water table is under Ballynakill hill. The section shows the gravel at the Longwood borehole site confined by till, and the gravel on Ballynakill hill is also covered by till. The slope of the water table line implies a gradient and hence a groundwater flow direction.

The section implies that groundwater flows from the southeast to the northwest along the valley from the direction of St Gorman's Well, but not from St Gorman's Well. Instead the section shows water flowing from the gravels under the valley back towards St Gorman's Well. Whilst it is a conceptual section, this is not realistic for two reasons; St Gorman's Well is not below the level of the valley, and the deep drainage ditch next to St Gorman's Well is not shown. This drainage ditch would intercept any shallow groundwater flowing from under the lands to the northwest or west. The base of the ditch is over a metre lower than the base of St Gorman's Well. However, assuming that the gravel aquifer underlies the valley, the conceptual section is generally correct in showing groundwater flowing from the St Gorman's Well area, and the base of the western slope of Ballynakill hill.

I have drawn a small conceptual detail as an insert above the conceptual section to show the relative position of the Well and the drainage ditch, and a very gently sloping water table from the ditch through the gravels to the northwest.

The significance of the section is that the Tobin team recognise that the water level and flow from St Gorman's Well is partly determined by the groundwater level in the till and or gravels on the flank of Ballynakill hill, and that groundwater flow in these superficial deposits drains into the ditches and under the ditches to the northwest towards the Longwood borehole. This implies that if the Longwood borehole drains water out of the gravels at the northern end then this will draw down the water level in the gravels to the southeast in the direction of St Gorman's Well. This could be a significant implication.

In 2009-2010 Tobins defined a zone of contribution for the Longwood borehole, based on average annual rainfall and estimates of recharge based on a series of assumptions. The zone of contribution extends due south for about 1km. They partly limited the extent because the Longwood borehole was not able to meet the required pumping rate. The zone of contribution does not take into account the construction of the second borehole that draws water from the karst Waulsortian below the gravels, or the operation of the two boreholes.

Currently, the two boreholes are each pumped on an automatic cycle of 12 hours on and 12 hours off. In other words, borehole 1 is pumped from midnight to midday, and borehole 2 from midday to midnight.

When either borehole stops pumping the water level in the borehole recovers within a few minutes, and groundwater begins to flow out of the borehole under artesian pressure. Unfortunately, the top of the boreholes have not been sealed to prevent this artesian flow. Instead, the well heads of both boreholes have a drainage system that has been designed to solve what could be seen as 'overflow problem'. This well engineered drainage system of pipes and concrete channels takes the excess artesian flow to the adjacent ditch. This excess water drains via the ditch or stream into the River Blackwater.

Figure 5.13 Borehole SG4 and St Gorman's Well on 21st September 2009

I visited the Longwood site on the 19th July 2021, during the summer groundwater recession. St Gorman's Well was dry and the water level in St Gorman's borehole SG4 was 3.5 metres below the top of the casing. In other words, there was no artesian flow at St Gorman's site, but there was artesian flow from the Longwood boreholes.

The quantity of water pumped from the Longwood boreholes on the 18th, the previous day, was 395 cubic metres. I could not measure the artesian flow from borehole 1 which is lower than borehole 2, and hence likely to have a greater artesian flow.

I was able to measure the artesian flow from Borehole 2 because the drain pipe from the new borehole enters the ditch at a high level. The flow was about 5 cubic metres an hour, or 120cubic metres per day.

Therefore, the amount of water taken from the groundwater system at the Longwood water supply site is not just the amount of water pumped into the distribution system to meet the demand from the town. The combination of pumped water and artesian flow in July 2021 would have been at least 500 cubic metres a day. This was at a time of low summer groundwater levels.

In winter, when the water level or, more correctly, the artesian water pressure, is several metres higher, the artesian flow from each borehole, when not in use, would be much more prolific.

Unfortunately, I did not arrange to re-visit the Longwood borehole site during the winter of 2021-2022. I was waiting for normal high winter water levels before going to the site, but the autumn and winter was so dry that normal groundwater levels were never achieved.

In summary, the two Longwood boreholes are intentionally pumping, as well as unintentionally draining, water from both the gravel and the Waulsortian limestone artesian groundwater flow systems, down gradient of St Gorman's Well.

Before Borehole 2 was constructed, Borehole 1 was not able to keep pace with the peak demand because there was a limited amount of water that it could draw from the gravel, and the low productivity Lucan formation bedrock below. The pumping water level was 45 metres below ground level, as measured by Tobins on the 17th September 2009. This is a deep drawdown for a relatively small yield. This was the justification for drilling the second borehole.

One of the consequences of bringing Borehole 2 into production was that both boreholes were not being pumped continuously, and when they were not being pumped, the water levels recovered rapidly and artesian flow took place from one or both boreholes. The opportunity for unrestrained artesian flow had been small when there had been just one borehole struggling to meet demand, and pumping most of the time. When a second and more productive borehole was installed, the amount of time that the boreholes were not pumping, and artesian flow was

Figure 5.14 St Gorman's Well and Boreholes SG4 and SG7 21st April 2011

occurring, increased greatly.

The Tobin team visited St Gorman's Well 23rd September 2009. It had been usual for St Gorman's Well and boreholes SG4 and SG7 not to flow at the end of summer each year, but the rainfall pattern and intensity in 2009 was unusual. The most unusual weather occurred when it rained almost every day in Ireland in November 2009, and there was significant flooding across the country. The intense rain in November was preceded by a large amount of rain in July and August 2009. There was little rain in the two weeks before the Tobin site visit in September, they found that the Well contained water, and there was a flow from borehole SG4. There was also flow in the drainage ditches and streams. The electrical conductivity of the water in these surface water course was high, indicating that the water was groundwater and not recent rainfall run off from the fields. They also found springs on the edge of the Clonguiffen stream, parallel, and to the west of the Ballinakill stream, where groundwater was flowing from gravels.

Tobins measured the temperature of the water in St Gorman's Well and borehole SG4. Figure 5.13 shows the borehole and the Well. They also estimated the flow from the borehole(s) at a rate of 850m^3/d, and a flow in the drainage ditch of 900m^3/d.

The temperature of the water flowing from borehole SG4 was 20.6°C. The temperature of the water from the Well was much lower, at 14.4°C. The conductivity of both was 590µS/cm.

The unusual flow from both the boreholes and the Well in September and the low conductivity results and the temperature difference, indicate that the rainfall had recharged both the deep and shallow groundwater systems. Warm water was coming up borehole SG4 from depth, whereas the water arising in the Well was a blend of shallow cool water, from recent rainfall recharge into the overburden/gravels aquifer, mixed with some warmer water rising from the bedrock.

The information in the 'Longwood Water Supply Borehole Source Protection Report' and the results of drilling a second borehole at Longwood in 2011, indicate that there is a link between these boreholes and St Gorman's Well and boreholes.

5.2.8 Richard Langford (Parkmore Environmental Services)

The next investigation at St Gorman's Well and boreholes was a site survey by Richard Langford for the Geological Survey of Ireland Groundwater Section in April 2011, 18 months after the site visit by Tobins. Richard had been asked to visit several warm springs and to take measurements of temperature, conductivity and flow.

Richard's photographs in Figure 5.14 of the Well show that there is no open water, though

Figure 5.15 R. Langford measuring flows at Site 2 & field notes from the 21st April 2011

apparently there was a small flow through the old duck pond area, into the drainage ditch.

The photograph of the two boreholes shows that they are overgrown, but it is still possible to see that there is flow from borehole SG4 in the foreground. There does not appear to be flow from SG7, but there is water around the base of the casing. This may be because of the effect of tides on the water levels in both holes. This will be discussed in detail later in the Chapter.

Figure 5.15 shows the flow in the drainage ditch being measured by Richard. It gives a good visual representation of the flow in the ditch. The maximum depth of water was 6cm. The measured flow was 14.4m^3/h or 346m^3/d.

He measured the combined flow from the boreholes as 10.8m^3/h or 259m^3/d. By subtraction it appears that the seepage from the Well would have been about 90 m^3/d

A summary of his field data and the location of his measurements is shown on the lower image in Figure 5.15.

His temperature and conductivity data for the boreholes is not shown on the image.

The temperature of one borehole was 14.8°C and the conductivity was 485µS/cm.

A second borehole had a temperature of 21.8°C and a conductivity of 572µS/cm.

The water temperature in the Well pool was 10.5°C with a conductivity of 788µS/cm.

From the previous work it appears unusual that the temperatures and conductivities of the two flowing boreholes are different, and that the water temperature of the Well was so low but the conductivity was much higher.

A possible reason for the higher conductivity of the water from the Well could be the spreading of animal manures on the large field up gradient of the Well. The lower south west corner of this field is only 200 feet or 60 metres from the Well.

5.2.9 Sarah Blake

Sarah Blake was the next person to visit the site.

Sarah carried out extensive work on warm springs and St Gorman's Well for her PhD thesis and published several subsequent papers, between 2013 and 2021.

Her information on flow and temperatures for the natural St Gorman's Well reproduces the information from the Minerex (Burdon and Aldwell) paper in 1986. Sarah did not measure the flow from the Well, but instead her research focused on monitoring temperature, conductivity and water levels in borehole SG4 and carrying out an AMT geophysical survey in order to try to understand the geology and groundwater systems creating the flow regime and temperature of the Well. To focus on the borehole was sensible, because the Well is sometimes dry, whereas

Figure 5.16 Flow from Borehole SG4 before a flange was installed on the wellhead.

Photograph of flow from SG4 presented by Dr Sarah Blake at the IRETHERM Workshop in Dublin 1st April 2016
"An investigation of Irish thermal springs- provenance, pathways and potential"

placing logging instruments into the borehole would provide a continuous record of groundwater temperatures, water levels, and conductivity.

Sarah Blake measured, or estimated, the flow from the borehole(s) as 1,000 m^3/d, but there is no date for the measurement.

Figure 5.16 shows the flow from borehole SG4 before the flange and heavy steel covers were installed on boreholes SG4 and SG7. It is a photograph presented by Sarah Blake at an Iretherm Workshop in Dublin in 2016. The photograph shows water flowing through two holes cut in the casing below the top of the casing. For clarity, the level of the water inside the casing is marked with a small white arrow added to the photograph.

The outlet holes are relatively small. As long as the artesian flow up the borehole does not exceed the capacity of the outlet holes accommodate the flow, the water level will not rise above the top of these holes. However, if the flow up the borehole exceeds the capacity of the outlet holes then the water level will slowly rise in the casing until the water flows over the top of the casing. Though these holes are a reference point, the level of the water may exceed this reference point.

5.2.10 Kilsaran

The monitoring work carried out in the present investigation carried on from Sarah's work, and focused on monitoring the water levels and water temperature in borehole SG4. However, we witnessed the Well contain water in late January, February and early March 2021.

Figure 5.4 shows the Well depression when it was dry on the 11th March 2021, and Figure 5.5 shows the small flow from the depression on the 5th February 2021.

To provide a range of views, Figure 5.17 is a collage of four photographs of the Well depression containing water in 2021.

The first photograph shows that a small amount of water had seeped into the depression by the 21st January. The water level was just covering the grass at its deepest point. The water level in borehole SG4 on this day was 0.49 metres below the top of the casing. In other words the Well starts to contain water before the boreholes start to flow, because the bottom of the Well depression is 0.69 metres below the top of the well head casing in borehole SG4. There was no flow out of the Well.

The following measurements were made at the site on the 21st January

A Diver pressure transducer was placed in the deepest water in the Well at 12.20pm and the temperature was 7.7°C.

The temperature of water in the borehole SG4 was 16.7°C.

Figure 5 17 Photographs of St Gorman's Well in January and February 2021

The temperature of the flowing water in the drain was 7.4°C.

The air temperature at Dunsany met station was 4.6°C.

The air temperature at Rathcore quarry was 3.6°C.

The lower middle photograph in Figure 5.17 shows St Gorman's Well when it is near its maximum depth and extent. By the 12th February the water level is starting to recede. And by the 26th February it has receded slightly further. By the 11th March the Well was dry.

On the 5th February there was a slight flow from the Well and also the borehole SG4 and SG7 were flowing. I took the opportunity again to measure the temperatures and electrical conductivities of the water flowing from both boreholes, water in the Well and flowing water in the curved section of the drainage ditch next to borehole SG6. This measurement point is above confluence with the straight drain, that was receiving the additional flow from the boreholes SG4 and SG7.

The values for the 5th February were:-

Site	Temperature °C	Electrical Conductivity (EC) µS/cm
St Gorman's Well pool	10.6	740
Drain next to SG6	9.6	736
Borehole SG4	17.0	766
Borehole SG7	17.0	765
The air temperature at Dunsany @ 15.00h	5.2	
The air temperature at Rathcore @ 15.00h	5.3	

The data are revealing.

First, they show that the water coming out of the boreholes is much warmer than the water flowing up into the Well.

This could be because the water in the Well is being cooled by the low temperature air above the open pool. It also could be because the natural upward flow of warm water from the deep bedrock is being mixed with colder shallow groundwater in the upper bedrock and overburden, just before it arises in the Well.

Second, the data shows that the water in the drain is groundwater, and not surface water. Surface water, or even water from soil drains, would have a lower Electrical Conductivity (EC), and would be much cooler.

The EC and temperature of the water in the drain is similar to the water flowing up in the Well. The EC of the water in the drain is similar to the EC of the water flowing out of the boreholes. The water in the drainage ditch may be a mix of two groundwaters.

Figure 5.18 Artesian flow from Boreholes SG4 and SG7 on the 5th February 2021

SG4 SG7

Note: these two photographs were taken under the shade of the coniferous trees, at 1/25th second exposure. The moving water is blurred at this shutter speed, and therefore the volume of the flow looks greater than in reality. The combined flow was estimated as a maximum of 4 litres per second; i.e. about 350 cubic metres per day.

To complete the record of flows and temperatures at the St Gorman's Well site, Figure 5.18 shows the artesian flow from boreholes SG4 and SG7. The steel covers had been removed from the boreholes to let the water flow freely under artesian pressure from each hole. The flow from each hole looks more prolific than it was at the time, because the photographs were taken with a slow shutter speed and the water flow is blurred. I estimated the flow was not more than 4 litres per second or about 350 cubic metres per day.

From the foregoing; it can be seen that the temperature and flow at St Gorman's Well site varies, and has varied over time with the seasons and over the years. The measurement of a temperature in the Well of 25°C in 2003 is not supported by other measurements both before and after 2003 and should be discounted. The highest reliable temperatures measured in the Well are between 21 and 22°C. In summer, the Well is often not flowing and as Du Noyer noted in 1859 it is often 'not the least warm'.

5.3 Water Level and Temperature Monitoring 2013 - 2022

It was evident from Stephen Peel's manual monitoring of the Well in the early 1980's that conditions change throughout the year. It is also evident that short term monitoring or spot measurements since 1983 have not greatly improved the understanding of the reasons behind the changes during the year or the processes giving rise to these changes.

The availability of modern logging equipment that can measure different parameters reliably and store large amounts of data has meant that the conditions at the site can be measured frequently and without a need to visit the site daily.

Sarah Blake started monitoring borehole SG4 in July 2013 as a part of her PhD thesis entitled "A multi-disciplinary investigation of the provenance, pathways and geothermal potential of Irish thermal springs". Her thesis was accepted in February 2016.

Routine monitoring has been carried out on borehole SG4 because it is accessible and it taps into cavities deep in the Waulsortian limestone bedrock.

Borehole SG4, and the other boreholes, are an integral part of the site of St Gorman's Well, but as the data described in the previous section has shown, they do not represent the characteristics of the water in the natural depression called St Gorman's Well.

The water entering St Gorman's Well has to flow either by gravity, or by upward pressure, through natural materials. The boreholes, by contrast are, in essence, open pipes or tubes that provide easy access to karst conduits below 90 metres depth in the bedrock

Sarah Blake first installed a HOBO U24-001 data logging device in borehole SG4 to measure temperature and electrical conductivity, then ten months later she installed a second instrument, a Solinst Levelogger LT unit, to measure water levels and temperature. The two blue cords attached to these instruments can be seen in Figure 5.16. She removed the instruments in September 2015.

Sarah's interest extended beyond the thesis, and she installed a Solinst temperature, water level and electrical conductivity logging device in August 2018, and let it collect data until August 2019.

Sarah's instrument was on loan, and she wished to move it to another location. With the agreement of Sarah and Nicholas Wilkinson (the owner of Hotwell House). I and Sarah swapped her instrument for a similar instrument (an Eijkelkamp 'Diver') that can measure water temperature and water levels.

Sarah has since given me a copy of the data collected by all her instruments.

I have kept one Diver in borehole SG4 from August 2019 to the present taking readings every 30 minutes. As I realised the importance of the data from SG4, and also the speed with which water levels fluctuated in the borehole, I installed a second Diver in the borehole in October 2020 as a back up, and to take more frequent readings. The second Diver has taken readings every minute in 2020-21, and every 5 minutes in 2022.

The first Diver was hung on the cord that Sarah used for her instrument. It is at 6.79 metres below the top of the casing.

The second Diver was put deeper in the hole at 13.4 metres below the top of the casing.

When I have visited Hotwell House to download the data from the instruments I have often met Nicholas Wilkinson, and showed him the data from his borehole. I have occasionally printed out graphs of the data for him when the data shows interesting changes or patterns, so that he can be aware of what we are finding. I have only been able to obtain the information from his borehole because he generously gave me permission on the basis that there would be transparency. I have been happy to discuss the data and share my interpretations as the data has come in.

As a result of Sarah sharing her data, and Nicholas Wilkinson's permission, there is now nearly 6 years of data since 2013, with a gap between October 2015 and August 2018.

I have managed to merge the data from Sarah Blake's instruments with Kilsaran's Diver data to compile a single composite series of graphs shown in Figure 5.19.

The graph consists of four elements superimposed one above the other.

At the bottom are the daily rainfall amount recorded at the synoptic weather station at Dunsany.

Above this is a graph, in green, showing the electrical conductivity recorded by Sarah's instruments.

Above this are the water temperature measurements, in pink,

At the top, are the water level measurements.

The scales for each graph are different and shown next to the data.

Though the graph shows a simple pattern of colours, it contains detail that is complex and very informative. It is necessary to go through the graph correlating the different elements in order to draw out the information.

Starting on the left side of Figure 5.19, in the summer of 2013. There is no water level information, but the temperature is decreasing gently and initially the conductivity (EC) seems stable at around 700µS/cm. The EC decreases erratically during the autumn, whilst the temperature falls at an increasing rate suddenly goes down by 4°C at the end of October. This appears to be in response to rain at the start of October and several days rain at the end of October. The temperature remains constant and low at 11°C for most of November and December and then suddenly rises by 9°C at the end of December. With a slight lag of 5 days the EC drops by 50µS/cm.

For the next four months the temperature and EC remain relatively constant. Though there is no water level data, it is reasonable to assume that the water level in borehole SG4 was high, and water was flowing freely from the open top of the borehole during most of this period, and certainly during February and March. During these two months the temperature was above 21°C, which is the highest temperature shown on the graph.

Sarah installed a second instrument to measure water levels and water temperature at the beginning of May 2014. It can be seen that the water levels were receding during May and the temperature was also going down. The EC remained constant.

There is a thin red line above the main temperature line. This is the temperature recorded by the second instrument. It gives readings that are about 1°C higher than the original instrument, but the pattern of temperature changes recorded by both instruments remain the same.

The flow of water out of the borehole stopped in May because the water level would have fallen below the level of the holes in the casing, that can be seen in Figure 5.18, and by the end of May the pool of water in the Well had probably disappeared. .

Though the water level declined steadily throughout May and June, the EC suddenly rose from 550 to 740µS/cm and the temperature dropped by 5°C at the end of May. It is as if one source of water in the borehole had suddenly been 'switched off' and replaced by another water with a lower temperature and a higher level of dissolved minerals.

It is important to recognise when interpreting the data that borehole SG4 is not free flowing at this time. So these changes are happening in borehole with no apparent movement of water. It

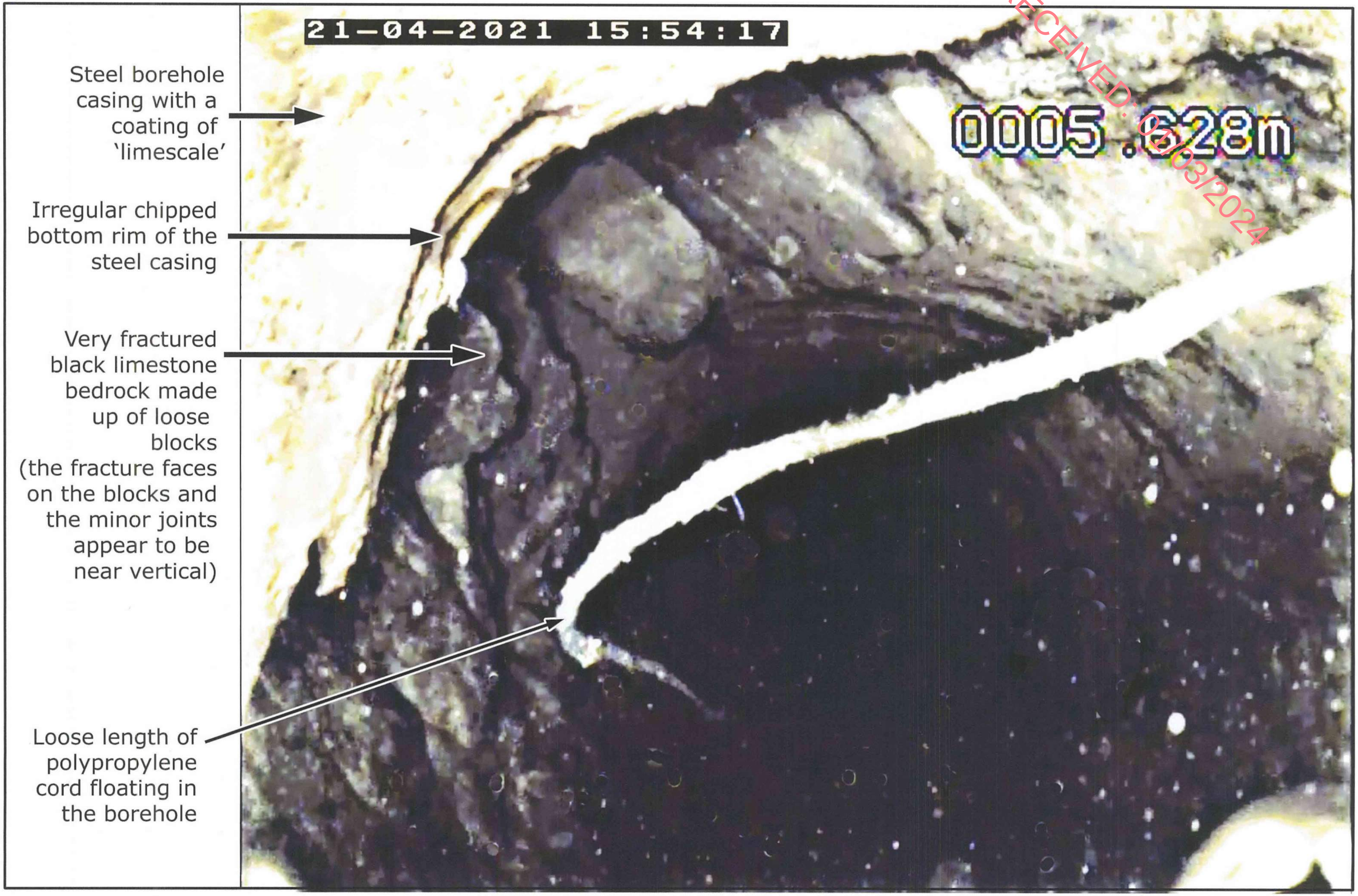


Figure 5.20 Borehole SG4 Video Survey by GSI - Broken rock at bottom of steel casing

is also important to recognise that the borehole is, what is called, 'open hole'. This term means that the borehole is not lined with a blank casing and with the annular space between the casing and the rock and overburden sealed with a cement grout. In other words, there is nothing to stop water flowing into the hole and out of the hole through the breaks in the rock down the full depth of the hole. Therefore, water can flow up the hole from, say, the large cavity below 90metres, or flow across the hole from side to side, or can flow down the hole from, say, the gravels and till at the top, down to the cavity at 90metres. The instruments in the hole are at only 6.5 metres depth, just below the bottom of the unsealed steel casing. This is a good position for measuring the characteristics of the water flowing out of the hole under artesian pressure, but in this position the instrument may be only picking up indirect evidence of changes taking place deeper in the hole when the artesian flow has stopped.

Flow in the borehole need not stop just because the artesian pressure is not sufficient to push water out of the hole. The upward pressure from deep in the rock may still be sufficient to push water up the hole, but the water does not come out of the top, but leaves the hole in the upper part of the bedrock or in the overburden. It is also important to recognise that groundwater is always moving. It is usually moving sideways from places where the water level is high to places where the water level is lower. Therefore, water flows across boreholes from an open crack in the rock on one side to a corresponding crack in the rock on the other side.

Therefore, a potential scenario is that warm, lower EC water was flowing up the hole and out of the top when the water level was at its height. Then the water level fell so that freeflow stopped, but the warm lower EC water was still being pushed into the bottom of the hole and instead of flowing out of the top it was flowing out of through the side into the rock and overburden near the top.

Figure 5.20 shows a screen grab from the borehole video taken by the Geological Survey in 2021. The video camera was at 5.628m below the top of the borehole. The instrument measuring the changes in May June 2014 referred to above, would have been at about 1 metre below the bottom of the casing shown in Figure 5.20.

The still from the video shows the ragged end of the steel casing in SG4 and below it, the broken top of the bedrock. There appear to be other open joints, cracks and bedding planes between 9 metres and 10.5 metres. These breaks in the bedrock along the length of the borehole are the potential routes for water to flow in or out of the borehole.

Therefore, if the upward pressure from deep in the rock makes the water level inside the borehole higher than the water level in the upper bedrock and bottom of the gravels/till overburden aquifer then water will flow up the hole and out into the shallow aquifer.

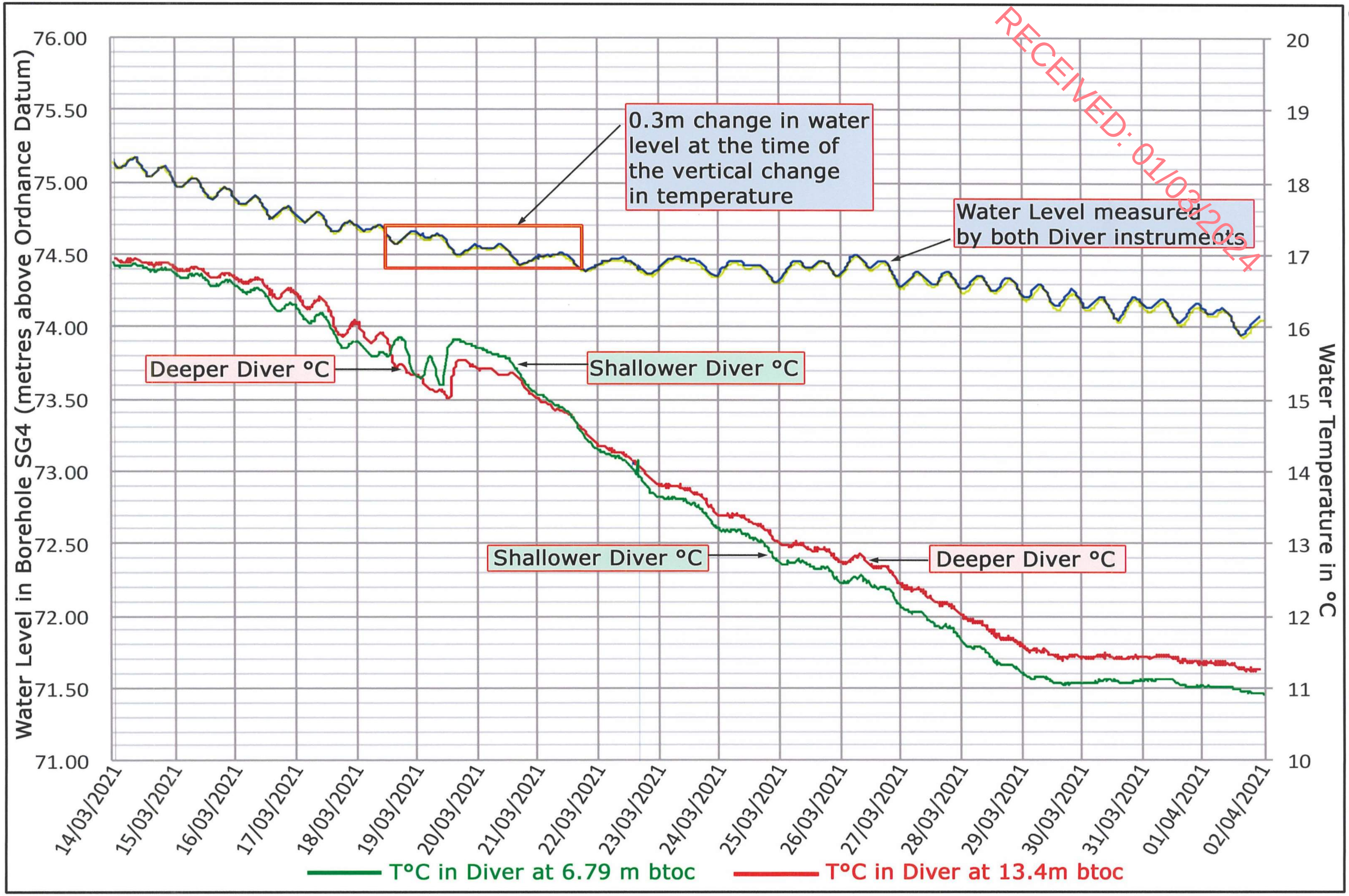


Figure 5.21 Borehole SG4 March 2021 - an example of vertical temperature differences

If the ability of the water to flow out of the hole is less than the rate at which it is flowing up the hole then the water would flow out of the top of the hole, but if the upward pressure diminishes the upward flow is reduced, and then a balance may temporarily occur where the water is able to flow out into the shallow bedrock at the same rate as it is coming in at the bottom.

Therefore, an instrument 6.76 metres below the top of the casing may have been detecting a flow up the hole and out sideways into the shallow bedrock early in May 2014, but by the end of May the upward pressure had declined so that it was not able to fill the hole with warm, low EC water up to -6.76 metre level. With this reduction in upward pressure the column of warmer water fell back and, cooler, higher EC water was able to leak into the hole from the shallow groundwater aquifer above. There may still have been some convectional mixing in the hole that created a blend of waters, but the temperature measured by the logger at 6.76 metres below the casing recorded a drop in temperature of 6°C in about ten days.

It is usually supposed that a measurement of the water temperature in a borehole gives a temperature that is representative of all the water in the hole and the water in the aquifer outside the hole. This is normally a reasonable assumption. However, water is often layered, or confined to different passageways in the rock that are separate and have a different age, chemistry and temperature.

Figure 5.21 illustrates this point. The figure shows the temperature and water level data from both Diver instruments in March 2021. The water level and temperature rise and fall with the effect of earth tides that will be discussed in detail later in this chapter.

The situation in March 2021 is analogous to the situation in May 2014.

In March 2021 the water temperature dropped by 6°C in two weeks.

The objective of the graph is to illustrate how water can enter a borehole and create a change at one level that is not detected at another level.

It can be seen in Figure 5.21, that on the 14th of March the temperature recorded by both instruments was the same at just under 17°C. Thereafter, the temperature data diverged slightly. The temperature of the shallow Diver at 6.76 metres below the casing, shown in green, was cooler than the temperature recorded by the deeper instrument, at 13.4 metres depth, shown in red.

At midday on the 18th March the temperature of the water at 13.4m metres depth suddenly fell by 0.4°C, but the temperature at 6.76 metres followed the preceding trend, and the two lines on the graph changed relative position; the water at a shallow level in the borehole was now warmer, and the deeper water was cooler.

The shallow temperature rose and fell with the tides, but the deeper temperature followed a small steady decline.

Then just after midday on the 19th March the temperature at both levels in the borehole rose abruptly, but still the deeper temperature was lower than the shallow temperature. By the 21st March both temperatures were the same and declining at the same rate.

After the 22nd of March the temperature of the shallow water declined more steeply and the temperature of the deeper water remained higher than the shallower water.

The two lines on the graph swapped positions again.

The decline stopped on the 29th March.

There was no obvious change in the pattern of water water levels recorded by either instrument, but it appears that during the fall in water levels of roughly 0.3 metres, between the 18th and 21st of March, the water column in the borehole changed, or became unstable, and some cooler water entered the borehole.

The obvious reason for this is that the water pressure on the inside of the borehole fell below the level of the water in the rock or gravels outside the hole, and cooler water entered the borehole from the surrounding rock at, or around, the 13.4 metre depth.

Then curiously some warmer water entered the borehole at midday on the 19th and gradually the deeper water in the hole became warmer than the water at a shallow depth.

There is no certain explanation for these temperature differences over such a short vertical distance in a borehole, but the graph serves to illustrate that the groundwater tapped into by SG4 is not homogenous. Nor is it representative of just the water flowing in the big karst conduit at below 90m depth, or the water in the rock below St Gorman's Well. Instead, at a particular moment in time, it probably represents a variable blend of different groundwater flow systems, at different levels, with different pressures and temperatures.

Returning to the large graph in Figure 5.19.

After the sudden decrease in temperature at the end of May 2014, the temperature remains in a narrow range between 14 and 15°C, but coincident with very heavy rain, of over 50mm in a day, at the beginning of August, the EC drops suddenly and then rebounds and spikes abruptly, followed by another drop and rise after a further 20mm rainfall event later in the week. There was a simultaneous rise in the water levels. The temperature had been rising slightly, and after the spikes in the EC and the rise in the water level, the temperature decreased.

The EC graph is less smooth than the temperature and water level graph during the summer and early autumn in 2014. The EC seems particularly responsive to rainfall. During a day of heavy rain, the EC of the water in the borehole drops suddenly but briefly.

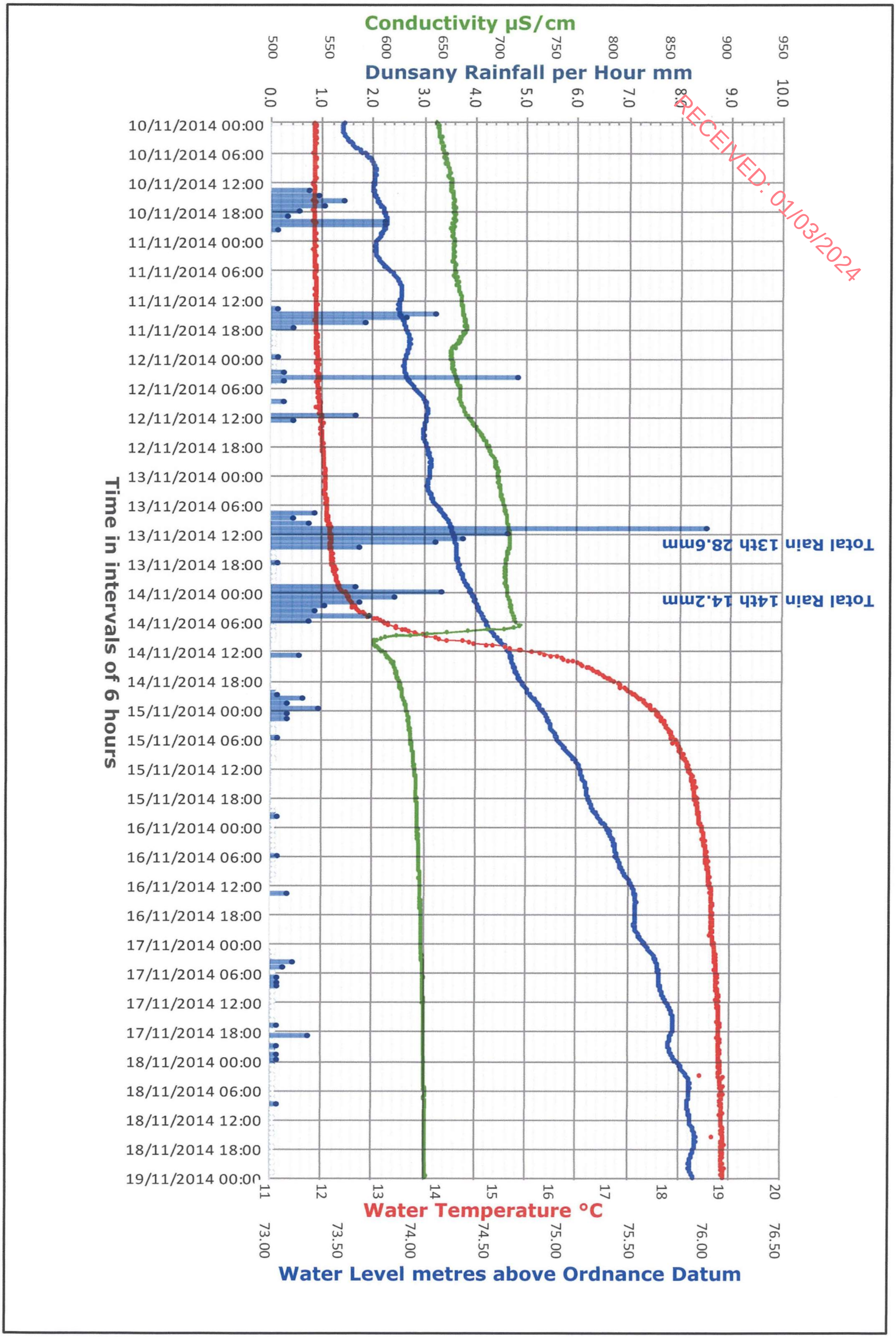


Figure 5.22 November 2014 Water Temperature, Level, Conductivity and Hourly Rainfall

The most obvious potential source for low conductivity water entering the borehole would be the nearby drainage ditch. Normally it would be dry with the groundwater level below 74 metres OD, but if it suddenly contained surface runoff during heavy rain, then the level of this low conductivity water in the ditch would be above the water level in the ground, and in the borehole. There would be the potential for this 'fresh water to flow down, and sideways by gravity, into the adjacent borehole.

The more sustained rise in conductivity for a few days after the rainfall may represent a second flush of recharge from the rain coming through the soil and overburden on the slopes of Ballynakill hill and down to the borehole.

The conductivity data in the summer and autumn of 2014 and later throughout 2018 gives an insight into the intimate connection between the events on the surface and conditions in deep borehole SG4. The conditions measured in the borehole are not just a measure of the conditions deep in the bedrock.

During the autumn of 2014 the temperature decreased by about 2°C, though the water level remained constant, then in early November the water level began to rise, followed in mid November by a rapid rise in the water temperature.

This can be seen in the large graph (Figure 5.19) but can be more clearly seen in the detail in the graphs in Figure 5.22. This figure shows the changes from the 10^{th} to the 19^{th} November 2014.

The figure shows the hourly rainfall measured at Dunsany. The timescale divisions are at 6 hour intervals. The daily total rainfall is labelled for the two large rainfall events on the 13^{th} and 14^{th} November. By comparison there was very little rain after the 14^{th},

The water level was rising steadily up until the 13^{th}, and then the rate of rise increased slightly. There was no sudden change in the steady rise of the water level in the borehole, yet suddenly the temperature rose by about 7 degrees in 30 hours. and the conductivity fell by about 130µS/cm in 4 hours.

It appears as if the intense rainfall triggered a sudden change. As if extra rainfall had caused some component of the groundwater system to go beyond a tipping point. However, as Sarah Blake said when interpreting the same data, the change isn't linear. It is probable that two or more things are happening at the same time. A similar pattern occurs in all other years, and having reviewed the full data set, the pattern will be more fully discussed.

The sudden drop in conductivity in November 2014 was followed by a smooth partial rebound before yet again falling to 550µS/cm in February 2015. The water level rose above 76 metres OD and the borehole started to flow. The borehole was open topped (as shown in Figure 5.16) and water could flow freely through the holes in the side of the casing. The temperature rose to 19°C by the end of November, and then rose again in January to reach a peak of 20.6° on the conductivity and temperature logger, and 21°C on the water level and temperature logger. The borehole appears to have flowed from the end of November to the middle of February 2015, except for a small interval in December.

The temperature and conductivity appeared to remain relatively constant despite the cessation of flow from the top of the borehole.

As has been said above, the normal temperature for ordinary groundwater in Ireland at this latitude is between 9.5 and 10.5°C. If the upward flow of warm water had ceased once the water level was insufficient to push water out of the top of the borehole casing, then the column of warm water in the borehole would have cooled if there was cool water around the hole. The fact that it didn't cool, and high temperatures lingered, indicates that the warm water was also in the rock around the borehole.

In other words, if the borehole is acting as a passageway for warm water from depth to rise to the surface, when the flow to the surface has ceased, then the warm water must be still flowing up the hole and out into the fractures, joints, bedding planes gaps in the rock around the borehole.

It is equally possible that the borehole is not a short circuit express route for warm water to rise towards the surface, but that warm water is generally rising to the surface or near surface throughout all the cracks and conduits in the rock mass in the general area of the St Gorman's. Stephen Peel's monitoring in the 1980s showed that warm water rises up in the Well pool, and the Wilkinson family would bathe in the relatively warm water pool in winter, but the recent measurements made by Richard Langford in April 2011 record that the temperature in the Well while it was flowing was only 10.5°C. Tobins measured the temperature of the Well in September 2009 as 14.4°C, at a time when borehole SG4 was flowing with a temperature of 20.6°C.

The sustained high temperatures remaining in the borehole in the late winter and spring of 2015, when there was no flow from either the boreholes or the Well, raises the question of, to where is this warm water flowing?

Groundwater is always moving down gradient. Therefore, the rising warm water in both the borehole and the cracks and conduits in the rock around, is probably mixing with cooler shallow water, and then flowing to the northwest in both the bedrock and the overburden/gravel groundwater systems.

A clue to the pathway of this possible plume of warm water may be found in the measurements of water temperatures made during pumping tests at Longwood Water Supply boreholes 1 and 2 in 2011. After the pumps had been stopped at the end of the tests tests the temperature of the natural artesian flow from the Waulsortian conduits in Borehole 2 was measured as 12.1°C, and the water from the shallow gravel aquifer feeding Borehole 1, was 11.4°C. These measurements were made by instruments in the boreholes.

These temperatures concur with earlier manual measurements made by EDA on water as it was being pumped from Longwood borehole 1 in 2001. On the 29^{th} March 2001 the average temperature was 12.35°C. On the 8^{th} June it was 12.65°C.

Water that is pumped from a borehole is usually warmer than water that is not being pumped. (Submersible pump motors, that are often 5-10kW, transfer their heat to the flow of water in a borehole before the water enters the pump intake and is pushed to the surface.)

Additional evidence is that Tobins on the 23^{rd} September 2009 also found a spring flowing from gravels on the banks of the Clonguiffen stream at site SW4 with an EC of 910 µS/cm and a temperature of 11.8°C.

These temperatures are elevated above normal groundwater temperatures. Normal temperatures are found in the boreholes drilled by EDA into the Waulsortian limestone on the western flank of Ballynakill hill, northeast of St Gorman's Well.

On the 18^{th} May 2001 these were:- Bh 4 10.15°C, Bh6 10.25°C, Bh 8 10.7°C, and during the pumping test on their Pumping Well from the 18th to the 21^{st} November 2002 the temperature fell from 10.1 to 9.8°C.

The temperatures at Rathcore quarry are also normal at 9.8 – 10.7 degrees.

The elevated water temperatures, in the shallow gravels and the artesian flow from the Longwood boreholes, may not have been generated by just a single point upwelling of, say, deep warm water at the site of St Gorman's Well. It is possible to consider a more widespread linear upwelling of water along, say, a northerly oriented faults in the Waulsortian. These upwellings need not have a surface expression like St Gorman's Well. The warm water rises from a fault in the rock and then flows down gradient in both the rock and the overlying gravels to the west. It does not need to rise to the surface. The warm water can rise into the top of the limestone or the overlying gravels and then mix with cooler waters and flow down gradient within the rock or gravels.

Returning to Figure 5.19.

The water level in SG4 starts its summer recession in May 2015, and temperatures begin to fall in June. When the water level falls to 74 metres above datum the temperature drops more rapidly and the EC suddenly rises. It is as if one groundwater system is again exerting dominance over another.

The pattern is very clear in the data collected by Sarah Blake's instruments during 2013 -2015. However, though a change over occurred in 1981-1983, Stephen Peel's data showed that both the EC and temperature simultaneously fell at the end of summer.

It is difficult to draw conclusions from this clear difference, because the monitoring points providing the data sets may not be comparable; one is a pool in a shallow depression, and the other is a borehole connected to a deep cave system. However, if the data sets are comparable, then the difference in the change in conductivity response to the summer fall in water levels may indicate a change in the conditions affecting the St Gorman's site during the intervening 30 years.

Referring to Figure 5.19, Sarah Blake's data set for conductivity finishes in August 2015 and the water level and temperature data stops in September 2015.

There is no monitoring data for the three hydrological years between 2015 and 2018. However, Nicholas Wilkinson has quickly searched back through his family photographs and observations, and recalls that:-

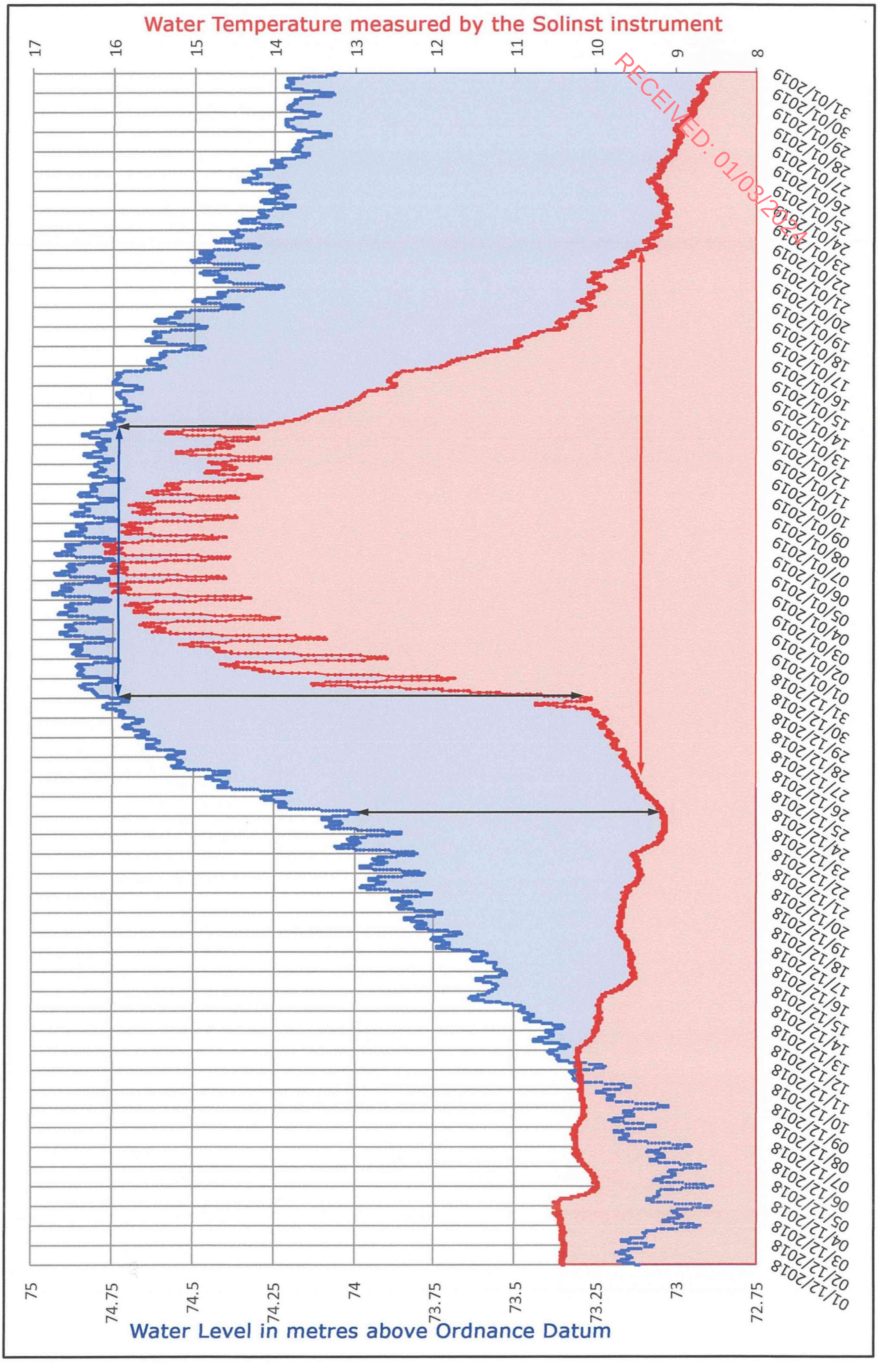
- in December 2015 there was a good flow from the Well;
- in March 2016 there was a full flow from the Well that then stopped in April 2016;
- in January 2017 there was no water in the Well;
- in March 2017 there was some water in the Well, but there was no flow from the Well
- in the winter of 2016-17 there was no flow at any time from boreholes SG4 and 7;
- in the winter of 2018, in anticipation of high water levels and flows, he cleared access to the boreholes and around the well, and got heavy flanged covers installed to seal boreholes SG4 and SG7; the water levels did rise and there was flow from the Well, but the anticipated high flows did not materialise.

Sarah Blake installed a combined EC, temperature and water level instrument at the end of the summer in 2018.

The water level and temperature level, shown in Figure 5.19, almost appear to be a continuation of the water levels and temperature in the summer of 2015. This would indicate that recharge and levels in the preceding winter of 2017-2018 were similar to the recharge and levels in the winter of 2014-15.

The difference in data between the years is that Sarah's new conductivity instrument recorded significantly higher conductivity levels than those in 2013-2015.

Figure 5.23Borehole SG4 Water Level &Temperature December 2018 -January 2019



The HOBO (2013-2015) and Solinst (2018-2019) instruments measure conductivity by different methods. I have assessed the possibility that the difference in conductivity levels relate to instrument type or instrument calibration, and concluded that the difference is real and natural, and not caused by instrument error or calibration.

The water conductivity in previous years had been high during the late summer when the water levels were low. The 2018 data shows the same pattern, but about 150µS/cm higher.

The rain in November and December 2018 causes the water levels in the borehole to rise and the temperature and conductivity to fall erratically.

Figure 5.23 shows the detail of the changes in water level and temperature taking place from the 1st December 2018 to the end of January 2019. The Figure has thin lines and arrows to show points of temperature change and corresponding water levels.

The start of the rise in temperatures occurs when the water level reaches 74.0 metres above Ordnance Datum. At first the rise in water levels is fast, but the rise in temperature is slow. Then, when the water level reaches 74.73metres the temperature rapidly rises from 10 to 16 degrees.

It is important to recognise that these changes were taking place in a sealed borehole. There was no flow up the hole and out of the hole. The slow rise with no tidal oscillation in temperature was probably a rising column of warm water that had not reached the datalogger at 6.76 metres below the top of the casing. The gradual rise in temperatures between the 24th and 30th December was probably convection mixing of warm water from further down the borehole with cooler water near the top of the borehole. When the water level in the borehole reached 74.73 metres the top of the column of warm water reached the datalogger.

The movement of the water levels under the influence of the tides was small; about 15-20cm, but every time the water level fell, some cool water came into the hole and the temperature recorded by the datalogger fell by 1.5 to 2 degrees. Then, every time the tide turned, the water level rose and pushed warm water up the hole and pushed the cooler water back out into the cracks in the surrounding rock.

The water levels gradually went down after the 9/10th January. as did the temperature, but when the water level had fallen to about 74.7metres the water temperature fell rapidly. This coincidence of a depth, just below 74.75 metres when the temperature rises rapidly and also falls rapidly suggests that in the groundwater system either in the borehole or in the conduits feeding water to the site, there is a step or critical level that controls the flow in and out of the borehole.

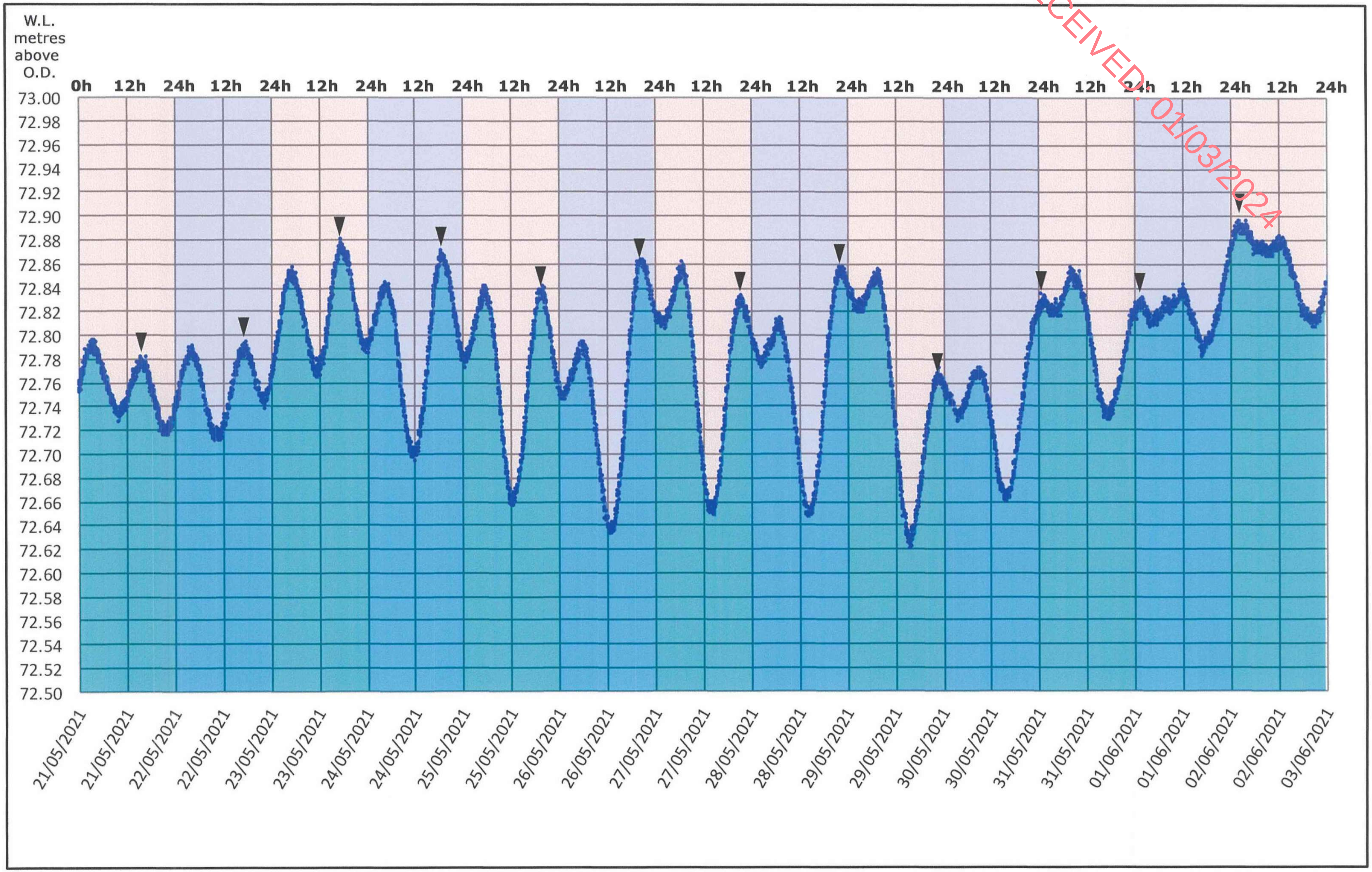


Figure 5.24 Borehole S.G 4 Water Level Fluctuations 21st May to 2nd June 2021

The rise and fall of the water levels and their influence on the temperatures is very noticeable in Figure 5.23.

Another example of a tidal movement may help clarify.

Figure 5.24 shows water levels measured by the second Diver instrument in borehole SG4 between the 21st May and the 3rd of June 2021. Each day has been given alternate colours for clarity. The vertical lines are at 12 hour intervals.

The figure illustrates the nature of the tidal movements. A black arrow head has been added to pick out alternate high tides. It can be seen that the high tide occurs later every day. On the 21st of May the tide is at about 4pm. By the 2nd June it is at 1-2am.

These tides look like marine tides, but they are different; they are earth tides and, though difficult to distinguish, atmospheric tides.

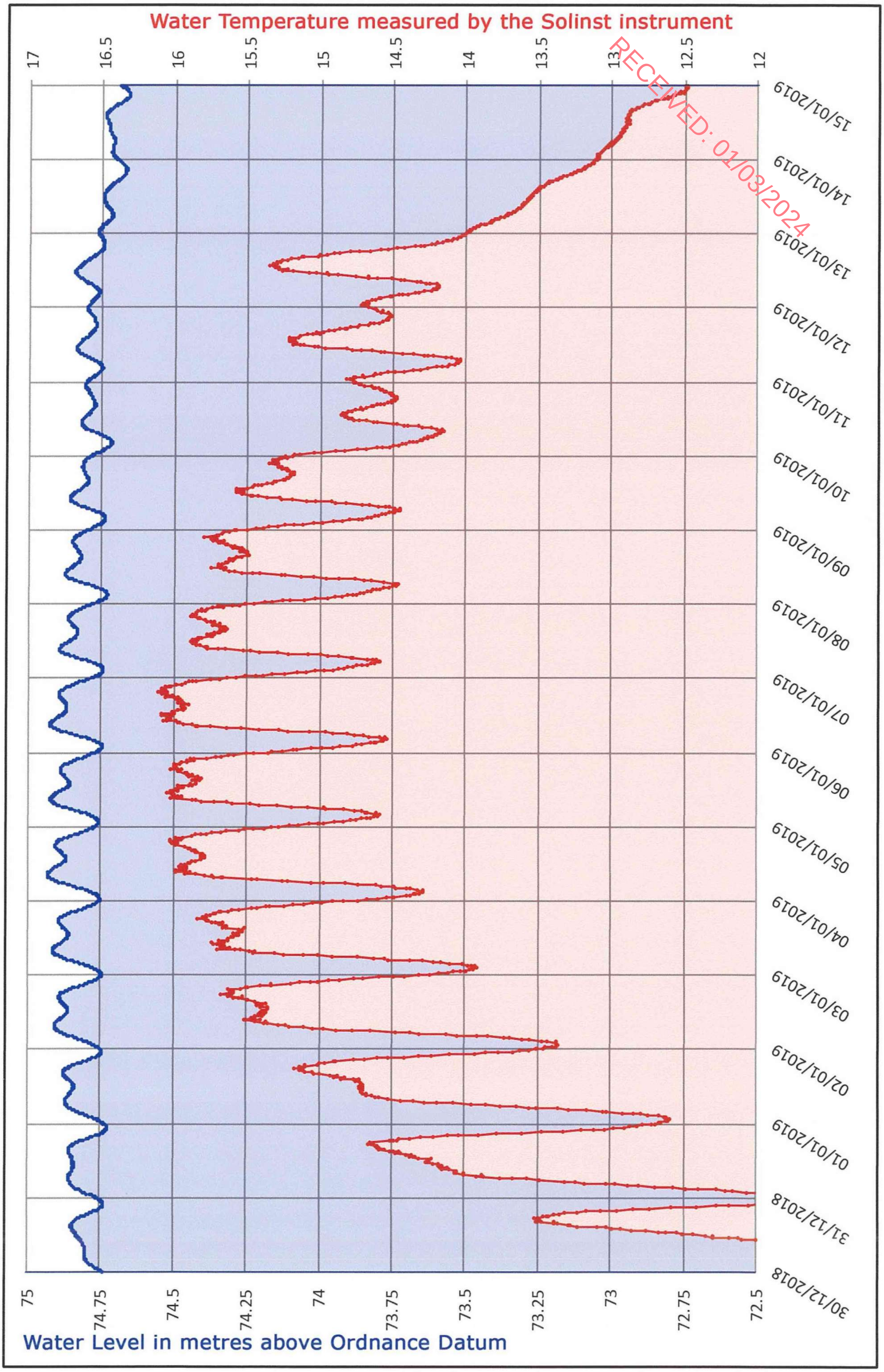
Marine tides are a result of the gravitational pull on the oceans as the earth rotates.

The same gravitational pull on the solid earth pulls or deforms the earth slightly. For example, as the moon's position, relative to the earth, passes overhead, the earth expands or is pulled in the direction of the moon. The rock doesn't break up, but the blocks of brittle rock move and existing cracks in the rock become slightly bigger. The effect of this is to create more space in the cracks for the water within them. So, the water fills the larger spaces between the blocks, and as a result, the water level measured in a borehole goes down a small amount. When the moon's position has just gone over the horizon the earth relaxes and the cracks get tighter, there is less space for water within them, and the water is squeezed up the borehole.

When an aquifer is confined, or sealed, by a low permeability layer of rock or clay the water in the confined aquifer is under pressure. Therefore, the small expansion and contraction of the earth is expressed more noticeably in a borehole that just taps into the confined aquifer. The moon's gravitational pull is the major cause of the tides, but there are about 10 different twice daily and once a day tides caused, for example, by the interplay of the sun's and the moon's gravitational pull. When the sun and the moon are lined up either together on the same side of the earth, or on opposite sides their combined gravitational distortion of the earth is greatest and the amplitude of the rise and fall in the borehole water level is also the greatest. This variation in amplitude can be seen in Figure 5.24.

The tide sequence is made more complex by a high tide in the day when the sun heats the atmosphere and it expands and becomes less dense. The atmospheric pressure on the pressurised water in the borehole becomes less and the water level rises. At night the pressure becomes greater and this depresses the water level in the borehole. There are other tides that relate to the distance of the moon from the earth. The moon has an elliptical orbit, and the

Figure 5.25 Borehole S.G.4 Water Level and Temperature 30th Dec. to 14th January 2019



distance and hence the magnitude of the gravitational distortion of the earth changes. The moon's orbit brings it 50,000 kilometres closer to the earth roughly every 28/29 days. For example, in Figure 5.24, the moon is the closest on the 26th of May at a distance of 357,311 km. There was a 22cm 'tide' in the water level in the borehole in the afternoon and evening of the 26th. The moon is furthest from earth on the 8th of June (off the graph) at 406,228 km. Meanwhile the moon and the sun are both above Ireland at the same time at midday on the 30th May (New moon phase) and the water levels are lowest.

Figure 5.25 is a detail from the crest of the temperature rise shown in figure 5.23 and covers the period from the 30th December 2018 to the 15th January 2019. The moon and sun are both overhead on the 2nd January and the moon is furthest from the earth on the 9th January. Though the water level scale is different from the scale in Figure 5.24 the tidal range is similar. Figure 5.25 illustrates how just a small movement of the water level can bring about a large but delayed change in the water temperature at a data logger positioned 6.76 metres below the top of the casing. The rise in level is not a great volume or surge of water rising up, or subsiding in the borehole.

The borehole is not flowing on the dates shown in the graph. The water level is at about the same level as the bottom of the adjacent ditch, and there is probably no water in the depression forming the Well. The graph of this data provides an insight into the small subtle changes taking place hidden underground.

Late December 2018 and early January had little rainfall. The rise in water level and temperature stalled, and then declined rapidly. The rise in water levels and temperature was like a 'false dawn'.

Meanwhile, in November-December 2018, the conductivity level had fallen abruptly with each rainfall event and then recovered quickly, but overall there was an erratic decline in conductivity between November and the beginning of March 2019.

After the first peak in temperatures and the rapid decline in January 2019, the water temperature, at the data logger depth, fell to below 8°C. This was the lowest temperature in the six year data series.

8°C is below the 'normal' groundwater temperature and, with a simultaneous sharp fall in EC, the temperature provides a strong indication that rainwater or surface water was able to get into the borehole.

Cold low conductivity rain cannot get in through the top of the borehole because the top is sealed. The borehole is not situated in a hollow where rainwater collects therefore, rainwater

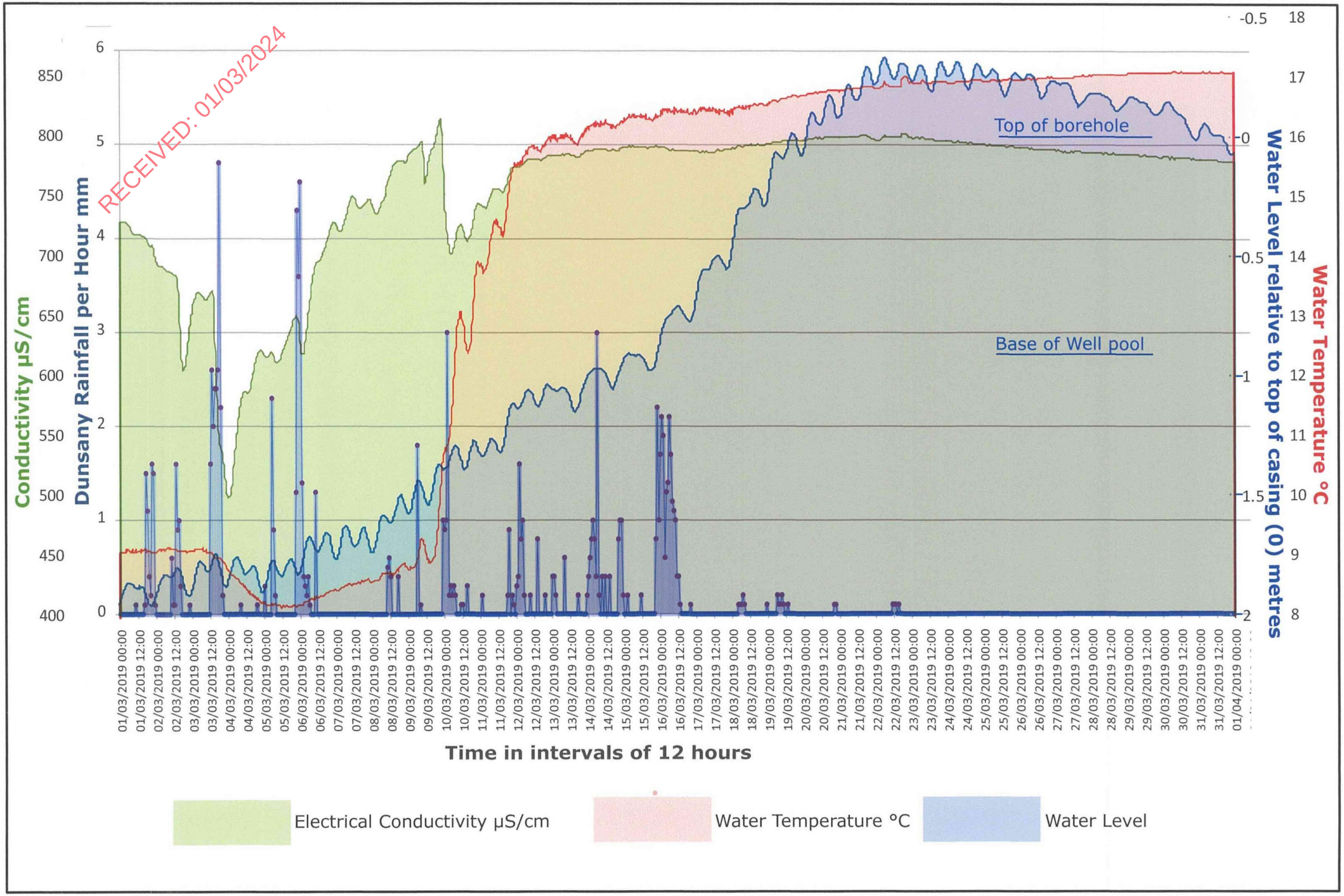


Figure 5.26 March 2019 Water Temperature, Level Conductivity and Hourly Rainfall,

did not flow down the outside of the steel casing from the surface. The data provides another indication that surface water probably is leaking into the borehole from the ditch 3 metres away. Water levels started to rise again after heavy rain at the beginning of March 2019.

Figure 5.26 shows a complex, detailed graph from the 1st March to the 1st April 2019. It is made up of four components. The rainfall from Dunsany is shown along the base. The rainfall is the hourly total measured at the Synoptic station. The advantage of showing the rainfall at hourly intervals is that it can be directly compared with the response in the other three components of the graph (water level, temperature and EC) measured by the instrument at 15 minute intervals. The rainfall essentially stopped after the 16th March, but the intense, and sometimes prolonged, rain before the 16th provided sufficient recharge to groundwater that the water level (pressure) rose above the bottom of the Well depression about the 15th March and continued rising for the next 6 days.

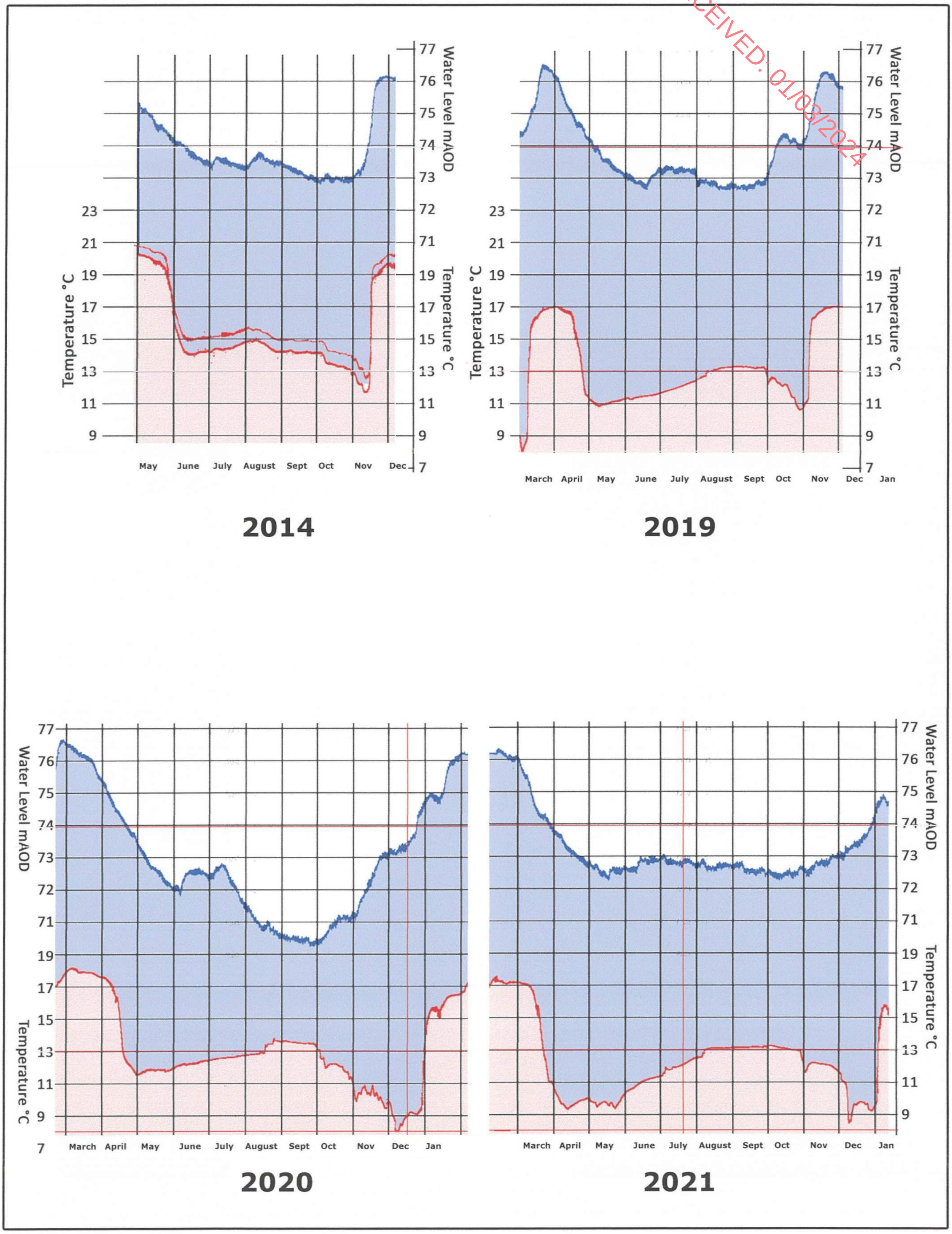
It is important to recognise that the water level is a pressure because the cover on the borehole was bolted down. Though the pressure was higher than the top of the borehole casing, there was no flow from the borehole because it was sealed.

As the water pressure built up inside the borehole casing, it rose and fell with the influence of the earth tides. The conductivity, and also the temperature, fluctuated with the rise and fall of the water pressure up until the 18th March, which was abut 36 hours before the water level reached the top of the casing. In other words the conductivity and the temperature stopped oscillating because water physically could not move up the inside of the casing any further, because it could not flow out of the top of the borehole.

The temperature did continue to rise further, at a gentle rate, which indicates that either water was flowing up the borehole past the data logger, and out into the fractures in the rock and the overburden outside the borehole, or warmer water was coming into the cave at 90 metres and the extra warmth was easing in convection currents inside the borehole. The conductivity data suggests that the first alternative is more likely.

The conductivity data shows the very rapid response to the major rainfall events up until the 10th March. During every major rainfall the conductivity fell and then slowly recovered. The graph shows how quickly low conductivity water can enter the borehole and change the readings made by the instrument. The response to rainfall appears to stop after the water level in the borehole rises above the level of the base of the nearby ditch. Water cannot flow into the overburden and the rock if the water level in the ground is higher than the water level in the ditch.

Figure 5.27 Borehole SG4 Temperature rise in late summer 2014, 2019, 2020, 2021



The warm water having risen up the borehole, and up through the passageways in the surrounding rock, remains until the middle of April (see Figure 5.19). though the water level or pressure started to subside in early April.

The temperature drops from 17°C in the middle of April 2019 to 11°C by the end of April.

It is notable that the temperature in the borehole did not rise above 17 degrees in 2019. The temperatures were slightly above 17 degrees in the subsequent years when the Well and the boreholes flowed. It did not reach 17 degrees in the dry autumn and winter of 2021-2022 when there was no water in the Well.

Figure 5.27 shows the temperature and water level data for four years when there is a full data record for the spring summer and autumn months. The focus is on the summer months.

The temperature data shows a pattern that is similar in all four years.

In spring and early summer, the water level in the borehole slowly recedes, but the water temperature drops rapidly.

After the water temperature reaches its lowest level, it starts to climb slowly, increasing, in recent years, by two to three degrees over the next four to six months. In the last three years there has been a plateau where the temperature remains fairly constant around 13°C for one to three months in the late summer. These summer temperatures are not high, but they are significantly about the temperature for 'normal' groundwater.

This pattern of gradual rise and plateau indicates, with the exception of 2021, that groundwater above 11°C is still in the bedrock at the start of the summer and that warmer water (13°C) is either added to the shallow groundwater system measured in SG4 by rainfall recharge during the summer or warmer water is rising up from below.

This is important, because it indicates the possibility that the circulation system that introduces warm water in winter could be, to some degree, active throughout the year. In winter, it is very active, but in summer it may still taking place, gently and hidden from view. The reason for a small rise in temperature in summer is explored and discussed further below.

The temperatures of 11 to 15 degrees in summer at 6 metres below ground level in borehole SG4 may tie in with 12 degree temperatures found in the spring in the Clonguiffen stream and the Longwood water supply boreholes.

Historically, St Gorman's Well has been seen as the unique site where warm water rises to the surface, but the summer temperatures in SG4 provide evidence that there is a background level of warm water at a shallow depth throughout the year, that may be widely distributed

The temperature rise in summer does not appear always to be directly related to rises in the water level in summer. In 2014 the temperature rises and peaks before a small peak in water levels in August. Whereas, in 2019, 2020, and 2021 there is a rise in water levels before the plateau in water temperatures.

In recent years, there appears to be a coincidence between the lowest water levels and the highest summer temperatures. 2020 was a special year that will be discussed in detail below, but when the water level was at its lowest the water temperature was higher than in 2019 and 2021.

The deep warm water flow is controlled by the pressure or head of water at its source. For the warm water to rise at St Gorman's, or elsewhere, the head of water driving the upward moving water has to be higher than the head of water in the shallow aquifer at the outlet. Water cannot flow upward if the driving head is less than the downward head of water exerted by the shallow groundwater system at the outlet. The water temperatures from the end of August through September in 2020 are slightly higher than in 2019 and 2021 possibly because the 'water table' or head of water in SG4 was lowered by the pumping from the Rathcore boreholes, whereas, the pumping did not drawdown the head of water in the area driving the deep warm water flow. Therefore, there was possibly a slightly greater difference between the head in the input area and the head at the outlet area (SG4). A small amount of warm water moved into the large conduit at the base of borehole SG4, and some of this warmth migrated up the borehole by convection. This is just a possible explanation.

The recent graphs in Figure 5.27 show that after the late summer plateau in temperatures, the temperatures fall as autumn rainfall recharges the shallow aquifer, and the 'water table' rises. This is because cooler water has entered the shallow groundwater system, but also could be because the increased head of shallow water at SG4 is reducing the head difference between the inlet and outlet. The temperatures suddenly rises later when the head driving the deep warm water increases with recharge in the inlet area sufficiently to overcome the head at SG4 and upward flow is unleashed. The speed of the upward flow may also be assisted by a density difference. Warm water has a lower density than cold water. Low EC water contains fewer dissolved minerals and it is also less dense than a higher EC water. The differences are very small and probably would not make any difference if the warm water was trying to push up through the severely constricted pore spaces in, say, a fine sand aquifer, but could make a difference in a wide unobstructed vertical cave or borehole. There would be gentle convection currents, that would mix cooler water with the warmer water. This is explored further below.

Returning to Figure 5.19; the rain in September and early October 2019 brought about a rise in the water level and a depression in temperatures. There was a fall in water level during a dry end to October, followed by a rise created by several consecutive days with more than 10mm of rain at the beginning of November 2019. The temperature rose abruptly and water gathered in the base of the Well. The Well started flowing in November, but though it contained water until the end of January, there was little flow from the Well during this first phase of high water levels in the winter of 2019-2020.

The borehole flowed for two weeks in November 2019 but the water levels receded with two peaks and troughs to the end of January 2020. The water level oscillated with the tides during this period but the temperature did not oscillate significantly. It appears that the water temperature does not oscillate significantly with the tides if the heavy steel lid is on the borehole, and the water level in the borehole is above 75 metres above Ordnance Datum. It appears to oscillate more with the tides if water is either able to freely flow out of the borehole or up and down inside the borehole casing.

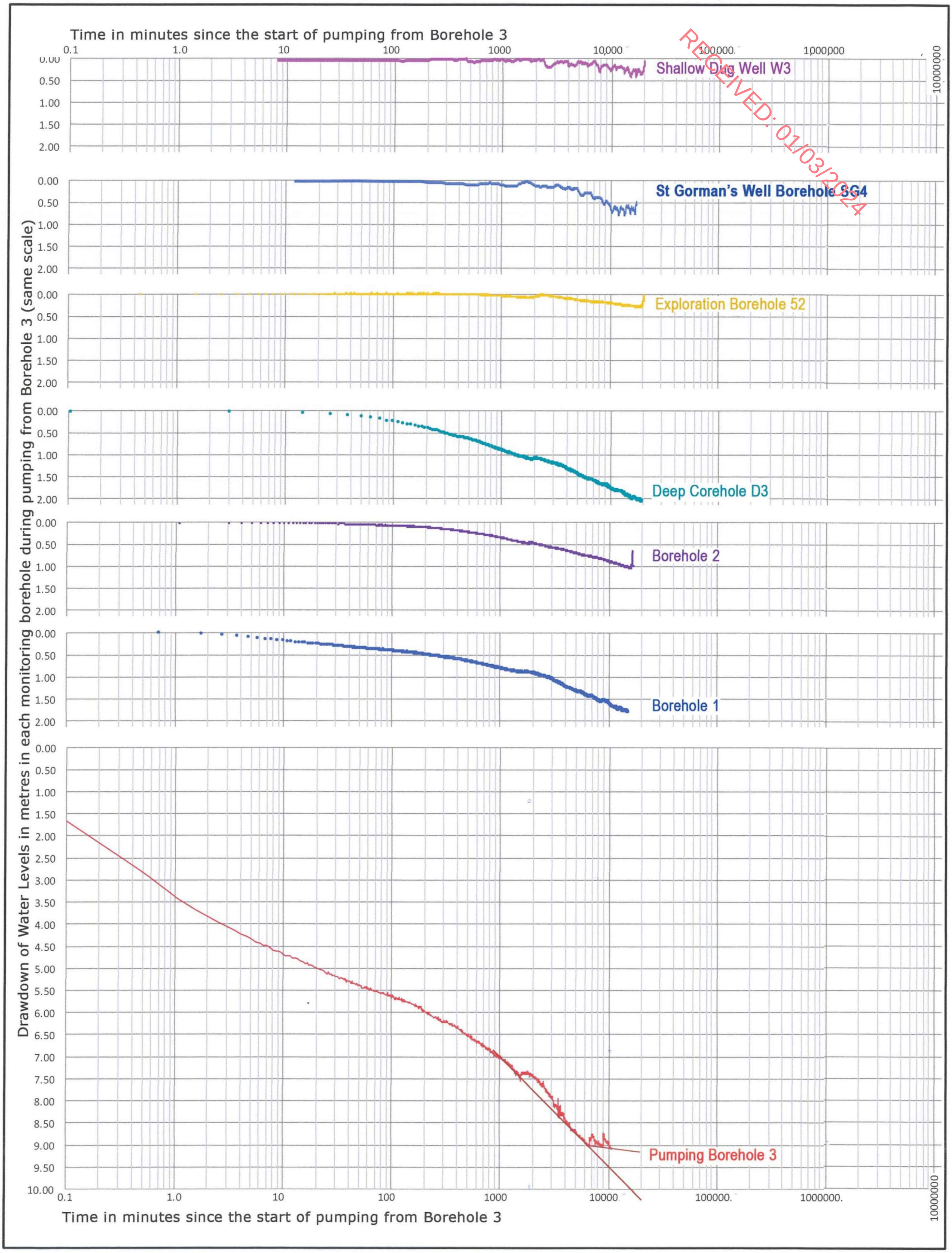
There was little rainfall from mid January 2020 to the end of the first week in February. The water level fell and so did the temperature. There was very heavy rain at the end of the first week in February and in response both water levels and temperatures rose to a peak at the end of February.

The temperature at the beginning of March 2020 was 18.2°C. The highest temperature recorded in the borehole between August 2018 to June 2022.

The dip in water levels and temperature in early February 2020 was coincident with a short development, or proving, test on borehole 3 within Rathcore quarry. The water was pumped from the borehole onto the quarry floor to allow the clay in the water to settle out in the layer of broken rock forming the quarry floor. Water was pumped from the quarry sump as usual to clear rainwater as necessary. Little water was pumped from the sump during the test because there was little rainfall. The water pumped from borehole 3 was largely flowing back into the karst cavities and re-circulating back to the borehole.

It was considered a possibility that the small lowering of the water level in SG4 might be a response to pumping in borehole 3 in the quarry, not because of the removal of water from the karst limestone, but by reducing pressure in the confined karst conduit system in the limestone. If one considers this system to be like a buried horizontal pipeline full of water and closed at both ends but with two vertical pipes running up to the surface. Then the water level in each vertical pipe would be the same. However, if a quantity of water is taken out of one vertical pipe and a new water level is created, then the water in the other vertical pipe would immediately fall and the water level in the first vertical pipe would rise, until both water levels were again the same.

Figure 5.28 Water levels during pumping of Borehole 3 29th January to 10th February 2020



It was considered possible that the small fall in water levels in SG4 might be as a result of a drop in water level (water pressure) in borehole 3 created by the pumping.

The water level in SG4 is not simply a measure of the upward pressure from a deep confined karst conduit system. The water level, as has been discussed in this chapter, is also a reflection of water levels in the shallow, unconfined, groundwater system in the overburden and the upper bedrock. Therefore, the small fall in water levels in SG4 in early February may have been just a natural recession in the shallow groundwater level or increased drainage into the adjacent ditch that contained little water during the dry period.

In order to assess whether pumping caused a pressure decrease in the confined karst conduit system, the water levels in SG4 were plotted on the same semi-log graph as was shown in Figure 4.19 in the previous chapter. A new version with the data from SG4 is shown in Figure 5.28.

It can be seen that the water level in SG4, whilst making allowance for tidal movements, remained the same for the first 2,000 minutes of the pumping test on borehole 3. Therefore, there was no evidence of an immediate pressure drop at the start of the test. The water level in W3, the overburden dug well, at the top of the graph, started a similar natural recession in the water level at about the same time.

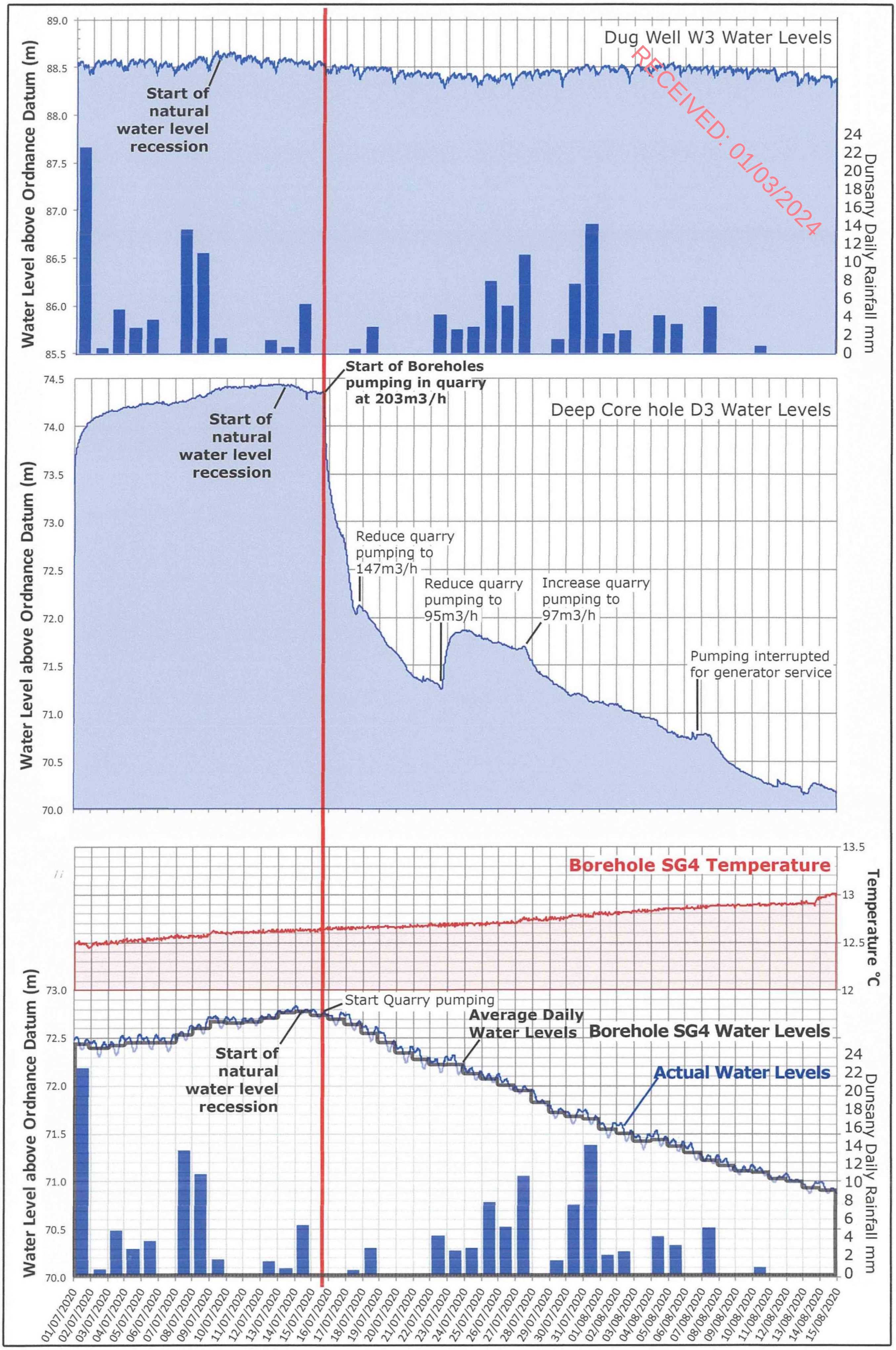
Therefore, the small fall in the water level in SG4 may have been just a coincidental natural recession in the water levels at SG4. However, the coincidental recession in the water level in SG4 alerted me to the possibility of a pressure link between the karst under the quarry tapped by the boreholes, and a potential extensive network of karst conduits throughout the Waulsortian in the area joined to SG4 at St Gorman's Well. This confined and pressurised network therefore, might provide an indirect pressure link to the confined karst conduits tapped by SG4.

For this reason, we designed the later pumping test in the quarry in the summer of 2020, to continue for a sufficiently long time to thoroughly stress the groundwater system, and gather evidence to find out whether a link could be established between water pressures in the karst under the quarry and the karst in the St Gorman's area. As described in Chapter 3, the pumping test went beyond the normal 3, 7 or 14 day tests, commonly carried out for planning applications. It extended for nearly 5 months.

Returning to Figure 5.19; The heavy rain in mid February 2020 caused the Well to fill and overflow and the two boreholes to flow.

The heavy lid on borehole SG4 was not tightly bolted down, with a rubber gasket seal, and water was able to squirt out from under the lid. As the water rose and flowed the temperature

Figure 5.29 Water Levels before, and at the start of long pumping test



continued to rise by a further 1°C, without any tidal oscillations. In other words there was a continual slow flow of warm water leaving the borehole. It was only on about the 7th March 2020 that the water level fell a little that both the water level and the temperature began to oscillate with the tides. From the graph it appears that the Well contained water until the end of March. I was not able to visit the site at this time, because the country was in Covid-19 'lock down'.

When the water level fell to about 74.5 metres above Ordnance Datum, the temperature fell rapidly from 17°C to 12°C.

There was a long recession of water levels in borehole SG4 from March to the start of June. This period was notably dry. During May and June, we carried out a series of pumping tests at the quarry to develop the boreholes by cleaning clay from the cavities feeding water into the boreholes. The objective was to create conditions where we could confidently pump water, with minimal clay content turbidity, direct to the quarry sump, and then let the pump in the sump lift the water to the settlement pond. These periods of pumping did not appear to have affected water levels in SG4. In fact, water levels in SG4 rose during this work with the heavy rain in June and early July.

Figure 5.29 is a multi-component graph.

It shows the water levels recorded by Diver pressure transducers in three monitoring wells and rainfall from the 1st July to the 15th August 2022. This time period covers the time before the start of the long pumping test in the quarry and extends for a month after.

The water level in all three monitoring wells is shown at the same vertical scale interval in metres above Ordnance Datum. Therefore, the amplitude of any water level change can be directly compared between each of the three graphs.

Shallow domestic dug Well W3 is shown at the top It represents the shallow groundwater response to rainfall recharge. The water levels fluctuate by small amounts each day because the well is pumped for short intervals to provide water for the house.

Deep core hole D3 is shown because the water levels show a rapid and pronounced response to pumping from the boreholes in the quarry. It is used as a proxy for the water level drawdown in the quarry boreholes during pumping at the start of the test because the water levels can be shown on the same vertical scale as the water levels in the other monitoring wells. The changes in the pumping rate in the quarry boreholes, during the first month of the test, are labelled on the D3 graph.

The lower graph shows the water level and temperature measured in borehole SG4 at St Gorman's Well. The graph is the equivalent of a close-up extract from the long graph shown in Figure 5.19.

The water levels in SG4 are shown in two ways.

There is a thin blue line showing the actual water levels measured by the Diver pressure transducer. This hydrograph fluctuates by as much as 20cm each day depending upon the strength of the lunar tides. Therefore, it is difficult to observe the subtle changes in water level. To assist, I have calculated an average water level for each day from all the water level measurements recorded by the Diver. Each average is based on 48 readings. The average water level is shown as a thicker black line.

The temperature of the water in borehole SG4 is also shown.

The daily rainfall totals measured at Dunsany are shown on the top and bottom graphs.

A red line down across all three graphs shows the start of the long pumping test.

The rainfall in May and at the beginning of July appears to have reversed the summer water level recession in all three monitoring wells. The water levels stopped rising before the start of the long test at different dates.

The water levels stopped rising and started to decline in the shallow dug well on the 9th/10th July. The water levels in the deep core hole peaked and started to go down on the night of the 12th / 13th July.

The water level in SG4 peaked and started to go down naturally on the night of the 13th / 14th July.

When pumping started in the quarry in the mid afternoon of the 15th July, the water levels were also naturally falling in D3, but they fell sharply almost immediately the pumping boreholes started. D3 is 350 metres north of the nearest pumping borehole (No.3) in the quarry. The water levels in D3 fell rapidly in response to the very high initial pumping rates from the boreholes in the quarry, until these rates were reduced on the 22nd July.

The top graph shows that the water levels in the shallow dug well W3 were not affected by the onset of pumping in the quarry.

At the start of the pumping from the quarry boreholes, the water levels in borehole SG4 were naturally falling. Therefore, it is difficult to detect when, or whether, the water levels in borehole SG4 were drawn down by the pumping in the quarry. With reference to Figure 5.19, it is evident that the water levels in borehole SG4 were lower in July, August, September and October 2020 than in previous years and in 2021. The obvious probable reason is that the withdrawal of water from the boreholes in the quarry created a drawdown of water levels in borehole SG4. But defining the moment when this drawdown started is not obvious in Figure 5.29.

The average water level graph in Figure 5.29 appears to show that the slope of the natural recession continues into the 16th /17th July. From the 18th to the 22nd the graph steepens. It levels out on the 22nd and 23rd of July. This levelling out supports the interpretation that the water levels are being affected by the pumping rate in the quarry boreholes. Coincident with the levelling out, the pumping rate was throttled back to $95m^3/h$ and the water level in D3 rose by 0.5 metres.

The water level in SG4 continued to decline gently after the 23rd July during a period of persistent rainfall that brought an end to the recession of the water levels in the shallow dug well W3.

The pumping rate from the quarry boreholes was increased slightly on the 27th July and the water levels in D3 and SG4 began to decrease more rapidly for two days. This also supports the interpretation that the water levels in SG4 are affected by pumping from the quarry boreholes. The water levels in D3 and SG4 also level off slightly on the 30th and 31st of July coincident with two days of heavy rain.

The water levels in SG4 continue thereafter to recede gently into August. It is noticeable that the water levels in D3 rose when pumping from the quarry boreholes was interrupted for a service of the generator, but the effect of this interruption did not appear to spread as far as borehole SG4.

Though the evidence shows that pumping from the quarry boreholes affects the water level data, it is interesting to observe that there is no evidence that it affects the temperature of the water in borehole SG4. This is evidence that suggests that the pumping from the quarry boreholes is affecting one of the groundwater systems that control water levels in SG4, but it is the first piece of indirect evidence that indicates that pumping is not affecting the deep groundwater system that provides the warm groundwater in SG4.

Borehole SG4 is nearly 2 kilometres from the pumping boreholes in the quarry. If, hypothetically, the aquifer feeding both the quarry and the St Gorman's Well area were a porous media, such as a soft sandstone or sand and gravel, then the drawdown created by pumping from the quarry boreholes would not be expected to extend out 2 kilometres for several months, if not several years. In this hypothetical scenario, the eventual drawdown 2 kilometres from the quarry would be expected to be a matter of, probably, less than 10 centimetres. The fact that the water levels in SG4 appear to have been drawn down by over a

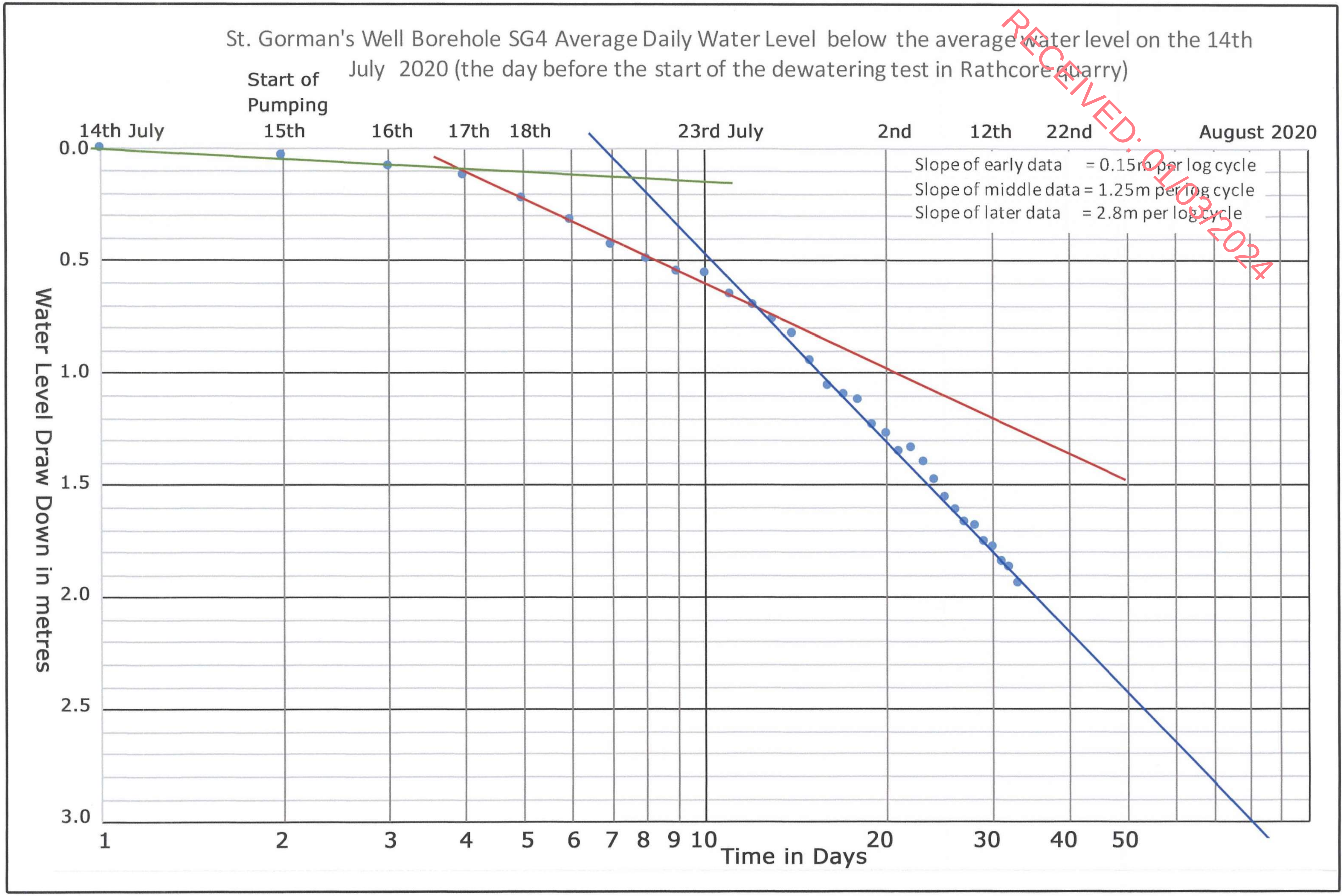


Figure 5.30 Borehole SG4 Average Daily Water Levels 14th July to 15th August 2020

metre in less than 2 weeks shows that the quarry boreholes are not creating a cone of drawdown that extends out 2 kilometres in a porous aquifer, such as the shallow sands gravels and sandy till.

The data appears to show that the effect of pumping the boreholes in the quarry is spread rapidly throughout a system of karst conduits, not by a process of slow water drainage, but, probably, by a drop in pressure in a pressurised conduit system.

It is important to try to obtain information on the speed of response in order to understand the nature of the link through the system of karst conduits in the limestone.

In Figure 5.29 the graphs are shown as time-series data on an arithmetic time scale. The average daily water level data from the 14th July for SG4 appears to be an irregular gently sloping line with some slight changes in gradient. It is difficult to tell when the the water level starts to decline as a result of pumping in the quarry.

Figure 5.30 shows the average daily water level data plotted on a logarithmic time scale (semi-log graph), that can convert gentle curving data on an arithmetic scale, into straight lines with different slopes.

Figure 5.30 is an important graph, because it allows a close inspection of the data just before and in the days shortly after the start of the pumps in the quarry boreholes.

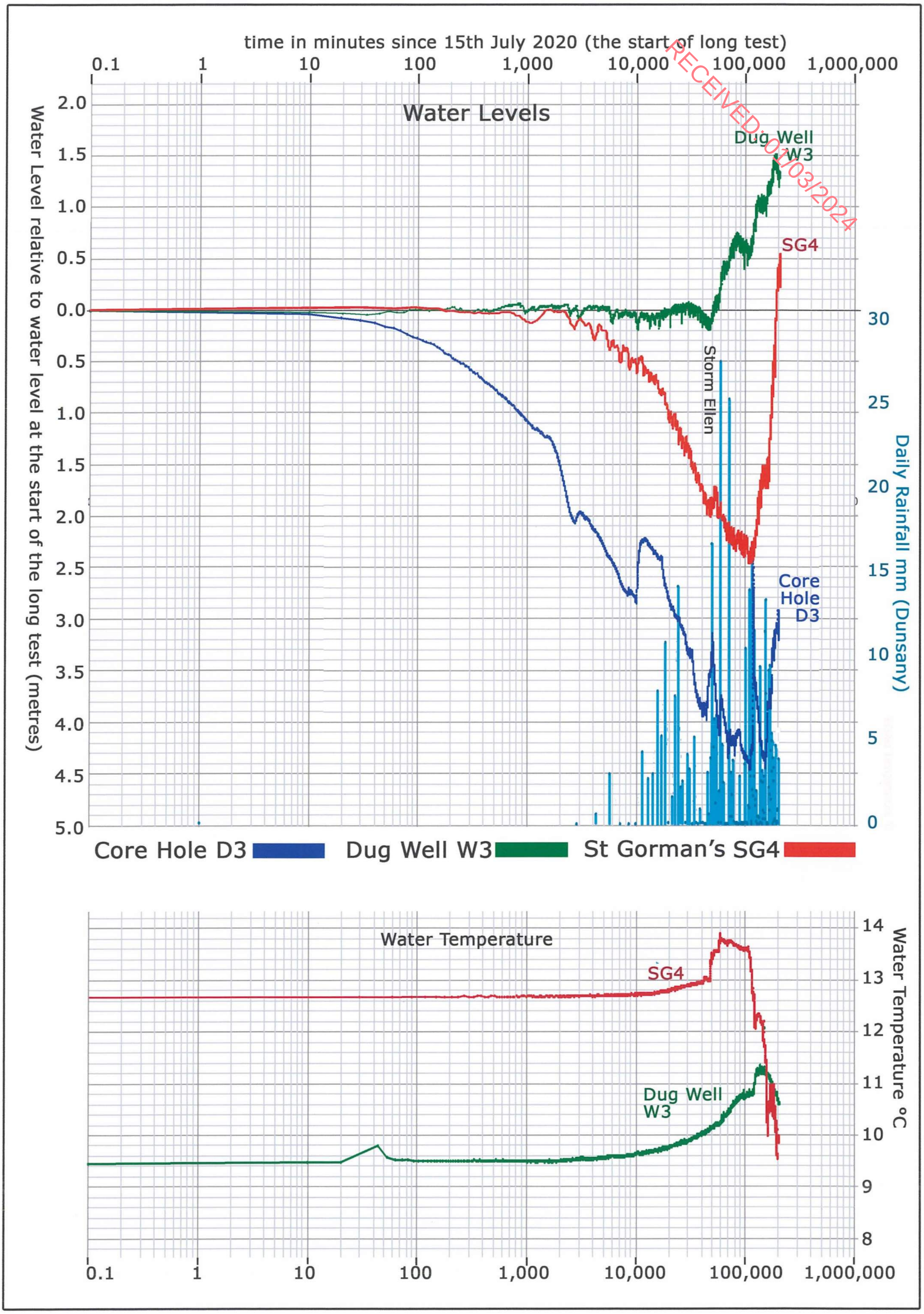
It can be seen that Day 1 is the 14th July 2020, 24 hours before the start of the pumps. It can be seen that the water level data for the 14th, 15th, 16th and 17th form a straight line with a gentle gradient. Then, from the 18th to the 26th/27th, the data forms a straight line with a steeper gradient. Finally, from the 25th/27th to the end of the graph on the 15th August the data forms a roughly straight line with an even steeper gradient.

The semi-log graph reveals that the water level decline is made up of three distinct components. The early data with a gradient of roughly 0.15 metres per log cycle probably represents the natural recession of the water levels that started before the boreholes were pumped in the quarry.

The change of slope at some time on the 17th July indicates that the effect of pumping the quarry boreholes took about 48 hours to travel through the karst conduit system to reach borehole SG4. In other words, there is a clear delay between pumps being turned on in boreholes in the quarry and an effect being observed on the water levels in borehole SG4.

The final change of slope from the 25th/27th shows that the drawdown of water levels in SG4 increased after about 10 to 12 days, even though the pumping rate in the quarry boreholes had been reduced from 147 to 95m^3/h. Therefore, there does not appear to be a direct correlation between rate of pumping from the quarry and the drawdown of water levels in SG4.

Figure 5.31 Temperature and Water Levels during long test July - December 2020



The semi-log plot of the data reveals that there appear to be two phases of response in the drawdown in the groundwater system between the quarry and St Gorman's Well SG4.

The first phase probably represents an initial pressure drop in the conduit system intersected by borehole SG4, ameliorated or buffered by either of two releases of water from storage. The first is the leakage of water into the borehole from the shallow groundwater system in the overburden and weathered Calp/Waulsortian limestone around borehole SG4. As discussed earlier, because SG4 has only a short length of casing, shallow water can flow into or out from the borehole. The water level in SG4 does not only represent the water pressure in the deep cave system at the bottom of the borehole.

The second potential release of water may be that, as water is withdrawn from the larger conduit system, there is a pressure drop, that induces water stored in minor conduits fractures joints and zones of weathered dolomite to flow into the main conduits. The release of water from this storage in the weathered bedrock and fractured bedrock, into the main conduits, temporarily buffers the pressure drop created by the pumping.

The semi-log graph indicates that the main effect of this buffering eases off 10 to 12 days after the start of pumping; i.e. between the 25^{th} and 27^{th} July.

The late phase, steeper, fall in water levels in SG4 probably reflects the pressure drop in the main conduit system as water is withdrawn by the quarry boreholes from the complex system of conduits extending throughout the limestone bedrock to the west of Rathcore.

The graph shown in Figure 5.30 has steep gradients in the data that visually suggest a large drawdown of water levels in SG4, but it is important to keep in mind that the vertical scale of the graph is from 0 to 3 metres, and the drawdown over the 33 days shown on the graph is less than 2 metres. It is also important to bear in mind that the graph shows just the early part of the water level data from SG4 during the long test at the quarry.

Figure 5.31 shows all the water level data for SG4 during the course of the long pumping test at the quarry. Again the data is shown on a semi-log graph. The timescale is in minutes starting at 0.1 minute

The figure shows the data for the same monitoring points used in Figure 5.29 with an arithmetic timescale, but in this graph for the full duration of the long test from July to early December 2020.

The upper graph shows the water levels, and the daily rainfall measured at Dunsany, all on a log timescale.

The lower graph shows the change in temperature for SG4 and shallow dug well W3. The temperature data for D3 is not shown because it did not change throughout the test. It remained in the range 9.75 to 9.8°C.

Figure 5.31, again is an important graph.

The graph for W3 is shown for reference, because pumping from the bedrock boreholes in the quarry do not affect the water level in dug well W3. The change in water levels in W3 is in response to rainfall recharge into the shallow sand gravel and sandy till aquifer system.

The graph for deep core hole D3 shows how water levels start to go down 1 minute after the first borehole pump is turned on in the quarry. The fall is about 5cm within 10 minutes. The slope of the curve on the graph steadily steepens with the duration of pumping. By 100 minutes it is 30cm; by 200 minutes it is 50cm; by 1,000 minutes (the morning of the 16^{th} July) it is 1.1 metres.

Meanwhile, the water level in SG4 is fluctuating with the tides, but the high tide after a day and a half of pumping (2,160 minutes) is still at the same level as the starting water level.

The gradient in the data for D3 between 200 minutes and 1,500 minutes is roughly parallel to the middle data gradient for SG4 shown in Figure 5.30, which occurs between 3,000 minutes and 15,000 minutes on Figure 5.31.

This suggests that out of the two drawdown buffering options, discussed above, the more gentle gradient of the middle data could be an 'aquifer characteristic' rather than a borehole characteristic.

The gradient for D3 after 1,500 minutes varies in line with the stoppages and changes in pumping rate in the quarry boreholes, but the water levels in SG4 follow a constant gradient down to 2 metres at 45,000 minutes of pumping; roughly 31 days.

It can be seen that the water levels in all three monitoring holes rise with the rainfall during Storm Ellen (labelled on the graph). The water levels in W3 rise in response to this rainfall event and the two subsequent storms in late August. The water levels in D3 and SG4 rise and fall within 10,000 minutes (roughly a week) and continue to go down in response to the continued pumping from the quarry boreholes.

It can be seen that water level response in SG4 to the three storms also corresponds to a 0.8°C rise in water temperature, as if some of the rainfall either has recharged the system driving the warm water up from depth into the bottom of SG4, or there is a flush of warm shallow recharge water entering the borehole via the warm summer soil, or a direct leakage sideways from warm surface water in the adjacent ditch.

The first or third alternatives seems more likely because though there is a rise in water temperature in shallow dug well W3, it only reaches a maximum of 11.4°C, whereas the temperature in SG4 reaches a maximum of 13.6°C. In other words, if the small rise in water levels in SG4 was only caused by a rise in the water levels in the shallow groundwater system then the temperature would have been expected to fall.

The lateral leakage from the ditch is possible because it is likely that the ditch contained water during these days with over 20mm of rainfall, and the air temperatures on these days with heavy rain were above 20 degrees and the 10cm deep soil temperatures at Dunsany were also 15-17°C.

The first alternative, however, is most probable because the data in the long graph Figure 5.19 shows a similar small rise and plateau of temperatures at the end of every summer since 2014. The pattern of a small rise in the temperature of the water measured by the Diver in SG4 suggests that the mechanism driving warm water temperature was not affected by the drawdown of water levels during the long pumping test in the quarry.

After the rise and fall of the water levels in D3 and SG4 between 50,000 and 60,000 minutes, the water levels in both holes continue to decline, but the gradient of the data in both holes is less than the gradient before the rainfall storms. It appears that the water levels are falling either more slowly because the the groundwater system in the limestone conduits is approaching ‘steady state’, where a balance is beginning to be achieved between the continued pumping from the quarry and release of water from storage in the aquifer, or because recharge is entering the bedrock system somewhere in the area. The input of recent recharge water, rather than the release of stored groundwater will tend to bring about near steady state conditions.

There is a sharp turning point at 110,000 minutes (late September 2020) in borehole SG4. Water levels start to rise and the water temperature sharply falls.

The water levels in SG4 rose by 3 metres over the next 2 months, overcoming the draw down created by the pumping, and reaching a level 0.5 metre above the starting water level at the beginning of the test.

Meanwhile, the combined pumping rate from the quarry boreholes was increased from 2,500m3/day to 2.900m3/day.

This is one of the most important findings in the testing programme. The data shows that even though the pumping in the quarry continued and increased, the water levels in SG4 recovered, and, as will be shown later, water levels continued to rise and St Gorman’s Well eventually filled and flowed.