Figure 2.47 Potential Fault alignments from Sections & Conductivity at 29.3 metres depth

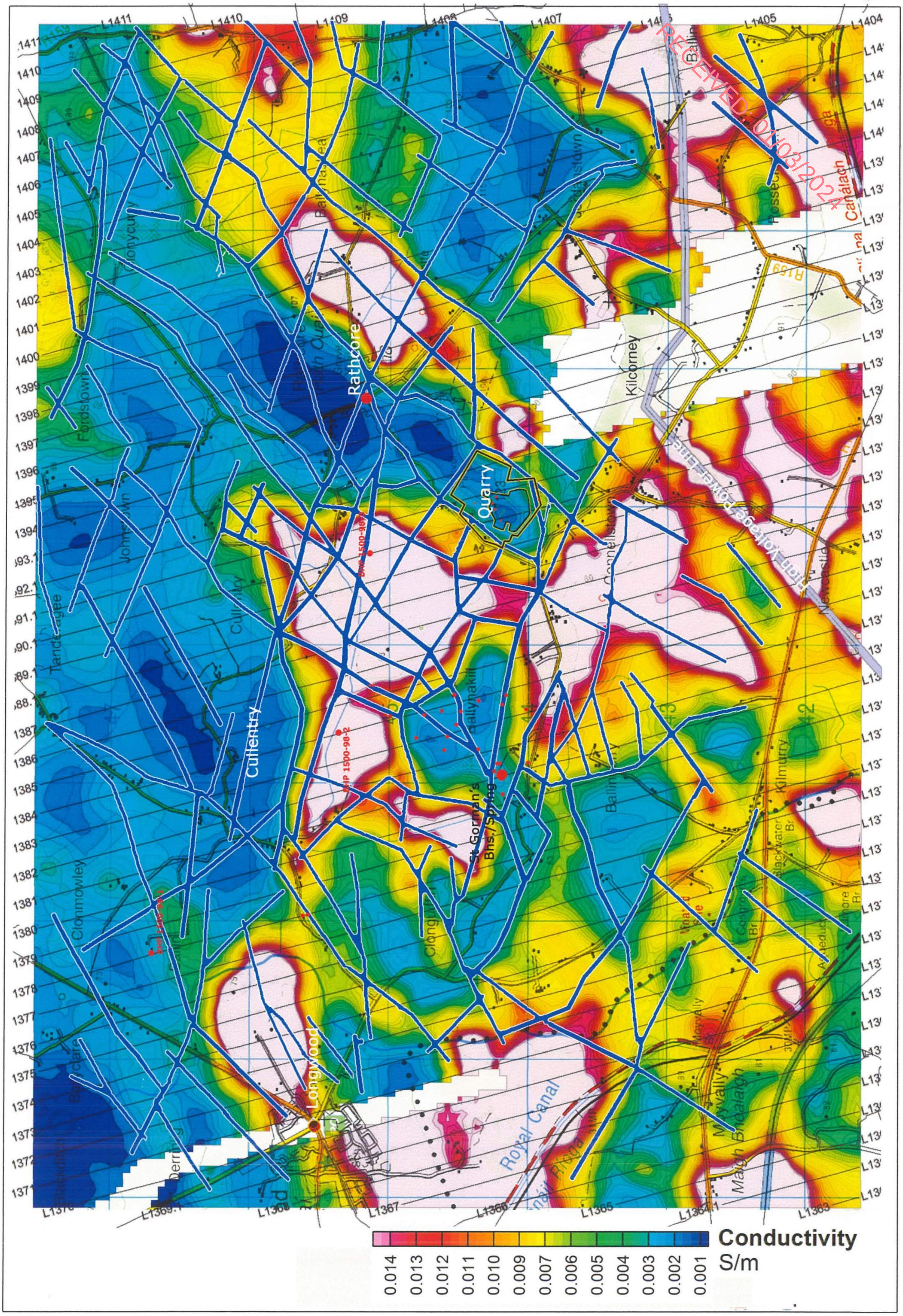


Figure 2.48 Schematic diagram showing the main post-Devonian fault and fracture systems controlling groundwater flow in Ireland (Moore JP & Walsh J 2021)

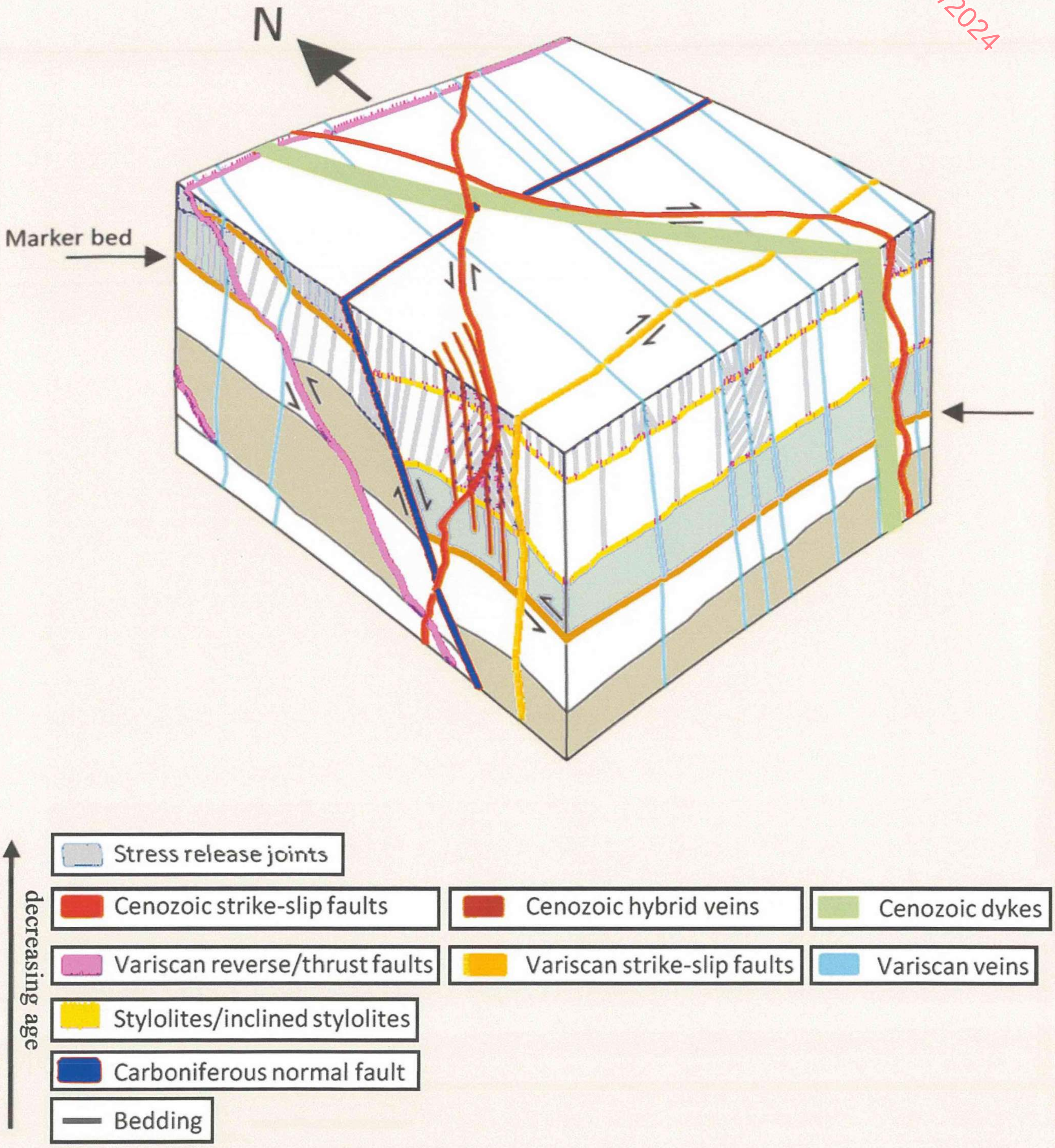


Figure from "Quantitative analysis of Cenozoic faults and fractures and theirimpact on groundwater flow in the bedrock aquifers of Ireland" J. P. Moore & J. J. Walsh in Hydrogeology Journal published on-line October 2021

The faults picked from the sections and the core hole log data from Ballinakill show that a major normal fault passes through, or a few metres north of, St Gorman's spring and forms the boundary between the Waulsortian to the north and Lucan formation to the south. This fault on the conductivity sections appears to extend to the east, and run south of the southern tip of the Rathcore block of Waulsortian.

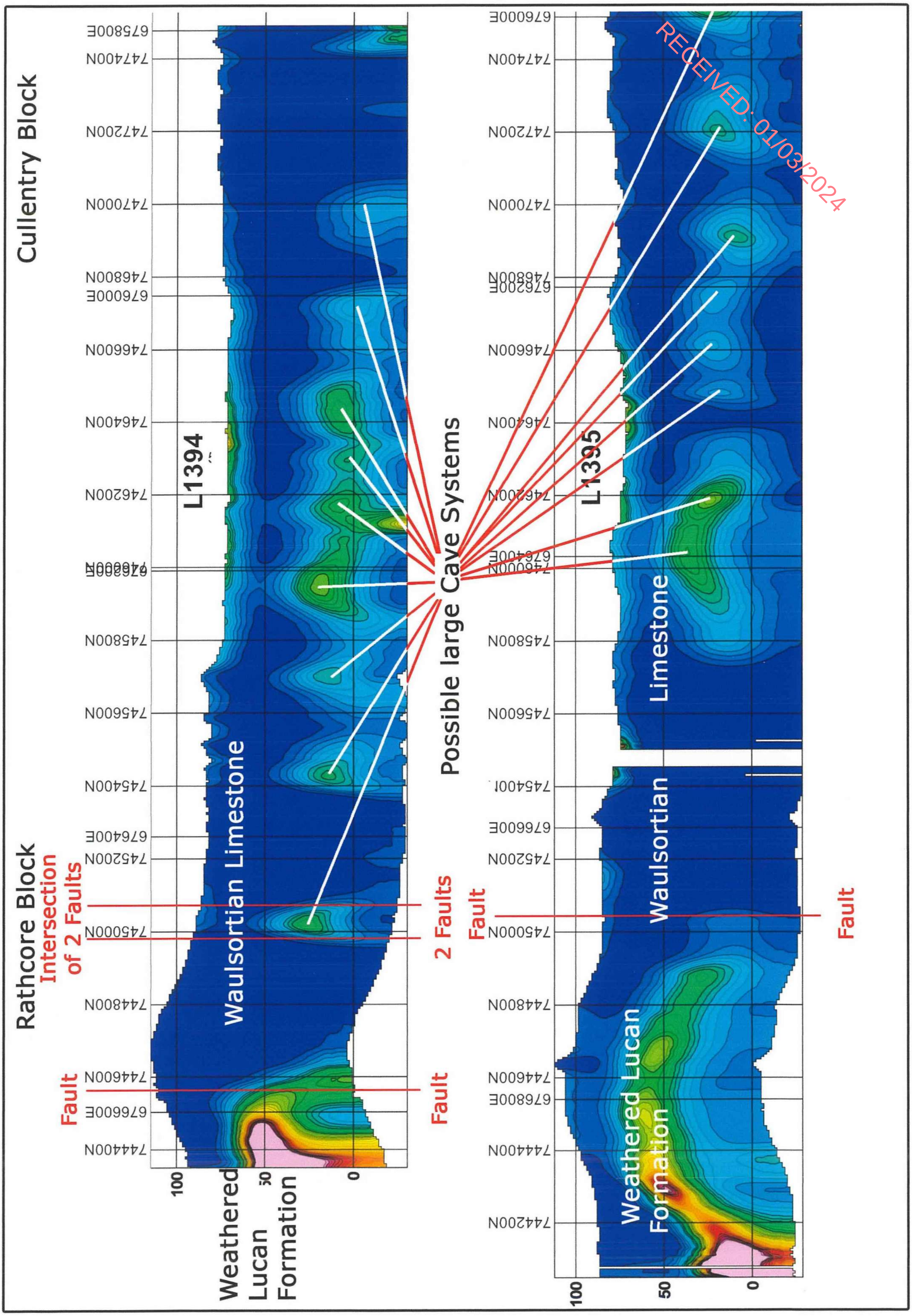
The interpretation of the faults on the sections when drawn on the map, shows that there is a second fault to the south that roughly follows the GSI's fault alignment. But the major fault appears to be to the north. The shorter southern fault may indicate that the two faults are part of a series of two or more stepped normal faults of Carboniferous alignment. It is assumed that the faults on this alignment, and not precisely on an east-west alignment, are early Carboniferous, or later Variscan, in age. The analysis of the apparent faults on the sections does not indicate that there is a Carboniferous aligned fault directly joining Rathcore quarry to St Gorman's Well.

Two major faults on the west northwest to east southeast alignment can be seen on the southern boundary of the Cullentry block. The southern fault appears to extend through the BHP 1500-98-3 core hole, and into the Rathcore block south of Rathcore village cross roads. The northern fault of the pair, either turns, or is intercepted and deflected by a fault with an east northeast to west southwest alignment (Cenozoic alignment) to form the 'elbow shaped' south east boundary of the Cullentry block.

An important feature from the sections and the maps is that the Rathcore block of Waulsortian is bounded by fault boundaries aligned along the Cenozoic north east to south west trend. This suggests that karst solution conduits may have developed along these faults on either side of the block, and therefore, if water is withdrawn from the quarry, that the initial drawdown of water levels outside the quarry may extend preferentially north east or south west. Faults with the same alignment and age were observed in the quarry.

The dark blue of the Rathcore block also forms a 'dog leg' on the map. A fault running up the west side of the southern part of the block appears to slice diagonally across the block in the direction of Rathcore village cross roads. It stops at the intersection with a Carboniferous normal fault alignment that extends from along the southern boundary of the Cullentry block The displacement of the southern part of the Rathcore block relative to the northern block, indicates that this is probably a shear or strike-slip fault. The apparent sheering movement alignment indicates that it is a Cenozoic age fault and therefore could be open and form a preferential route for the flow of groundwater and the development of large karst conduits. It is notable on the sections that there appear to be many slightly higher conductivity 'holes' in

Figure 2.49 Tellus Conductivity Sections long Flight Lines L 1394 and 1395 showing Possible Large Cave Systems in the Waulsortian Limestone just West of Rathcore Village



the otherwise very low conductivity (dark blue) Waulsortian limestone bedrock. They are shown in Figure 2.49.

The figure shows the conductivity sections along flight lines L1394 and 1395. The large possible caves appear to be at a level between modern sea level and 30-40 metres above sea level. This a similar depth to the deeper caves found in borehole 1, 2 and 3 in the quarry that are on structures with a Cenozoic alignment. It appears that the groundwater system conduits found under the quarry could linked to, what appear to be, large caves in these sections.

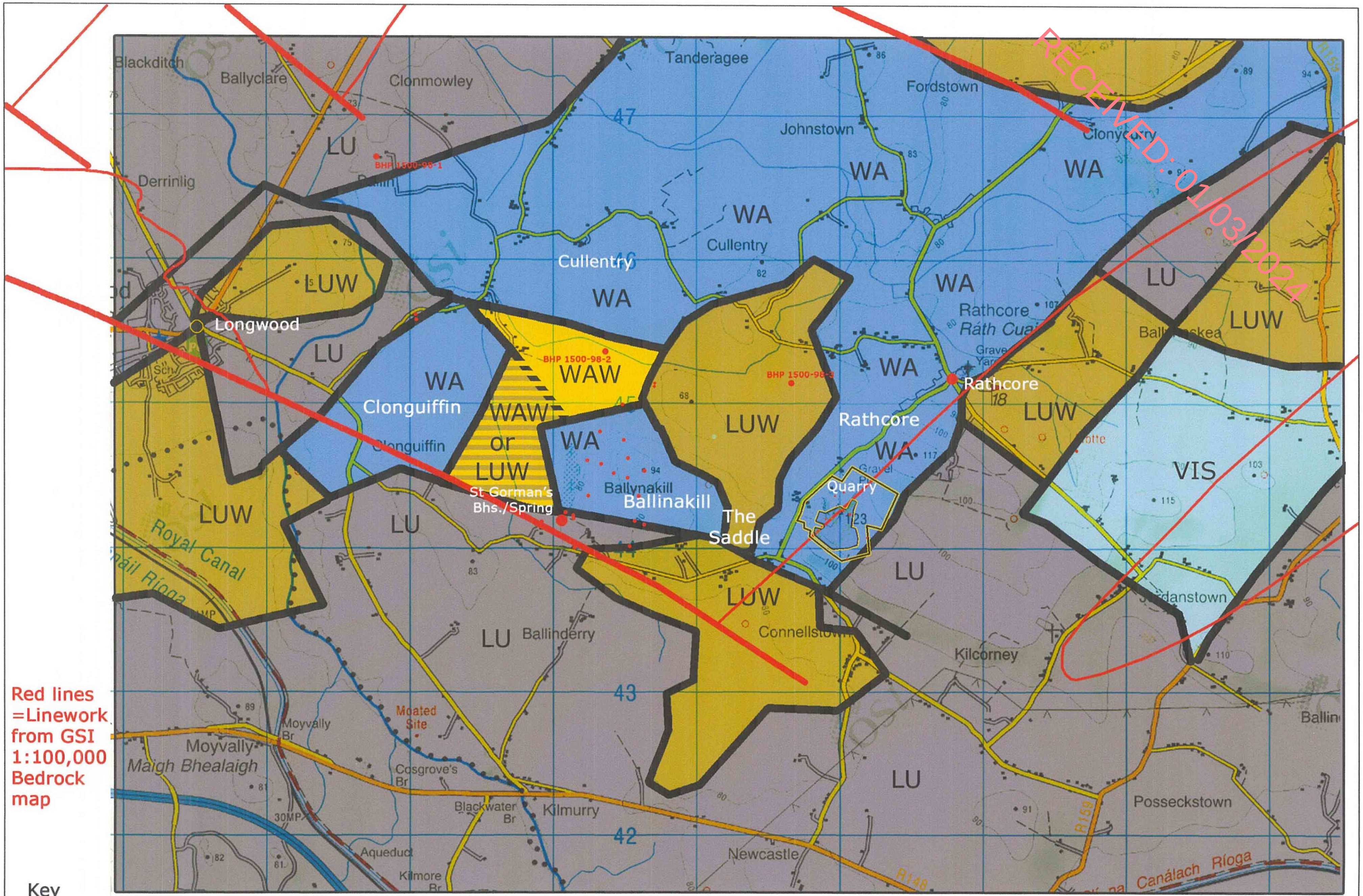
The saddle between the southern tip of the Rathcore block and the south eastern end of the Ballinakill block. appears to be the intersection of several faults within, and under, the deep weathered zone shown in red and pink on the map and in the sections in Figure 2.40.

There appears to be a similar intersection of several faults at the south western tip of the Ballinakill block. These appear to be Cenozoic strike-slip faults intersecting Carboniferous normal faults.

There appears to be a notable northeast to southwest aligned fault that starts at St Gorman's Well, passes into the centre of the Ballinakill block and then forks. The southern branch of the fork goes straight into the centre of a high conductivity area that represents a thick zone of highly weathered limestone (karst infill in the log of BHP 1500-98-3) lying above dark grey limestone and black shales described as Supra Waulsortian limestone. Meanwhile the northern branch after the fork appears to head in a more northerly direction, through a Cenozoic fault on the northern side of the Ballinakill block, then to the western end of the highly weathered Supra Waulsortian and intersects several Carboniferous age faults and a Cenozoic fault on the south eastern edge of the Cullentry block of Waulsortian. This is an interesting area for four reasons. There appear to be many fault lineaments converging. The area is reportedly underlain by gravel (GSI quaternary map see Figure 2.51). The bedrock appears to be Waulsortian limestone. The ground elevation is above 80 metres AOD, i.e. it is more elevated than St Gorman's Well and borehole SG4.

The forked Cenozoic fault in the Ballinakill block is evident as possible large cavities on the airborne geophysical sections (see Figures 2.36 and 2.37), but is also on the alignment of a zone of broken rock (breccia) in the Waulsortian identified by the EDA surface geophysical survey and their exploration boreholes.

The overall finding from the plot of apparent breaks in the bedrock on the conductivity sections is that there appears to be continuity of breaks from one section to the next; suggesting that these breaks are persistent structures. The plot of these on a map shows a very complex mesh made up of many structures. If these are real, and karst solution weathering has developed



Key
WA = Waulsortian WAW = Weathered Waulsortian LU = Grey Limestone and black Shale LUW = Weathered LU VIS = Visean Limestone

Figure 2.50 Bedrock Geology interpreted from Geophysics and Borehole logs conduits along some of them, they could form the skeleton of a network of preferential flow paths deep in the bedrock.

Figure 2.47 also illustrates the blocky nature of the bedrock, where boundaries between formations are sharply defined by faults. The investigations by others and during this study have revealed that the bedrock geology and structure in this area is far from simple.

2.8.6 Bedrock Summary

Figure 2.50 is a map that is an attempt to summarise the results of the previous and recent work on the geology of the area. It shows the bedrock geology divided into irregular blocks. The geophysics and the drilling data all show that the GSI's depiction of the Waulsortian bedrock geology is an understandable simplification at 1:100,000 scale. Instead the bedrock consists of upward, downward and sideways juxtaposed blocks of different limestones separated by Carboniferous and Cenozoic age faults.

The map is labelled with abbreviations. Areas underlain by Waulsortian limestone blocks are labelled WA. Areas underlain by Waulsortian limestone that has been heavily weathered and decomposed are labelled WAW. Similarly, Lucan limestone formation and other dark limestone and black shale formations that have not been heavily weathered are labelled together as LU, and areas underlain by deep weathered versions of these limestones are labelled LUW.

It can be seen that there is a large area underlain by largely unweathered Waulsortian to the north. The southern side of this block (for brevity called the Cullentry block) is broken up into a south eastern limb, called the Rathcore block, a central isolated block called the Ballinakill block and a western block that is called the Clonguiffin block. Between the blocks are topographic lows underlain by highly weathered limestones. The small flat valley separating Ballinakill from Clonguiffin is either highly weathered Waulsortian or Dark grey limestone and shale. This is the feature identified in Sarah Blake's AMT research. This area is marked WAW or LUW.

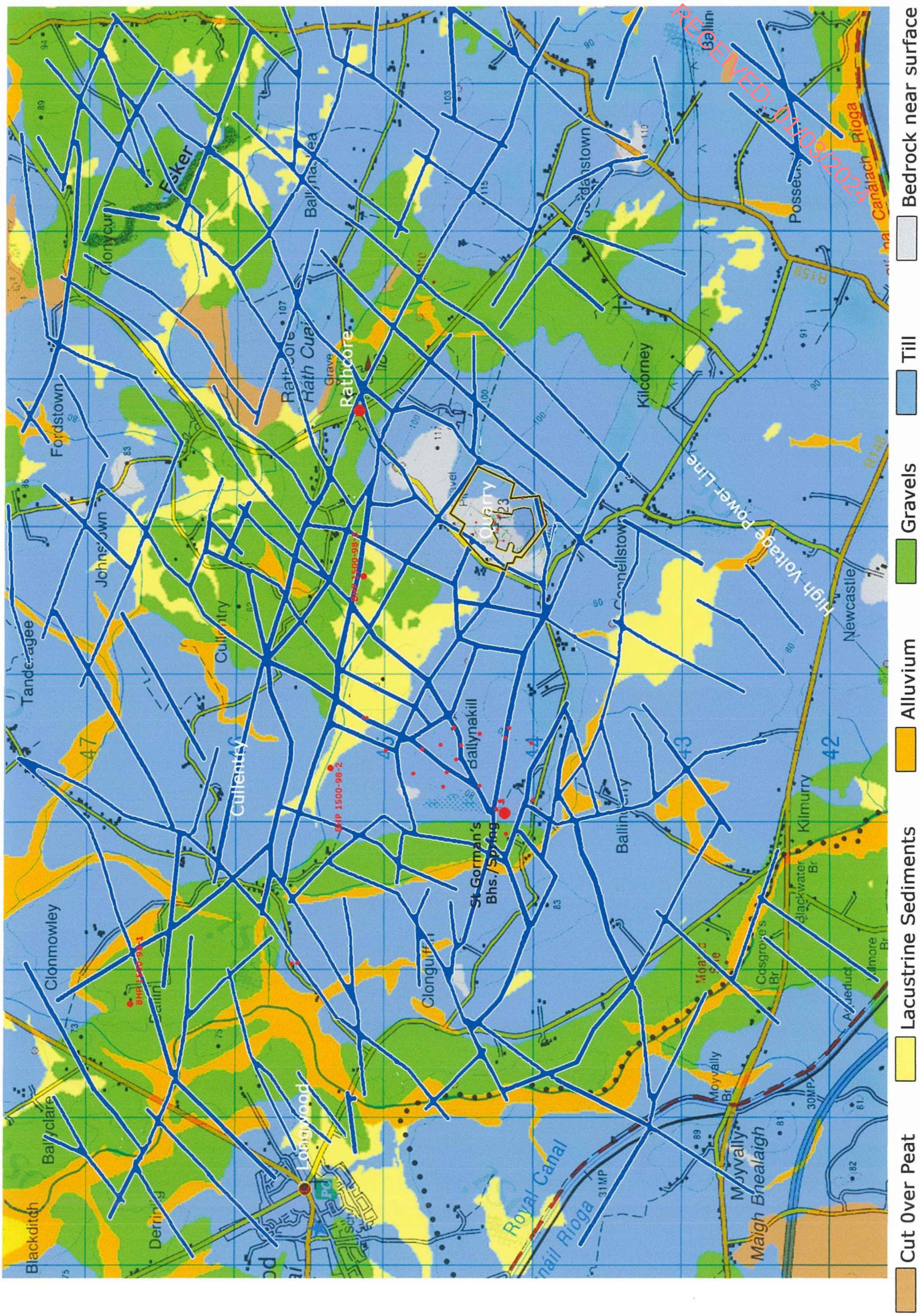
To the north west of the Ballinakill block is the very deep weathered Waulsortian limestone identified in BHP core hole 98-2.

To the south of all the Waulsortian blocks is a single, or series of, normal faults following the approximate Carboniferous fault alignment.

To the south of these faults there is Lucan formation.

The large area underlain by deep weathered Supra Waulsortian appears to extend south over and across the 'Saddle' between the Rathcore and Ballinakill blocks. Figure 2.40 shows that the weathering zone and the underlying less weathered rock are displaced upwards under the

Figure 2.51 Quaternary Sediments (GSI) &Potential Fault alignments from Sections



saddle and then downwards south of the Carboniferous age fault.

The map in Figure 2.50 shows that for there to be a groundwater hydraulic connection between the three smaller blocks of Waulsortian (Rathcore, Ballinakill and Clonguiffin) groundwater will either need to pass through, around or underneath the weathered zones. The critical potential barrier for groundwater connection and movement is the zone of deep weathering between the Rathcore and the Ballinakill blocks, but it is evident from the sections through the saddle and from the numerous faults shown in Figure 2.47 that there are many potential pathways for water and water pressure changes to be transmitted through the Supra Waulsortian beneath the weathered zone. In other words, the map appears to show a lithological barrier between the Rathcore and Ballinakill blocks, and several presumably closed Carboniferous alignment faults, but it is probable that there are indirect links through the network Cenozoic faults in the dark grey shaley limestone bedrock below the thick upper weathered zone. It is important to repeat that the northwest to southeast Cenozoic alignment faults are not well represented in either Figures 2.47 and 2.50 because this is close to the alignment of the aircraft flight lines. However, as shown in the block diagram in Figure 2.48, the Cenozoic strike slip faults (red fault lines in the figure) often occur in pairs that cross each other. The northeast to southwest part of the pairs are well represented in 2.47 and 2.50. It is assumed that there are a similar number of northwest to southeast faults, but they are just less evident on the conductivity sections. Therefore, the pathways through the dark grey limestones between the blocks of Waulsortian are probably a zig-zag through the more open Cenozoic faults rather than straight lines along the Carboniferous age faults.

2.9 Overburden

Figure 2.51 shows the GSI's map of the Quaternary Sediments above the bedrock. I added the possible fault alignments from Figure 2.47 for ease of reference. The GSI depict overburden in the area as being a layer of till derived from limestone rock covering all the bedrock except over Rathcore hill and a few small outcrops. Whilst it is probably correct that the till would be thinner over the higher ground, such as Rathcore hill, it is evident from the quarry that the till is still quite thick on top of the hill. This is shown in the photographs in Figures 2.23 and 2.24. The GSI map shows that the till or boulder clay is overlain by a variable thickness and extent of lacustrine sediments (marls, fine silts and clays), alluvium (clays, silts sands and gravel), cut over peat and gravels.

The large area of lacustrine sediment shown in the shallow valley northwest of the quarry and between Ballinakill hill and the Cullentry block, is at variance with the field notes of Du Noyer

Figure 2.52 Face of a 10 metre deep gravel pit adjacent to Tobertynan House

who identified it as "Reclaimed Bog". It is assumed that the GSI characterisation of the sediments as 'Lacustrine" relates to the sediments below the original peat. It is also possible that Du Noyer mis-identified the material on the valley floor, because our field inspection of the sides of the main drain down the centre of the valley did not reveal any evidence of a peat layer.

The area of alluvium is mapped as linear strips along the river Blackwater and various small streams and drains.

There are large areas of gravels on the map, shown in green. The gravels areas are irregular in shape, and not confined to valleys or low ground. They appear to form or cover higher ground. The gravels were laid down either by water under the ice or by waters flooding off the last ice sheet as it retreated. Figure 2.52 shows the depth of a gravel deposit next to Tobertynan House, about 1 kilometre north of the northern margin of the map shown in Figure 2.51. The deposit contains rounded boulders as well as cobbles, gravel and sand. It can be seen that there is bedding and cross bedding in the deposit. The volume and force of the water can be gauged by the size of the boulders laid down in an upper and lower bed. There were no layers of clay or silt in this deposit. The photograph illustrates the coarse nature of the deposit and the ease with which rainfall recharge could percolate down through these gravel deposits. The water level in the gravel pit in the foreground of the photograph has been kept low by dewatering pumps on the floor of the excavation.

The precision in mapping the gravels is not clear. For example, Tobin in 2009 studying the first Longwood water supply borehole, found and mapped extra gravels between this borehole and St Gorman's Well. The additional gravel deposit is shown in Figure 5.12 but not included in Figure 2.51.

It is also of note that the Rathcore quarry was initially a sand and gravel pit on the side of Rathcore hill. Therefore, there may be similar gravels along the northwest side of the Rathcore block. There are several very productive shallow dug wells for houses along the road on the northwest side of the block.

The EDA exploration drilling on Ballinakill hill also recorded 10 to 20 metre thicknesses of sand and gravel above the bedrock.

The Tellus airborne conductivity sections and the 10.3 metre depth slice conductivity map, show that the overburden generally has a low to very low conductivity. Water saturated clays would be expected to have higher conductivities.

Therefore, field observations, drilling at different sites and the geophysics all appear to indicate that the gravel deposits are more widespread than shown in Figure 2.52.

The abundance and location of sand and gravel deposits is important in the context of conceptualising groundwater recharge, storage and resources, both in the gravel and the karst limestone bedrock below.

2.10 Summary

This long Chapter has shown that the geology under this gently rolling landscape with very little outcrop of solid rock is far more complex than previously understood. The investigation has shown that the current bedrock map at 1:100,000 scale is not sufficiently detailed for the purposes of this study.

The Tellus airborne geophysics has been revelatory. The depth slice maps and new sections processed for this hydrogeology investigation, have shown a remarkably good correlation with the results from the several drilling programmes in the last 40 years. This correlation has enable us to extend the understanding into areas where there are no borehole records. Correlation of the conductivity sections with the records from boreholes that encountered karst conduits, has enabled the identification of a large number of probable karst conduits elsewhere. It has also brought about the realisation that the Waulsortian limestone has been highly karstified throughout and not just at Rathcore and Ballinakill.

The investigation of the geology using different sources has shown that karst solution weathering is ubiquitous but also heterogeneous in the Waulsortian limestone. The karst solution process may be less developed in the variously named dark grey limestone and shale formations, but there is clear evidence of faults between, and within blocks of both limestone types. Not all the faults are likely to be open and hence susceptible to karst weathering. The younger Cenozoic faults with a NE-SW or NW-SE alignment are likely to provide the potential for a network of shallow to deep conduits and open faults that will permit the easy transfer of water and water pressure throughout the bedrock under the area.

In 1995 Geoff Wright (a highly respected Senior Hydrogeologist in the GSI) decided that the Waulsortian limestone of the north Midlands was less karstified and formed a less productive aquifer than the Waulsortian found in the central and south Midlands and Munster. He was being cautious because he had very few borehole pumping records from the Waulsortian in this area. Therefore, he provisionally classified the Waulsortian in the study area as a "Locally important aquifer moderately productive only in local zones", but he added that this could be changed in the light of new information.

This understandable decision, nearly 30 years ago, based on 1980-90s information, has carried forward to the present. The current aquifer classification for the Waulsortian in this area is still

'Locally important only in local zones'. This classification has carried on into documents such as the GSI's 'Initial Characterisation of the Longwood Groundwater Body' and the Meath Groundwater Protection Scheme report. The latter finishes the description of the Waulsortian with "The Waulsortian has the potential of being highly dolomitised and karstified, but with the lack of good evidence, it is classified as a 'Locally important aquifer – moderately productive only in local zones". It also carries on as the basis for the on-line groundwater maps, such as the map showing Water Framework Groundwater Bodies; where the Longwood Groundwater Body (IE_EA_G_018) is described as having a flow regime classified as "Poorly productive bedrock".

Another example of the knock-on effect of the cautious decision in 1995, is that because the Waulsortian limestone is classified as 'locally important and moderately productive only in localised zones', the rock is assumed to have insufficient storage space for water, within the rock mass to accept an annual recharge volume greater than 200mm. Amounts of recharge greater than this, are deemed 'rejected' by the aquifer. By contrast, the adjacent Calp or Lucan formation, is classified as a 'Locally important aquifer which is generally moderately productive'; in other words the dark grey shaley limestones are considered generally to be more able to store water, as well as provide water for wells and boreholes that tap into it. As a result, the Calp or Lucan is expected to be able to accept higher levels of recharge, and there is no arbitrary cap on recharge of 200mm.

The bedrock map and the classification of the bedrock aquifers, therefore creates an incongruous situation in the area. The map shows a formation boundary running northeast to southwest through the quarry and up the spine of the Rathcore ridge. On the east side it shows the Lucan formation, and the Waulsortian is on the west side of this line. Because of the bedrock type, and hence subsequent aquifer classification, the recharge on the west of the ridge and quarry is limited to 200mm, whereas on the east side it is 350 mm. The position of the formation boundary is obviously not correct, but as the subsequent chapters in this report will show, the widespread nature of a highly productive karst conduit system means that the aquifer classification is also incorrect.

Therefore, though the detailed investigation of the bedrock geology of the area in this chapter may seem somewhat detached from the quarry proposal, it is important to determine whether the published bedrock map makes sense, because it is the basis for many other published maps that could be used in the planning process.

This report will be given to the Geological Survey of Ireland. I think it is probable that they will be able to use the new borehole and geophysical information and the assessment in this chapter, along with the results from the pumping tests and monitoring in subsequent chapters, to amend the aquifer classification and characterisation of the Waulsortian limestone in this area. This would then lead to amendments to the information shown on maps based on this characterisation. I anticipate that the Waulsortian limestone in this area will be re-classified as, at least, a Locally important Karstified bedrock aquifer, if not a Regionally important Karstified bedrock aquifer.

Finally, the investigation described in this chapter has revealed that there is a complex ancient karst limestone landscape hidden below a complex overburden of gravel, till and possibly loess clays, under this gently undulating landscape in south Meath. Before being ground down in the last and the previous ice ages, the pre-glacial landscape probably consisted of steep sided conical hills of Waulsortian limestone, separated by flat bottomed doline or Uvala depressions with internal surface drainage systems connected to a shallow and deep karst conduit groundwater system. David Drew has identified a better exposed example of the remains of such a landscape around Lough Lene and the village of Fore in County Westmeath, just 35 km northwest of the Rathcore area.

Chapter 3 Groundwater Investigations at Rathcore quarry

3.1 Introduction

Pumping tests on boreholes and wells are commonly carried out in order to determine the properties of the aquifer penetrated by the borehole or well. Pumping tests are also carried out to determine the long term sustainable yield of a borehole or well, and pumping tests are carried out to determine whether changes in chemistry or quality occur over time. The determination of aquifer properties can be used to predict the drawdown of water levels some distance from the pumping borehole. Therefore, aquifer properties can be used to determine the impact of pumping on wells, boreholes, springs and wetlands some distance from the pumping well or borehole.

An aquifer is defined as a rock or strata that can both store and transmit water.

The Waulsortian limestone at Rathcore is not a classic 'aquifer'.

The limestone rock itself does not transmit water, or store water.

There are no pore spaces or other spaces in the actual fabric of the solid rock to permit the movement, or provide spaces for the storage, of water.

Therefore the term 'aquifer' is not appropriate for the Waulsortian limestone rock, and hence the rock does not have aquifer properties.

However, water moves into, and through, cracks, faults and fissures that form breaks in the limestone rock. Many of which have been widened by karst solution weathering of the limestone. In fact. it would be reasonable to assume that every open fracture connected to other open fractures in the rock have been subjected to karst solution weathering at some point in the past several million years. Therefore, the rock may not be an aquifer, but there could be a network of numerous widened passageways through the rock that allows the movement of significant quantities of water.

It is not the rock type that permits or controls the flow of water underground, but instead it is the characteristics of the passageways that control the flow of water. The size and shape, the amount of clay and other debris and the age, depth and orientation of the passageways, determines the ease with which water can flow, and the volume of the stored groundwater resource. It would be expected that none of the characteristics or properties of the passageways, or their connections, would be uniform, consistent or predictable across this small complex area.

There would be no purpose in carrying out a pumping test and expecting to be able to determine credible aquifer properties, when there is no aquifer. It would also be unrealistic and misleading to ignore the anisotropy and heterogeneity of the system of conduits in the area, and pretend that aquifer properties parameters determined from boreholes can be used to predict the impact of pumping from the quarry on wells, boreholes springs or wetlands some distance from the quarry.

Therefore, rather than using a pumping test to calculate aquifer properties and then, naively, make predictions, the objective of pumping tests for this investigation was to put a stress on the groundwater flow system, in the passageways or conduits under the quarry, and then observe whether this stress migrated out into the area around, and observe the response.

The drilling in the quarry and the drilling investigations elsewhere showed that there are some very large passageways that can permit large flows of water. Therefore, to determine the connection between the passageways under the quarry and those around the quarry, it was necessary to pump a large quantity of water from the quarry. There was no point in installing small low powered pumps and pumping gently for a short space of time. There would be no stress on the system and no measurable response.

There are obvious risks in stressing a groundwater flow system because a significant and negative impact might occur. Therefore, to stress the system responsibly, it was necessary to monitor the impact of a test carefully, and be prepared to stop the test immediately if any significant negative impact seemed imminent.

3.2 Construction Development and Testing of Boreholes in the Quarry

3.2.1 Borehole Design and Construction Constraints

Three boreholes were drilled to obtain access to the groundwater flow system under the quarry. As described in the previous chapter, these boreholes were sited on exploration boreholes that previously had encountered large open water bearing cavities.

The original objective was to drill high yielding boreholes in different parts of the quarry in order to try to spread the effect of pumping. A broad spread could not be achieved, because the exploration boreholes in the south of the quarry did not encounter conduits with sufficient potential for high yields.

Three boreholes were drilled in the north of the excavation. The geology encountered during the drilling is described in the previous chapter.

The drilling and construction was complicated.

In general, the easiest boreholes to drill are dry boreholes in competent rock. Conversely, a borehole that provides a prolific yield of water is invariably a borehole that encounters broken rock, or large solution cavities within the otherwise impermeable rock. There have to be gaps or breaks in the rock for water to flow through the rock and enter the borehole. Therefore, drilling boreholes to obtain a high yield means targeting areas where the rock is broken, or where open passageways have been developed. Therefore, the ground that will potentially provide a high yield is full of holes, and inherently unstable.

An added significant complication at Rathcore, and elsewhere in the area, is that the cavities and faults in the Waulsortian contain significant deposits of clay and sand.

Therefore, it was necessary to drill potentially unstable rock containing potentially unstable deposits, in order to attempt to create high yielding boreholes.

If an un-directed driller is asked to drill a hole in an area with unstable rock, he will install steel casing to hold back the unstable rock so that he is able to make progress to a greater depth below the zone of instability. If the driller encounters a second unstable zone, he will install a second casing inside the first, in order hold back the loose rock. A third zone of instability at greater depth will usually result in another casing. As a result, the internal diameter of the borehole decreases with each casing installed inside the other.

The process of telescoping casing down through each other to support zones of instability, means that a borehole needs to start at a wide diameter to allow for it to become progressively narrow, but still allow the drill tools to progress beyond the last casing.

A powerful drilling rig is needed to handle and use large heavy drilling tools that can make a wide diameter hole. The minimum diameter that a powerful rig can drill is 6 inches. The emplacement of casing enables the driller to make a hole in the ground that is stable and eventually reaches a target depth. However, stabilising the hole with casing excludes the water that could enter the hole from the fault zones or conduits in the upper or middle sections of the hole. Therefore, such a borehole is simply a 'stable hole', but it is not an efficient 'water well'.

Drilling a water well that is an efficient hydraulic structure that focuses on getting a high yield of water means letting water flow into the hole easily. This means drilling into an unstable section of ground, with the driller using all his skill and equipment to try to stabilise this section of the hole, without casing, before safely drilling the next section below.

Drilling in hard rock, to depths of at least 30 metres requires the use of down–the-hole hammers driven by compressed air. With this drilling method, the exhaust airflow from the hammer is used to bring water, broken rock and clay to the surface. It is necessary to maintain a strong up-hole air velocity, in order to bring the drill 'cuttings' to the surface and clear the hole efficiently.

Given the limits of compressor capacity, and the restricted diameter inside the drill rods and the ports on the drill bit for airflow, there are limits on the hole diameter that can be drilled in difficult ground by the most powerful rigs in the country. For example, a rig may be able to drill with a 12inch hammer bit and $4^3/_4$ inch drill rods in stable rock. The rock cuttings will be blown up the large gap between the drill pipes and the 12inch diameter hole, as fine dust and small chippings.

However, as soon as the 12inch hammer bit breaks through into a karst cavity containing unstable clay, large rocks and a big flow of water, the velocity of the airflow up the hole will not be sufficient to lift the heavy slurry of water, clay and rock debris.

For the reasons given above, drilling high yielding boreholes in karst limestones with clays in the cavities, requires powerful rigs and compressors, but also relatively narrow diameter holes to maintain up-hole air velocities to keep the hole clean.

It is proposed to deepen the quarry by a further 30 metres. A pumping test was carried out using all three boreholes. The boreholes had pumps installed to roughly 30 metres depth. The pumping test was carried out over several months. The pumping test was, in essence, a simulated dewatering test. The three boreholes constructed for the test are named simply as boreholes 1, 2 and 3

3.2.2 Borehole 1

Borehole 1 encountered a thick zone of fracturing between 17 and 26.5 metres that is believed to be a Cenozoic fault. The borehole was drilled at 10 inch diameter. Drilling had to cease at 36 metres because the unstable clay and rock, with large volumes of water, could not be cleared from the hole. Part of the problem was that drill cuttings and water were being blown out into cavities linked to nearby exploration boreholes. Air pressure and volume was being lost into these cavities. Drill cuttings and clay were not being blown to the surface from the hole. When the airflow was stopped to add another drill rod, the clay and cuttings fell back out of the cavities, and trapped the drill bit and hammer in borehole 1.

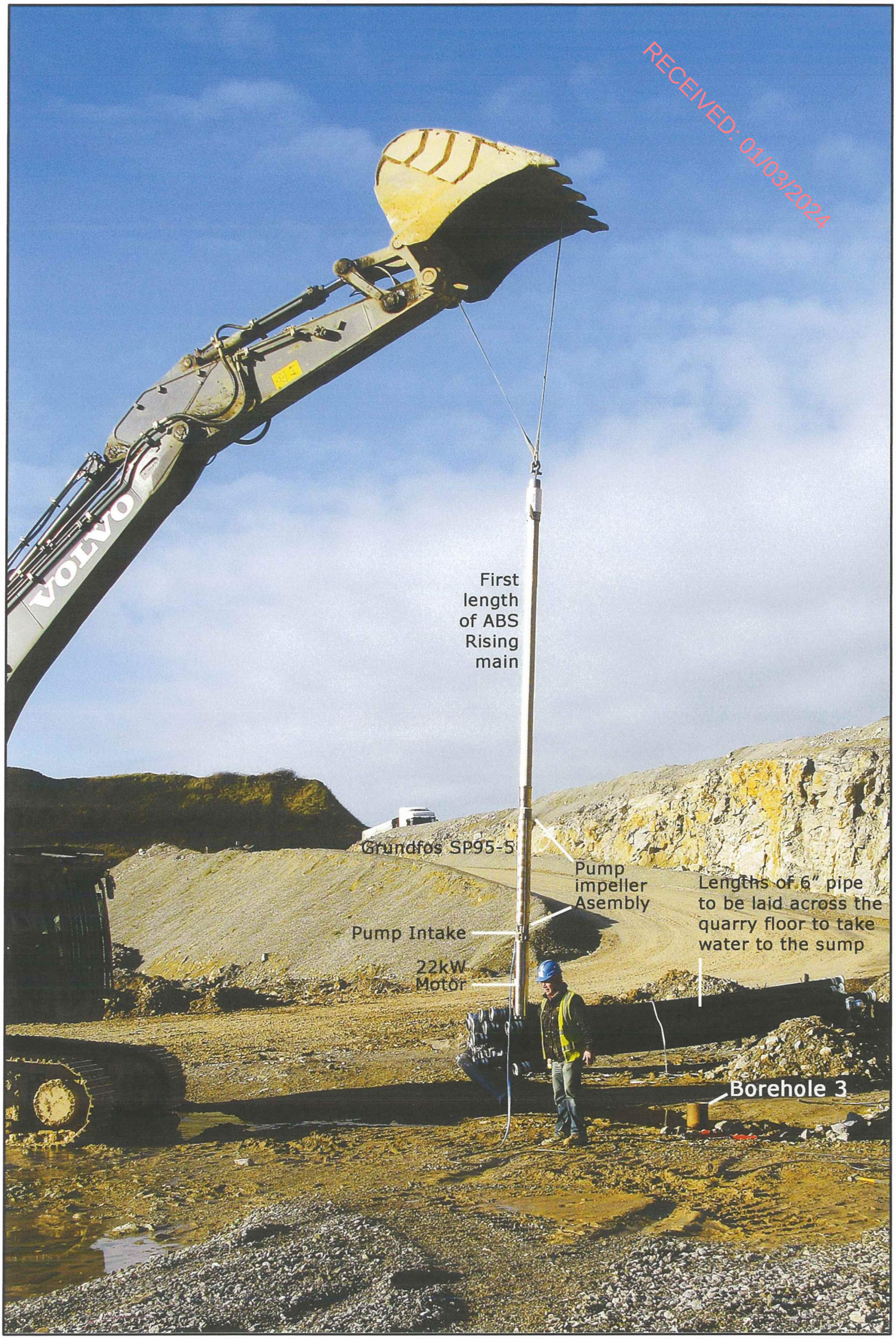
Borehole 1 had to be lined with Boode PVC casing above the cavities, and with Boode PVC water well screen adjacent to the cavities, to both support the hole sides, and also let water flow into the borehole from the fault zone and cavities. The yield from borehole 1 was estimated as about $25m^3/h$, or over half a million litres a day.

3.2.3 Borehole 2

Borehole 2 encountered several cavities but remained sufficiently stable to enable the hole to reach 56.5 metres depth.

There was a single large cavity at 17 metres and a large number of cavities between 24 and 30 metres. At 51 and 53 metres there were large cavities yielding extra water. The weight of clay and cuttings at this depth and the open nature of the cavities meant that compressed air from the hammer went into the cavities rather than back up the borehole to the surface. When the air

Figure 3.1 Installation of a powerful electric submersible pump in Borehole 3



flow down the drill rods was turned off, the compressed air in the cavities flowed back into the borehole, and air-lifted large volumes of water out of the hole, for a further 10 minutes.

The yield from borehole 2 appeared to be the equivalent of several million litres a day. It was not possible to measure the flow of water because it was so prolific. The amount of water that was coming out of the borehole is shown in **Figure** 2.27. The 10 inch open hole seemed stable. The wide diameter afforded the opportunity later to install a powerful 6inch or 8 inch pump, capable of pumping the large amount of apparently available water. Therefore, the borehole was left unlined.

Unfortunately, the high hydraulic heads created by the deep drawdown, during the subsequent pumping test caused large lumps of clay to move out of the fractures and cavities at 26 metres and fall into the hole, blocking the flow from the deeper cavities. The yield dropped dramatically.

3.2.4 Borehole 3

Borehole 3 encountered small cavities around 20 metres, a very large number of cavities between 24 and 30 metres, a 4 metre cavity mostly filled with clay below 36 metres, a 2 metre cavity containing clay below 53 metres, and a 3 metre large clay free cavity below 58 metres. The yield of water by the time the hole reached this depth was estimated at 1-2 million litres per day. The hole was stopped at 62 metres.

The borehole appeared stable during the drilling, and the intention was to leave it open hole at 10 inch diameter, in order to accommodate a large powerful pump. Fortunately, the rig did not move off the site, and the next morning it was found that clays from the cavities between 24 and 30 metres had slumped and blocked the hole. These clays were shown in **Figure** 2.28.

The hole was cleaned out and a steel casing, with a large number of hand cut slots, was driven through the unstable ground down to 30 metres. The hole was again airlift pumped, the yield returned and the hole seemed stable.

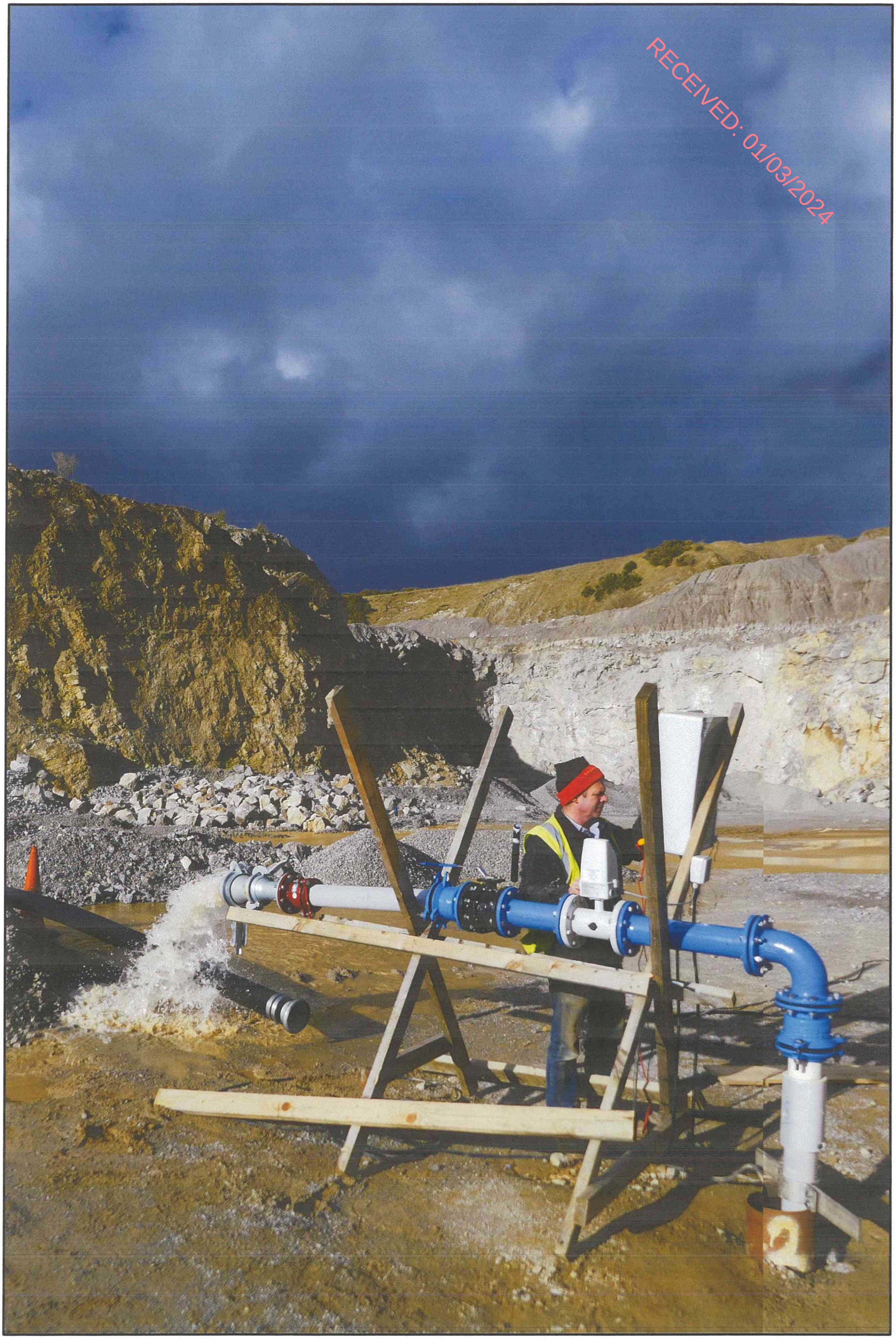
The three boreholes were drilled in November – December 2019.

3.3 Preparations for the Pumping Tests

Preparations for pumping tests were started in January 2020.

Rathcore quarry has a sump in the southwest corner, located and constructed to collect rainwater run-off from the quarry floor, sides, fixed crushing plant area, and the stock piles of overburden around the perimeter. The sump also collects groundwater when the winter water table rises to about 75metres+ OD during and after periods of heavy rainfall.

Figure 3.2 Proving test after pump installation



The floor of the quarry is mostly made up of 1-2 metre thick layer of loose rock and dust created by the blasting and crushing. This 'shatter zone' slows down the flow of water across the quarry floor allowing mud or clay in the water to settle out within it. By the time the water reaches the sump it is usually clay free and crystal clear.

It is the practice at Rathcore to pump water from the sump when the floor of the southern part of the quarry becomes slightly flooded.

The quarry does not have sufficient power to meet its needs from the ESB. Instead a large generator powers the fixed crushing plant near the quarry entrance.

A second, much smaller, generator is used to power a single powerful pump in the sump. It is therefore operated only when required and usually run during the working day.

The sump pump lifts water out of the quarry, and discharges the water into a large settlement pond. The water from the settlement pond passes through a hydrocarbon interceptor and a large reed bed, and flows out through a 'V' notch weir chamber. The flow over the weir is continuously monitored by an Ott water level pressure transducer, and the data recorded digitally. The water from the 'V' notch falls into a stilling well at the start of a pipeline that goes under the road, across and under a neighbouring field and discharges into a drain. The drain is the headwaters of a drain or stream straightened by the Office of Public Works, that flows along the floor of the shallow valley to the northwest and west of the quarry, before joining the River Blackwater.

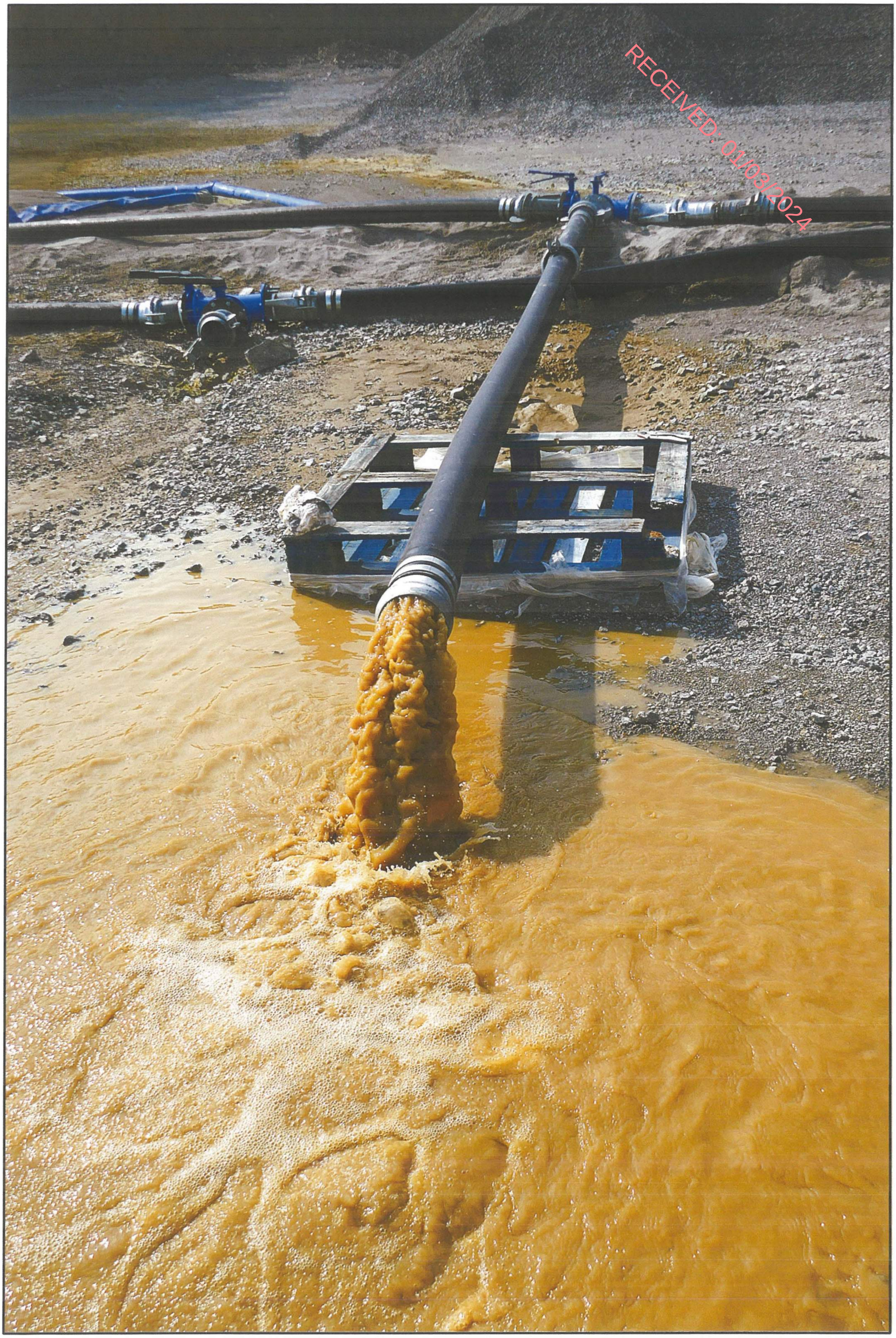
Kilsaran's discharge license correctly requires Kilsaran to ensure that the discharge water from the quarry does not contain suspended solids.

The boreholes had been 'airlift surged' during drilling, and it was apparent that water pumped from the boreholes would contain a significant amount of clay.

To carry out a pumping test or dewatering test it was essential to discharge the pumped water away from the quarry. If the water was discharged in the quarry the discharge water would simply re-circulate within the quarry and return to the boreholes. The pumping would not stress the groundwater system outside the quarry. Therefore, before any pumping test could start, it was essential to try to develop the boreholes and clean the unstable clay from the water yielding cavities. The clay laden water would need to be discharged onto the quarry floor to allow the clay to settle out in the shatter zone, some distance from each borehole, and also some distance from the sump. It was important to ensure that clay laden water did not reach the sump, or return via the shatter zone to the boreholes.

Airlift surging and pumping was considered as a technique for disturbing the clays in the cavities, but it would have been difficult to airlift pump the discharge water a sufficient distance

Figure 3.3 Pumping initial water with a heavy clay load to the quarry floor



from the boreholes to prevent re-circulation. The alternative of using pumps to 'raw-hide' the boreholes was chosen, and the water was at first discharged about 50 metres from the nearest borehole.

'Raw-hide' pumping is a hydrogeologist's - driller's term for aggressively cleaning or developing a borehole. The rapid, turbulent movement of water can be used to loosen and scour debris inside a borehole, or in the screen slots. The same principle is applied to loosen and remove clay and other material from conduits that are carrying water through the rock to the borehole.

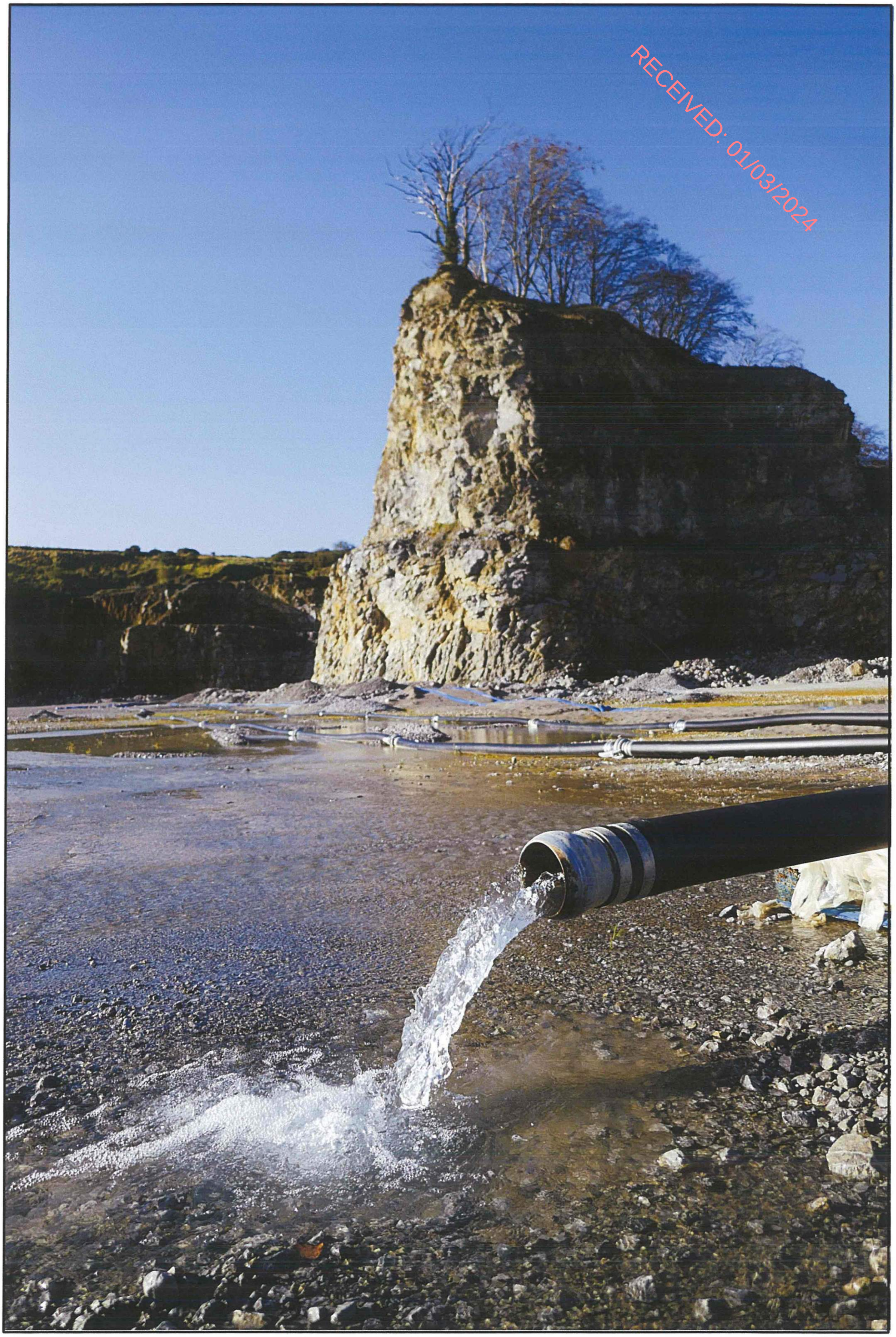
It is simple in principle.

Most open conduits deep in the bedrock contain a deposit of clay or sand on the base and sides. Conduits that were created many thousand, or million years ago may not form part of a present day active groundwater flow system, that is concentrated at a shallower depth. There is flow within these deeper palaeo-conduits, but it is relatively slow. The sediment was deposited as the sea level or base level changed over time, and the palaeo-conduits probably became increasingly redundant. However, for sediment to be deposited, there always had to be a flow of water carrying the sediment. Therefore, there is always a passageway, however small, above the layers of sediment on the floor of the conduit. The older sediment in the conduit may have become dense and compacted at the base of the deposit. Less consolidated, softer sediment often forms the upper layers.

When a borehole is drilled using a down-the-hole hammer, the flush of air removes water from the borehole, which in effect is like pumping a borehole. When a borehole penetrates an old conduit system, water starts to flow rapidly from the conduit into the borehole. The turbulence, in the sudden rapid flow of water along the conduit, disturbs and erodes the softer upper layers of sediment in the conduit and carries the clay and sand into the borehole. This erosion not only removes sediment but also creates a larger passageway for the flow of water. The flow of water usually increases, and this flow, in turn, erodes more sediment. The process of progressive erosion, and increase in flow, continues until there is a state of near equilibrium. There is a large flow, but the space in the conduit is sufficiently large for the flow that the flow is less turbulent and erosive. This balance, or near equilibrium, can be reached in a few minutes or hours if the layers of sediment in the conduit are hard and difficult to erode, or if the sediment deposit is thin and easily scoured from the floor of the conduit. The dewatering test borehole drilling found both hard and soft clay deposits of varying thickness in the conduits and faults of varying size under the quarry.

The flows achieved from the karst conduits and fault zones in each of the boreholes was large.

Figure 3.4 Clear water discharge before diverting the flow direct to the settlement pond



Therefore, they offered the opportunity to carry out a long pumping test to simulate dewatering of a future excavation to 30 metres below the present quarry floor. However, the test could not take place in earnest until the discharge from each borehole contained minimal clay.

The work to clear the clay from the cavities, and hence make the discharge from each borehole clear, began with installing a test pump in borehole 3 in January 2020.

The installation of the pump is shown in **Figure** 3.1. It was a powerful 22kW Grundfos SP90-5 pump capable of pumping water at a rate of over 2 million litres a day. Pumps were subsequently installed in the other two holes.

Proving tests were carried out after each pump was installed. One of the proving tests and the large flow from borehole 2 is shown in **Figure** 3.2. This shows the well head arrangement of starter box, Siemens Mag meter to measure the pumping rate and a large lever valve to regulate the flow on a wooden support horse.

The pump well head pipes were connected later to 6inch diameter pipeline to take the discharge water away from the borehole.

Step pumping tests were carried out to determine the highest optimum pumping rate for each borehole, and the drawdown. The step tests were also used to assess the clay content of the discharge at different pumping rates.

As expected, the clay content was minimal at low pumping rates of 10-20m^3/h, but increased significantly to a yellow-brown coloured water at the higher discharge rates.

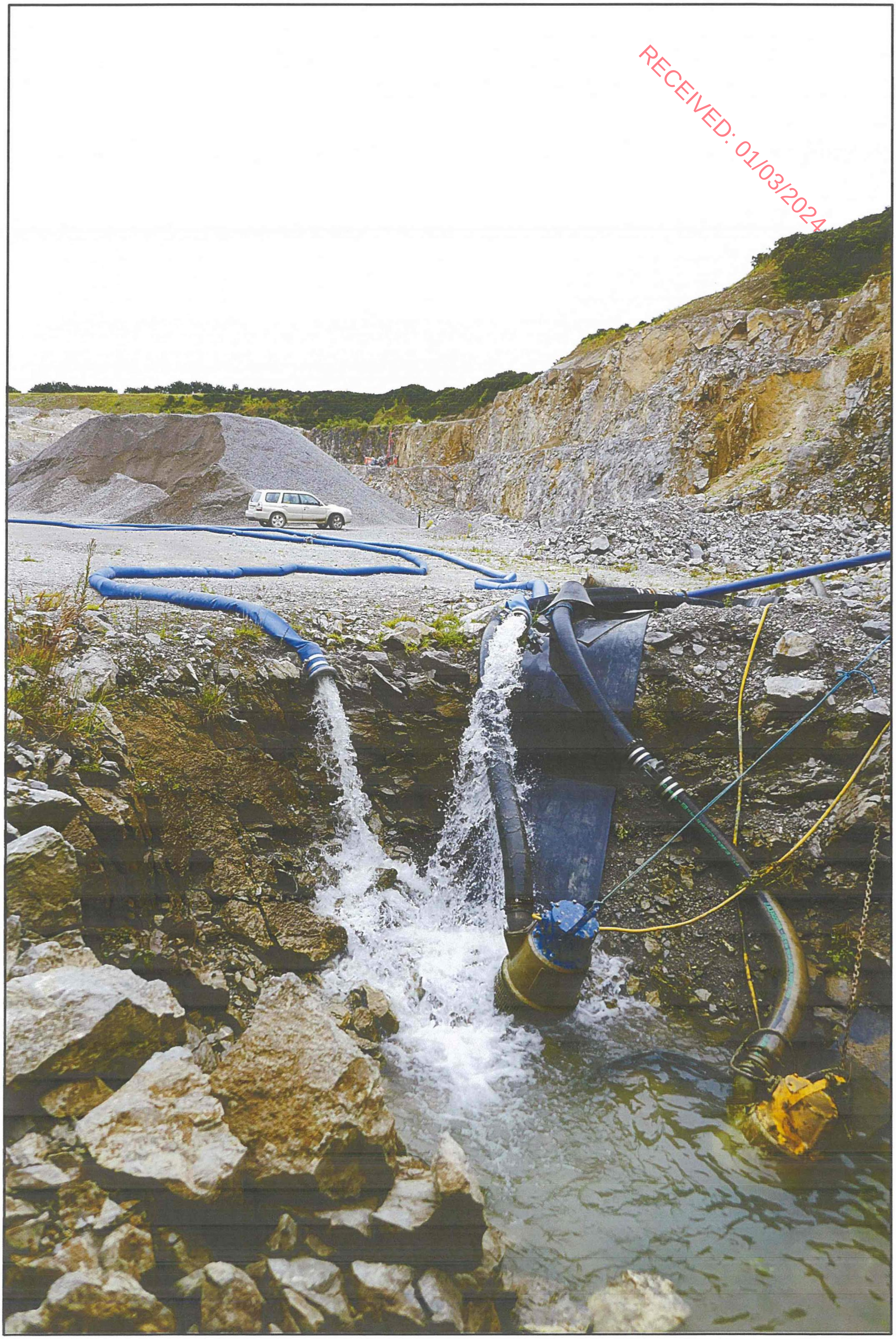
After the initial tests, the focus changed to short pumping episodes at the maximum pumping rate in order to scour clay from the water bearing passageways. The short episodes were necessary because the pumping rate would decrease as the water level was drawn down in each borehole to near the pump intake and hence the pumping head lift increased.

Figure 3.3 is a good example of the effectiveness of 'raw-hiding' the boreholes to clear clay from the water productive passageways below the northern part of the quarry. The photograph shows the heavy clay and sand content at the start of pumping with a flow rate of over 100m^3/h (2,400 m^3/d).

The objective was to try to obtain a flow with nearly clay free water at the maximum pumping rate, knowing that the sustainable pumping rate would be less when there was a large drawdown of the water levels. In other words, if we could get the borehole to produce nearly clay free water at an aggressive pumping rate of 100-120m^3/h then it would be almost certain that the water would be clay-free at a more gentle pumping rate of, say, 80m^3/h.

The three boreholes influenced each other to differing degrees. The water levels in each pumping borehole were monitored using Diver pressure transducers, and the data downloaded

Figure 3.5 Combined discharge from all boreholes into quarry sump prior to long test



and processed daily in order to find the optimum combined pumping rates. Meanwhile, the turbidity of the water in the sump, settlement pond and at the 'V' notch outlet was assessed daily. The boreholes were always supervised during the pumping periods. It was important and informative to continually monitor the clay in the discharge onto the quarry floor and the water in the sump.

Progressively, the discharge from borehole 1 and 3 became clear, except at the start of each pumping episode.

Figure 3.4 shows the discharge from the same borehole, shown in **Figure** 3.3. As can be seen the flow rate is lower and the water is clear of sediment.

Borehole 2, which had initially appeared to be the most productive borehole turned out to have a relatively low sustainable yield.

When the pump was started, the yield was high at about 80 m^3/h, and the water level drawdown was minimal; less than a metre. It appeared to be a hydraulically efficient borehole. However, after several hours the water level fell rapidly, the water became thick with clay, and then the water level fell to the pump intake. The pumping rate had to be reduced in order to find a sustainable yield at the maximum drawdown.

The analysis of the flow rate and water level drawdown data provided evidence that the initial high pumping rate was sustained by flow from the water stored in the thick shatter zone in the floor of the quarry next to the borehole. This zone of loose rock was about 2-3 metres thick in this area of the quarry, and water flowed through it freely.

The sudden drop in water levels occurred when the flow from the storage in the shatter zone was exhausted, and the majority of the water entering the hole came from just the cavities at depth.

However, it appeared that the clay in the cavities below 25 metres had fallen into the hole and progressively was blocking the upward flow from the cavities below 50 metres. During the testing in January to March 2020 the sustainable pumping rate was 25-30 m^3/h. Later in the year it fell to less than 9 m^3/h.

The 'raw hide' pumping programme was successful. The boreholes produced clean water except for a few minutes after the pumps were started. It was not possible to clear the clay out of the shatter zone and the upper cavities. Therefore, when each pump was started the discharge for the first 5-20 minutes was turbid.

We developed a system for diverting the flow to the middle of the quarry floor until the turbidity cleared, and only then, opening the valve to send the water on further towards the sump.

Figure 3.6 Downloading data from Ott flow meter in 'V' notch weir chamber

Eventually, by late March, the boreholes were able to pump to the quarry floor at the edge of sump 20 minutes after starting the pump.

The last day of fieldwork was on the 27th March 2020 when the Government gave the Covid-19 order to "Stay at home and cocoon". The pumps were run for a short period. Borehole 1 was pumped at 53 m^3/h. borehole 2 was pumped at 53 m^3/h and borehole 3 was pumped at 133 m^3/h. These pumping rates did not alter the rate of pumping from the sump which was controlled by the operation of the single sump pump.

The data collected in the first three months of 2020 was used to plan for a long pumping test, whenever lock down restrictions were lifted.

The pumping up until the end of March had been within the quarry. Some extra water had been discharged via the settlement lagoon and 'V' notch, but most of the water had been re-circulated within the quarry. These tests did not therefore give a realistic estimate of the sustainable discharge from the boreholes during a long test if all the pumped water was discharged from the site. Even so, it was realised that the existing discharge licence for the site would be exceeded during a long test.

The easing of Covid restrictions started on the 18th May. Initially, we worked in the field wearing masks and keeping a distance of 6 metres apart.

We asked Meath County Council for permission to amend the discharge licence for the duration of a long test at an increased rate of up to 6 million litres a day or 250 m^3/h.

We installed a second pump in the sump, extended the borehole discharge lines to the sump and carried out a test to find out whether the settlement pond and reed bed could remove the sediment from a larger discharge created by high pumping rates.

Figure 3.5 shows two pipelines feeding water into the quarry sump. One pipeline was carrying the discharge from two boreholes. The sump is nearly empty because the two sump pumps (the extra pump is seen in the water on the right) were able to pump at a higher rate than the borehole pumps on the day the photograph was taken.

We regularly downloaded the data on flow from the settlement pond and wetland from the Ott instrument mounted on the side of the concrete flume with the 'V' notch weir.

Figure 3.6 shows Ciara Bannon and James Kelliher, from Kilsaran, downloading the raw data. The data was then processed with an algorithm supplied by the instrument installers to compute daily flow totals.

The flow from the boreholes was measured at the well head by the Siemens Mag flow meters. We later found that the flow measured by the Ott instrument, in the 'V' notch weir chamber, seemed to understate the flow from the settlement pond and the wetland. At first we considered

Figure 3.7 Monitoring the turbidity of Borehole Discharge Water May 2020

Field use of the Palintest (Del Agua) Turbidity tube in the Rathcore quarry to monitor the turbidity of water from the test boreholes before pumping to the settlement pond the possibility of a significant leak in the settlement pond, or wetland. Eventually, we found that the algorithm supplied by the installers assumed that the instrument was set at a different level relative to the bottom of the 'V' notch weir. The error was about 4.5cms but it made a large difference to the calculated flow rates.

Using the new instrument reference level meant that the total flow calculated from the boreholes matched the flow over the 'V' notch weir. All the 'V' notch flow data used in this report has been re-calculated using the new instrument reference level and is accurate.

We measured the turbidity of the borehole discharge water in the field.

Figure 3.7 shows Ciara Bannon, in June 2020, using a simple but accurate Palintest Turbidity tube. The turbidity of the water is measured by finding the highest water level in the tube at which a small black circle is still visible on the bottom of the tube. The tube can be filled to the top with clear water and the black circle is still visible. The black circle is obscured by just two centimetres of highly turbid water. The example in the photograph shows the water level for water pumped from a borehole with a turbidity of 16NTU.

We also tested the accuracy of the field turbidity measurements by sending samples each day to City Analysts in Dublin. We also measured dissolved oxygen in the 'V' notch discharge chamber prior to, and during the subsequent pumping test.

We carried out two tests of the system.

Figure 3.8 shows a line of water samples in bottles on the roof of a car just before they were taken to Dublin for analysis. The light on the bottles is even, because there was no direct sunlight. The results of the analysis received a few days later are written below each bottle, and the location of the sample is written above.

It can be seen that the raw water from Borehole 3 is cloudy whereas the water from Borehole 1 is almost clear. These two boreholes pumped to the sump where the waters mixed. The water went through the settlement pond, which reduced the turbidity to 13.8 NTU. The water went through the wetland and the turbidity was reduced to 4.92NTU. The water went through the 'V' notch weir and through a pipe to the drain or stream. We took a sample at the end of the pipe, and then followed the drain for a kilometre downstream and took a final sample. The site for the final sample was just upstream of place where cattle enter the drain to drink and also raise mud off the bottom of the drain.

Kilsaran submitted a request to amend the discharge licence with details of the proposed test, data and photographs to the County Council, and were granted permission with conditions on the 8th July.

The long pumping test began on 15th July 2020 and continued until early December 2020. We

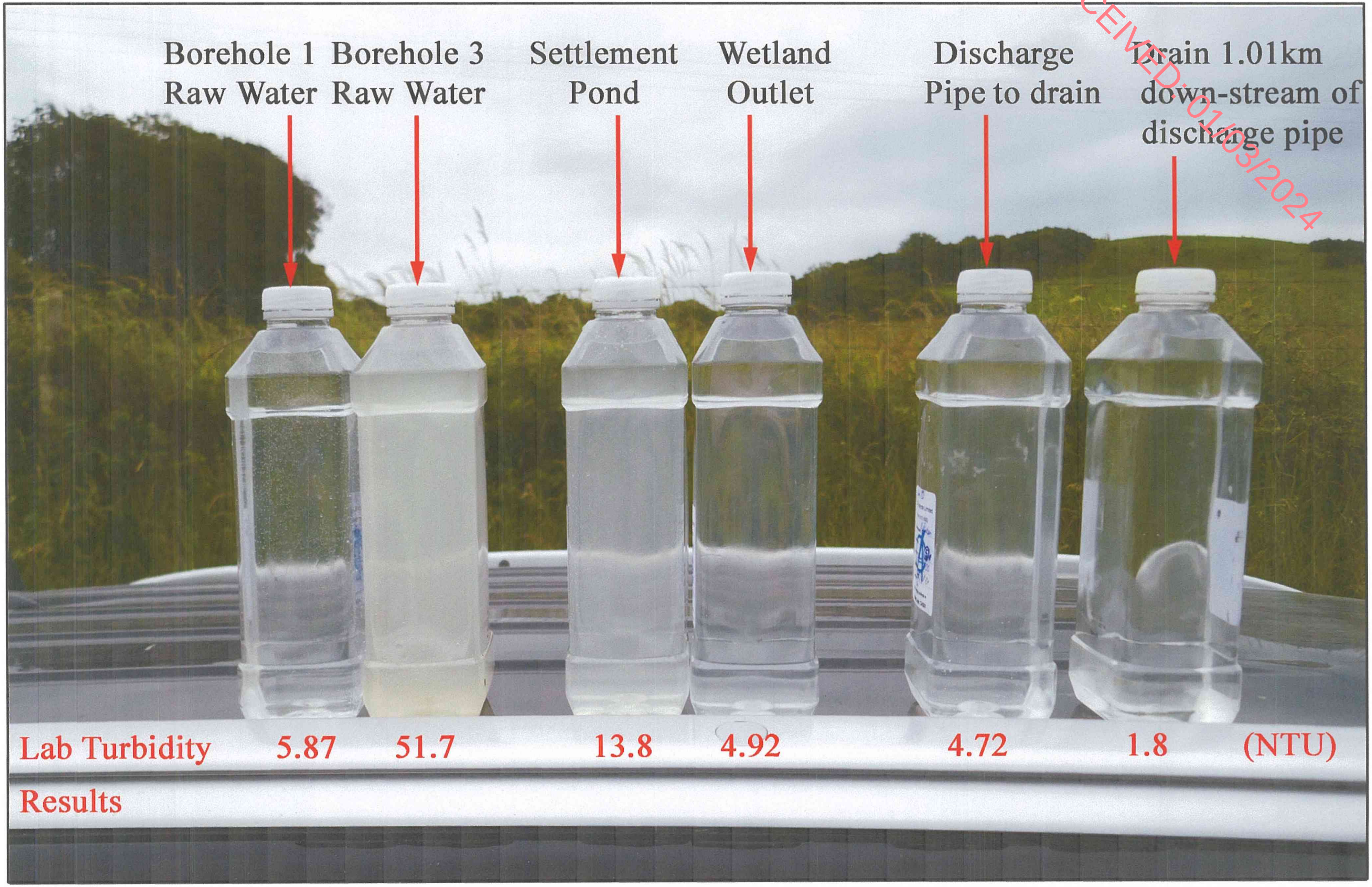


Figure 3.6 Results of sampling test to prove effectiveness of water treatment process

wanted to carry out the test under summer, autumn and, in particular, winter recharge conditions.

The pumps were also re-started in December before the Christmas New Year break in anticipation of heavy rain over the holiday. Borehole 3 was inadvertently turned on for a day in January 2021.

A supplementary winter long test was carried out in February and March 2021.

The system where the boreholes pumped via long pipelines to a sump with two sump pumps was changed during the first long test in 2020, because it wasn't possible to balance the sump pumping rate with the borehole pumping rate.

Instead the sump was cut out of the discharge arrangements and the borehole pipelines were extended direct to the settlement pond.

Figure 2.9 shows pumping direct to the settlement pond. This change affected the potential maximum borehole pumping rate. The borehole pumps faced a 30 metre increase in the headlift to get the water up and over the quarry cliff. The increase in headlift made the pumps work harder, and this reduced their pumping rates.

Monitoring of water levels in the quarry and in boreholes and wells around the quarry had taken place before the start of pumping. It continued during the test and has continued since.

The monitoring of pumping rates, discharges from the quarry and water levels in the pumping boreholes is described below in this chapter. The water level monitoring data for observation wells and boreholes and the interpretation will be described in the following Chapter 4.

3.4 Long Pumping Tests 2020 - 2021

The first long pumping test started in the middle of July 2020 seven months after the pumping boreholes had been drilled.

There had been a prolonged dry period from March to the beginning of June. We hoped that after rain in June, the remaining months of the summer would be dry, and that we could carry out the test and assess the response during a period with conditions of no effective rainfall recharge, and slowly declining groundwater levels. We hoped that we could observe the impact of pumping during a long natural recession, and then observe changes that might take place with the onset of the autumn rains in October.

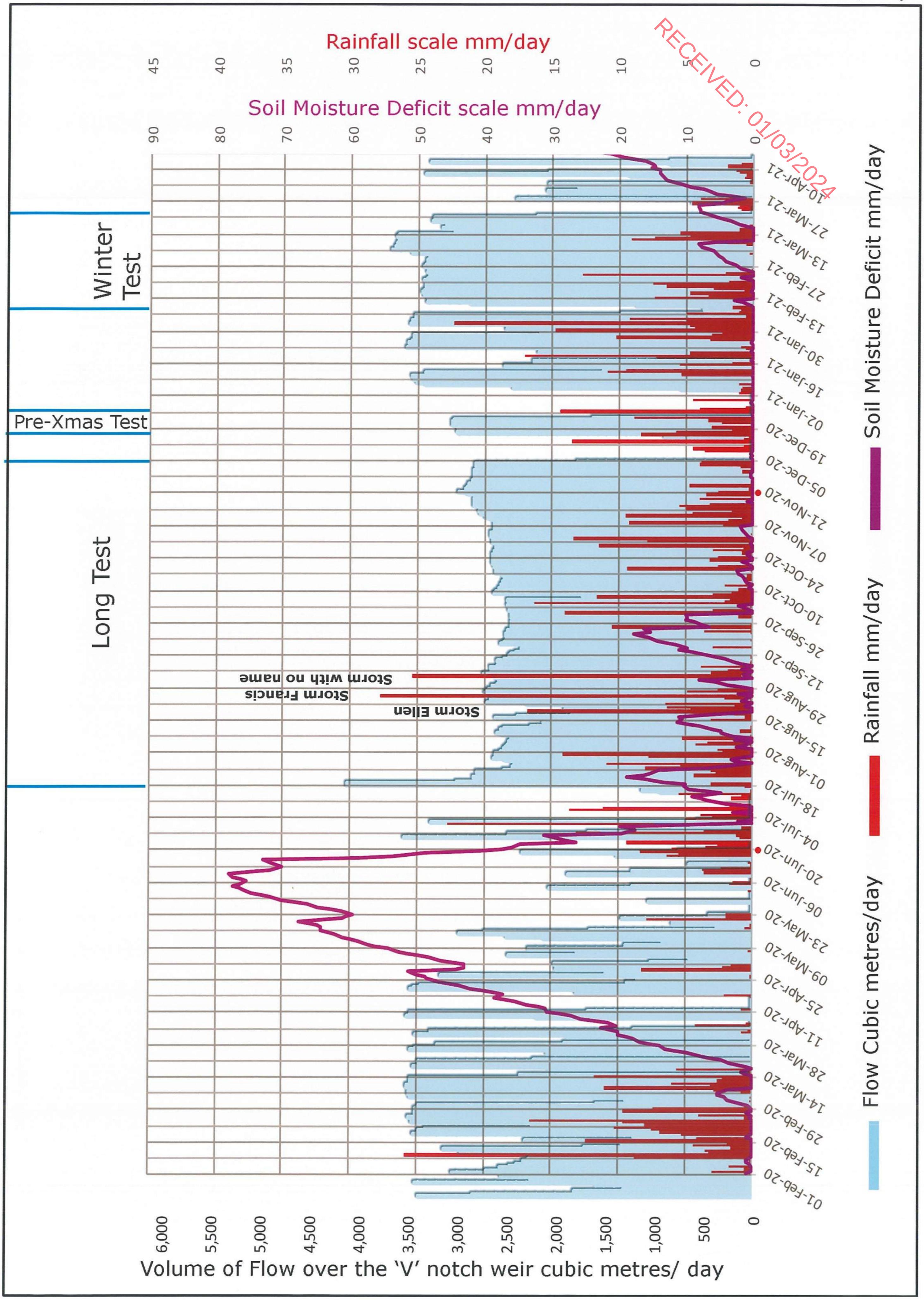
Figure 3.10 provides an overview of the daily rainfall pattern and the volume of water pumped from the quarry from February 2020 to April 2021.

It shows the heavy rain in February to mid March 2020 when we were doing the borehole development and testing to scour the clay from the cavities. The graph shows the prolonged

Figure 3.9 Three boreholes pumping into Settlement pond

dry period from March to mid June.
The daily rainfall data is from the weather station at the Agricultural Research Station at Dunsany where they also calculate the soil moisture deficit. The prolonged rise in the soil moisture deficit to nearly 80mm during the dry spring, can be seen on the graph.
The soil moisture deficit had been eliminated by the beginning of July. The pumping test began on the 15th July but shortly afterwards there was a heavy rainfall event, followed by three major storms and heavy rain in August. The first two storms were named Ellen and Francis. The third storm was principally a rainfall event, and not given a name. There was a very short dry period in September. The autumn rains and the elimination of the soil moisture deficit began at the end of September and continued through to March 2021.
The rainfall pattern and amounts were particularly important for the management of the long pumping test. Rain falling on the quarry immediately soaks into the loose rock on the quarry floor and recharges the groundwater system. The direct rainfall onto the quarry floor is augmented by sheet run-off from the quarry sides and roadways. Groundwater levels immediately rise in response to the rainfall. Attempts were made to try to increase the pumping rates in order maintain a steady drawdown curve, but there were problems with pump performance.
The pale blue column graph in **Figure** 3.10 shows the total flow out of the quarry. This flow is the combination of routine intermittent pumping from the sump, and, or alternatively, direct pumping from the boreholes. It shows how there was little need to pump from the quarry during the dry spring. It shows the near steady pumping from the boreholes between late July and September with an increase in pumping in late July and August to deal with the rainfall during the three rainstorms.
It shows the steady increase in pumping with the autumn rainfall recharge until the end of November and the slight decline before the end of the main test on the 4th December.
Figure 3.11 shows the water levels in pumping boreholes 1 and 3. The levels for borehole 2 have been left out because the pumping rate varied significantly as the borehole yield deteriorated.
The purpose of **Figure** 3.11 is to show the overall pattern of pumping water levels during the main test from July to December. It illustrates the rise in water levels after heavy rain. It also shows the artificial short periods when water levels rose because the pumps were switched off to service the generator, or a pump motor stopped working and the pump had to be replaced.
The initial pumping rates were 54 m^3/h from borehole 1, 26 m^3/h from borehole 2, and 123 m^3/h from borehole 3. These pumping rates were high because it was necessary to try to

Figure 3.10 Dunsany Rainfall and Soil Moisture Deficit and Flow out of the Quarry



dewater the storage in the 'shatter zone' on the floor of the quarry, and also keep pace with any water leaking out of the sump and re-circulating back into this layer and the deeper conduits. Pumping rates were adjusted over the next few days in response to drawdown data, the need to maintain clay free water, and the need to try to balance discharges with the capacity of the sump pumps. After a week borehole 2 was turned off because the yield had fallen to less than 10 m^3/h. The rates for boreholes 1 and 3 was also reduced to 40 m^3/h and 55 m^3/h respectively. The sharp rise in water levels can be seen in response on the graph in **Figure** 3.11. Pumping rates were increased over the next three weeks with borehole 1 producing 45 m^3/h and borehole 3 62 m^3/h.

In general, it can be seen how the water level in borehole 1 follows a similar pattern to borehole 3.

There are two exceptions; the first is in mid August when the pump in borehole 1 started to fail and had to be replaced. This was also coincident with Storm Ellen and the change over to pump direct to the settlement pond. The second exception is when the pumping rate in borehole 3 was increased slightly, but there was a rapid drawdown in the borehole of five metres. This was caused by the overall drawdown in the quarry, dewatering the conduits at around 20 metres depth that were feeding water into borehole 3. The reduction of water flow into the borehole at this level meant that the water level fell to the next level of productive conduits at 25 metres depth. These water levels were roughly maintained for a month until it was necessary to replace the pump motor in borehole 3. The sustained pumping rate during this period from borehole 1 was 38 m^3/h. Borehole 2 was not being pumped. Borehole 3 was able to sustain a pumping rate of 68 m^3/h.

There were two later periods when the pumping rate from borehole 3 was adjusted and increased. These were in response to rainfall in October and November. The adjustments had the objective of determining the pumping rate necessary to maintain a near constant water level during a period of autumn/winter recharge. In essence testing whether it was feasible to dewater the quarry during the autumn rains. The pumping rate from borehole 3 was 75 m^3/h in October and 84 m^3/h in November. The pumping rate from borehole 1 could not be increased because the pump was producing its maximum output of 38-39 m^3/h against the head necessary to lift the water direct to the settlement pond.

The water level graphs in **Figure** 3.11 show small sudden changes at frequent intervals. Mostly, these were caused by the need to stop the generator for servicing, roughly every two weeks. The servicing usually took less than 30 minutes, but during this time the pumps were off, and the water levels recovered rapidly in the boreholes. When the pumps were re-started, the water

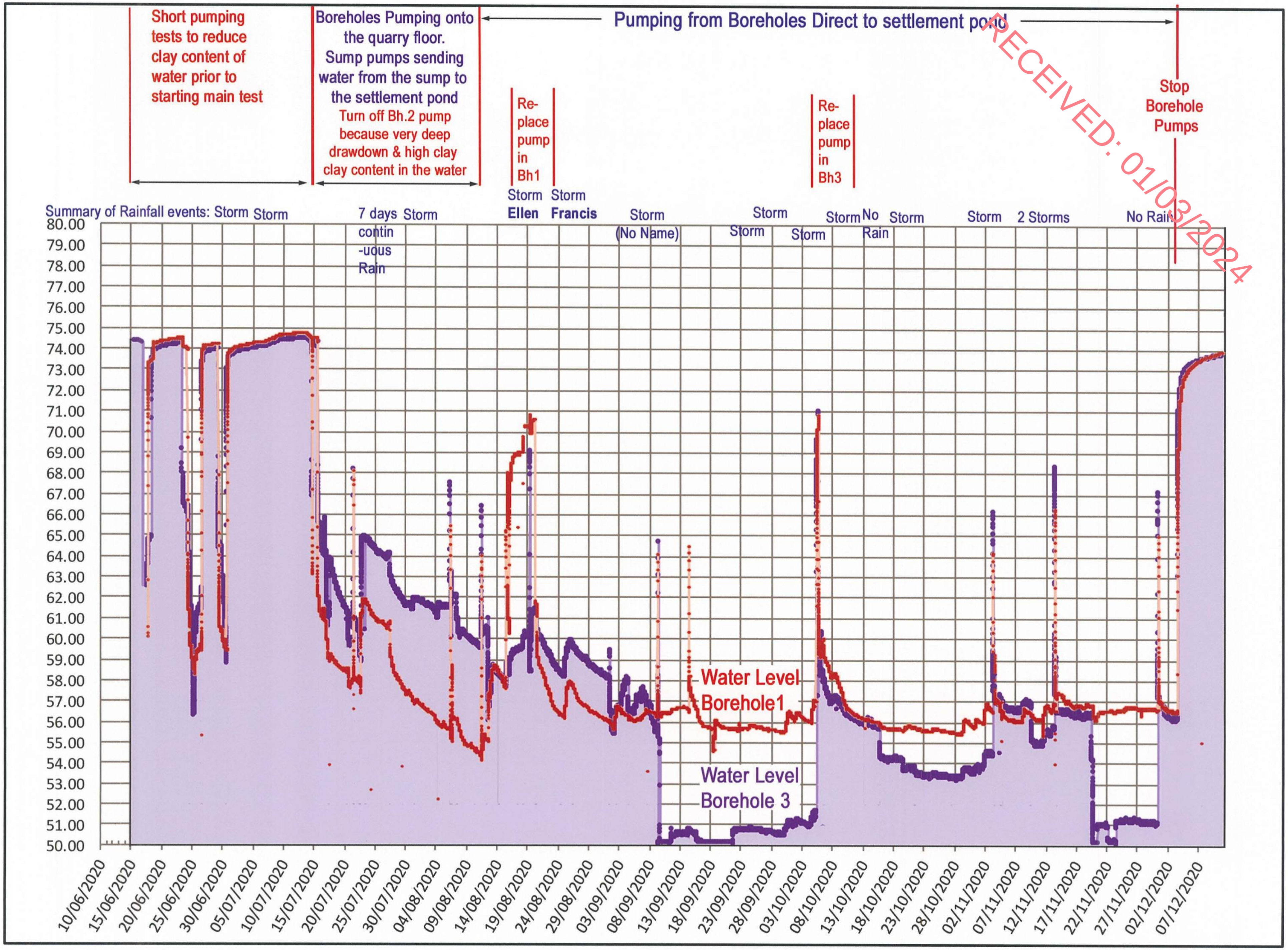


Figure 3.11 Long Pumping Test - Overview and Borehole 1 and 3 Water Levels

had to be pumped to the quarry floor until it was clear of turbidity. Then the valves were changed and water was pumped direct to the settlement pond.

We decided to take a one litre water sample everyday to keep as a record. We sent data on pumping rates, oxygen levels and turbidity to the County Council at the end of each week as required.

Figure 3.12 summarises the pumping from the boreholes before during and after the main long test. The boreholes have not been pumped since the end of March 2021. The pumps are still in place, but the generator and the discharge pipes across the quarry floor have been removed.

The graph shows two short periods and one longer period of pumping after the end of the main test. The short periods were to lower water levels in the quarry before and after the Christmas New Year holiday at the end of 2020.

The longer period of pumping was a supplementary long test to determine the level of pumping necessary to lower water levels in the quarry during highest winter water table conditions. It was also carried out in order to find out whether pumping at a high rate from the quarry could affect the flow and temperature from St Gorman's Well.

The graph shows that there was a combined borehole pumping rate of roughly 2,500 cubic metres per day in late September after a wet summer. The equivalent rate in mid February and March 2021 was 3.500 cubic metres per day.

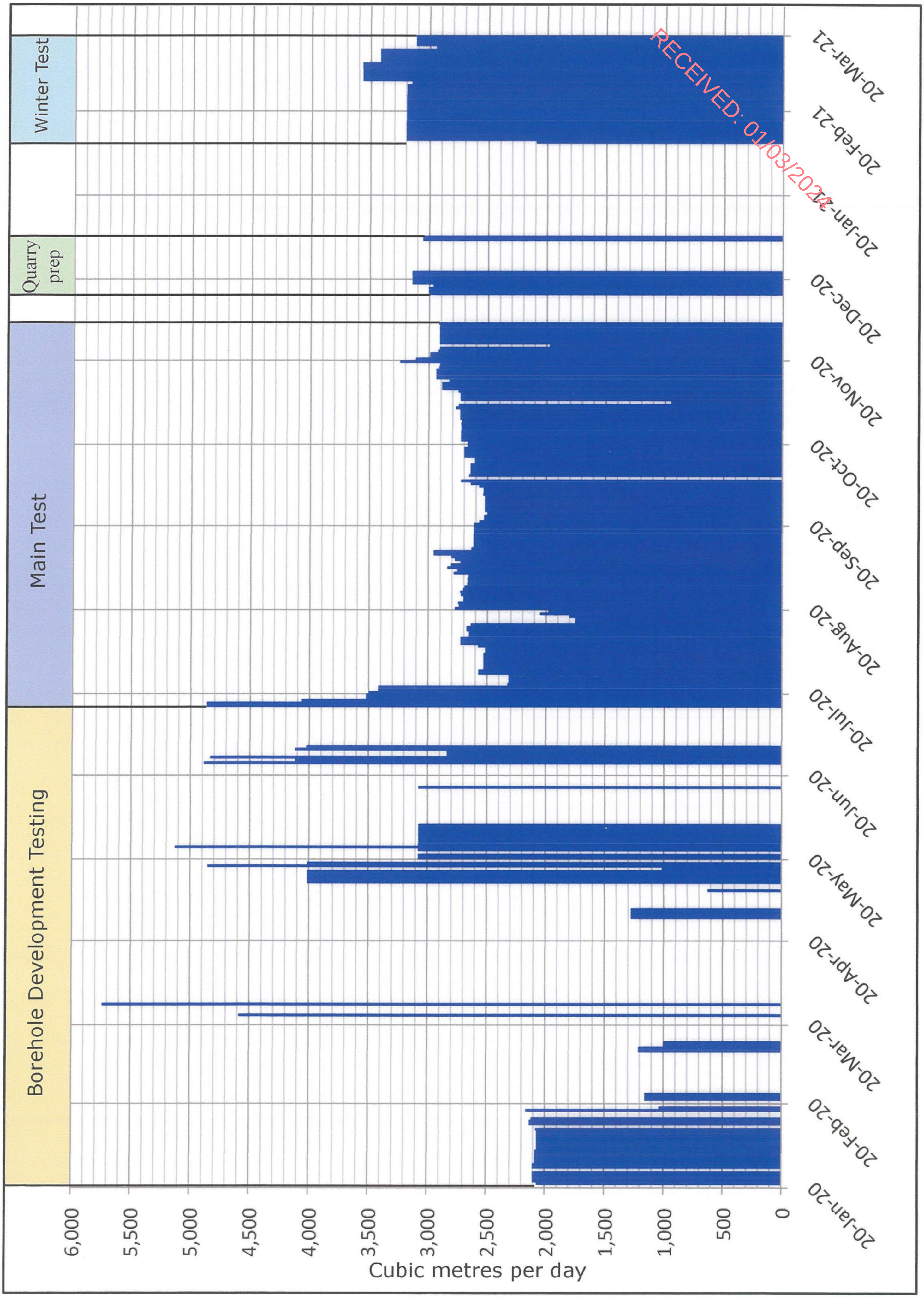
The County Council agreed an adjustment of the quarry discharge licence to a maximum of 6,000 cubic metres per day. Though high volumes were pumped for a few days at the beginning of the main test, it is evident that sustained pumping produces lower volumes.

Figure 3.13 shows details of the supplementary winter pumping test in 2021. The bottom panel shows the total daily volumes discharged by the quarry from December 2020 to April 2021. It shows the pre-Christmas pumping, followed by pumping from the sump to maintain working levels in the quarry, then from early February boreholes 1 and 3 were pumped.

The upper panel includes the daily rainfall and soil moisture deficit data from Dunsany for the same period. In addition the lower graph shows the water levels and pumping rates for borehole 3. The graph is shown because it is possible to write the pumping rates above the corresponding section of the water level hydrograph. It shows how the water levels rapidly respond to changes in the pumping rates.

The water level graph also shows that the water level in borehole 3 does not appear to respond to heavy rainfall in January and the beginning of February before the long winter test. This apparent lack of response is because the borehole became artesian and free flowing for most of this period. The free flow from borehole 3 was about 3-4 m^3/h.

Figure 3.12 Daily Combined Quarry Borehole Pumping Rates January 2020 - March 2021



3.5 Summary

In summary, the long pumping test from the boreholes in Rathcore quarry was one of the longest pumping tests carried out in the country. It was delayed by the need to clear clay from the karst conduits, so that the water pumped from the boreholes could be effectively treated before it was discharged from the quarry site. It was not a simple test to operate because the power supply had to be provided by a generator, that required servicing, and there were problems with the borehole pumps.

However, in spite of the problems and adjustments, it showed that the water levels could be held down in this northern area of the quarry, underlain by numerous highly productive karst conduits. The long period of pumping at a high rate would not be sustained if the sole origin of the water was just the rain falling on the quarry floor and its immediate surrounds, and storage within the conduits under the quarry.

The groundwater system in the conduits in the area around the quarry and connected to the conduits under the quarry, was induced to flow by the pumping from the boreholes. The conduits in the area around sustained a flow of over 2 million litres per day for nearly five months during the main test. This flow rate indicates that the water bearing conduits in the quarry are connected to a karst groundwater flow system that extends beyond the area of the quarry.

A feature of all karst conduits is that the dimensions of the conduit are not uniform. In some sections they are wide, and in other sections they are constricted. Constrictions can be created also by thick and compacted clay deposits within the karst conduits. The constrictions can throttle or constrain the volume and speed of water flowing along the conduit.

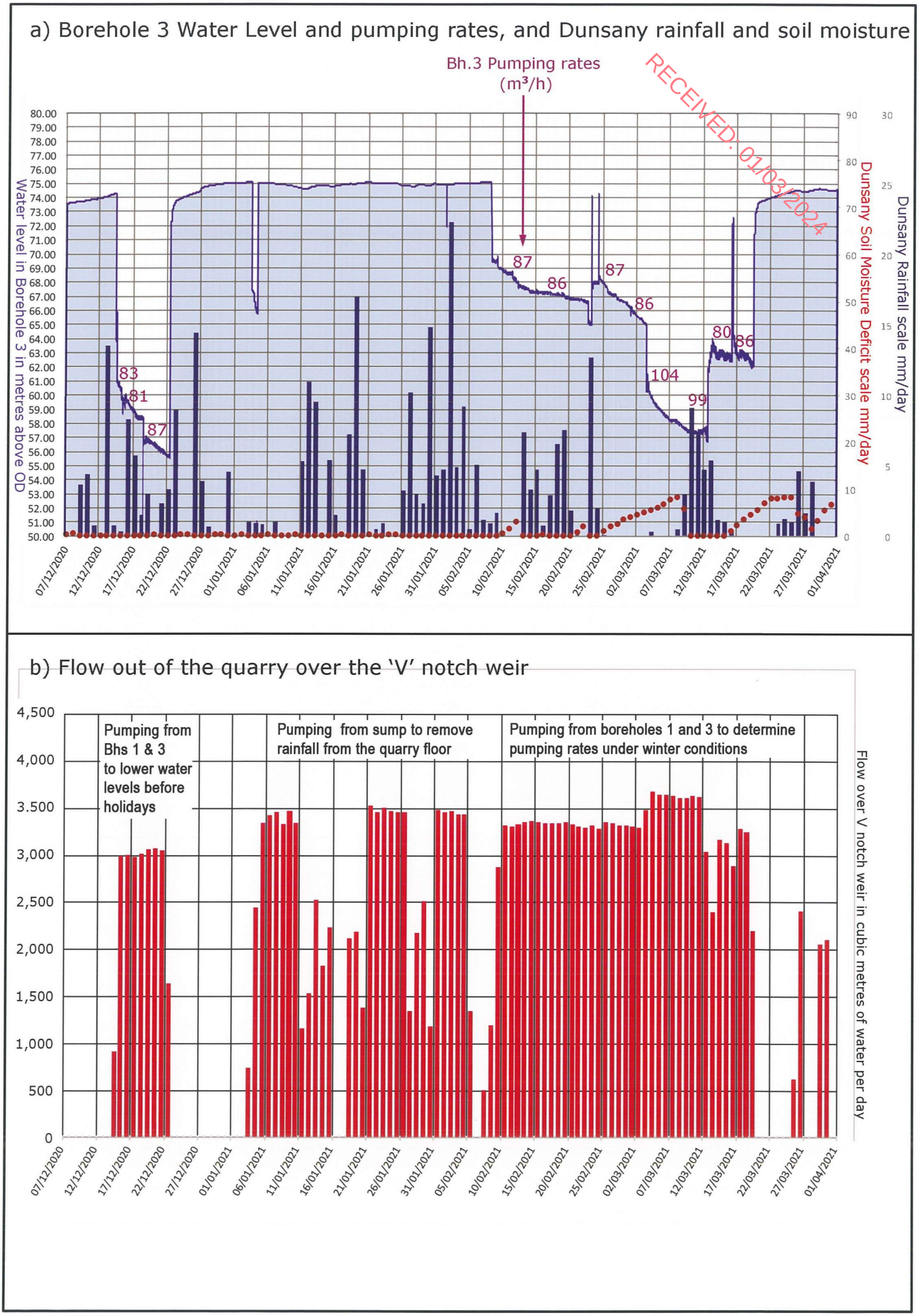
Experience in dewatering mines, and from long pumping tests on karst limestone boreholes, has shown that though initial flows along a conduit maybe large, the flow often tapers off with time, because the conduit is constricted at an unknown point some distance away.

One of the objectives of the long pumping test was to determine whether the flow in the conduits was constricted near to the boreholes, or at some distance away.

When the sustainable yield from borehole 2 decreased rapidly from over 50 m^3/h to less than 10 m^3/h, one of the first interpretations of the data was that the conduits feeding borehole 2 were constricted, and these conduits were a part of a conduit system different from the system supplying boreholes 1 and 3.

However, when we plumbed the depth of the borehole, we found that clay had slumped across the borehole below the pump. This observation corrected the initial interpretation. Flow up the borehole from the open conduits feeding the borehole below this slump had been impeded. It

Figure 3.13 Rathcore Quarry Pumping 7/12/2020 - 31/3/2021.



was a constriction in the borehole and not in the conduits through the rock.

The pumping from boreholes 1 and 3 provided evidence that there was a limit to the sustainable flow rate along the conduits connected by each borehole. For example, with reference to Figure 3.11, we increased the pumping rate from borehole 3 on the 10th September and the 19th November 2020, but each time we did this, the water level fell rapidly and we had to throttle the pumping rate back in order to bring the water level up slightly, and prevent the pump drawing in air and causing cavitation in the pump bowls.

Over the course of the several pumping tests we found no evidence to suggest that there was a significant constriction in the conduits some distance from the quarry, that restricted flow to the quarry. This evidence from the pumping tests fits with the findings in Chapter 2 that indicated there is a complex but extensive and interconnected system of karst conduits in the Waulsortian limestone and perhaps through less karstified faults in the dark grey limestone and shale formations.

The size of some of the conduits and the amount of clay and sand deposited within them, strongly indicates that this ‘plumbing system’ did not develop to meet the requirements of modern conditions. Instead, it appears to be a plumbing system that was developed under previous conditions, perhaps several million years ago. The system is over-sized for modern flow conditions, and the current slow flow of water within these passageways has not scoured out the clay deposits within them.

This clay may have been washed down into the caves and deposited at the end of the last ice age when there was no soil or vegetation cover at the surface, and the landscape was covered with loose material dropped by the ice sheets. Alternatively, the clay may have been deposited over a longer period, as groundwater gradients and flow rates decreased with the rise in sea levels and base levels. The sediment may have dropped out of suspension in the water over time, as the flows within the caves slowed. The overall impression is that the karst conduit system under natural conditions contains a lethargic groundwater flow that deposits clay rather than scours clay.

The effect of pumping from and, in effect, re-energising, this ancient drainage system, is described and assessed in the following Chapter 4.

Chapter 4 Water Level Monitoring and correlation with activities in Rathcore Quarry and Rainfall

4.1 Introduction

This chapter describes the monitoring of groundwater levels before, during and after the recent drilling and pumping tests at Rathcore quarry.

There is a long record of groundwater level monitoring associated with the quarry. Water levels have been manually measured every two weeks in core holes on Kilsaran's lands. Manual measurements have been made monthly in shallow wells and boreholes on neighbouring properties. There are gaps in the manual measurement record caused, for example, by recent Covid-19 restrictions.

The water level in a well or borehole is measured by a person using an electric contact water level gauge or tape, commonly called a 'sounding line' or 'dipper'. A light comes on in the instrument reel when the electrode in the probe makes contact with the water in the hole. The measurement is made each time from the same reference point at the top of the hole. These reference points have been surveyed by Kilsaran so that all the water level data can be referred to Ordnance Datum (Malin).

The act of measuring the water level in a hole below a reference point may appear to be simple, but in most holes there are pumps, rising main pipes, dual pipe systems for venturi pumps, security ropes, and electric cables. Most of these items have droplets of moisture adhering to their surfaces. Getting the contact probe at the end of the sounding line through the wet tight spaces, and down to the water, can sometimes lead to false, but plausible, readings.

It is a common assumption that the water level measured in a borehole or well is a measure of the position of the 'water table'; i.e. the level of the top of the zone of water saturation in the ground, or, phrased another way, the level, below which, all the open spaces in the soil or rock are filled with water. It is often assumed that there is a single 'water table'.

However, groundwater aquifers and flow systems are often stratified. Groundwater in sands and gravels in the overburden may be separated from groundwater in the bedrock by a layer of low permeability clay on top of the bedrock. The two groundwater systems may not be in 'hydraulic continuity' with each other. The water level in the overburden aquifer may be several metres higher than the water level in the bedrock. In effect, the water in the overburden may be 'perched' on a layer of clay at the base of the overburden, separating the overburden from the bedrock below.

The heterogeneous karst conduit systems that developed at different levels, at different times, in limestones also may not be in hydraulic continuity with each other. The karst conduits may have been developed under different conditions at different times, perhaps several million years apart, and with different base levels for the drainage through the limestone. They can be separated. This can make matters complicated.

Boreholes and wells are merely access holes into the subsurface.

It is commonly assumed that the static water level in the hole is an accurate measure of the water level in the rock or overburden around the hole. This is probably a correct assumption for a water level in a shallow (5-8 metres deep), wide diameter, dug well, only excavated into the overburden sands, gravels or sandy till layers.

It is also a correct assumption if the water level is measured in a modern, properly constructed water supply borehole, constructed in accordance with the IGI water well guidelines 2007, or EPA Advice Note 14 2013. Bedrock boreholes constructed to these standards will have a deep pump chamber casing. Around this 20-40 metre deep pump chamber casing, there will be a continuous cement grout seal. The seal is designed to prevent near surface groundwater, that can be more readily contaminated, from the overburden and upper bedrock, leaking down, around the outside of the casing, and into the borehole's open producing section. This critical part of the design of a modern borehole is to protect the quality of the water drawn from the borehole. However, the deep casing surrounded by a cement grout seal also will mean that groundwater in a perched aquifer in the overburden will not flow down around the outside of the casing into the bedrock part of the borehole below.

Unfortunately, most water supply boreholes for houses, farms and group schemes are not constructed to modern standards with a pump chamber casing and a complete cement grout seal. Therefore, a water level measured in these boreholes may be a measure of either the true water level in the deep bedrock, or the water level perched in the overburden, or some blend of both levels.

The water level also will not be the natural 'static' water level at the time of the measurement, if a borehole pump is in operation, or recently has been operating.

It has been important that Kilsaran has monitored water levels in both shallow dug wells and boreholes around the quarry, in order to find out whether the overburden and bedrock groundwater systems are separate, and understand the hydrogeology of the area adjacent to the quarry.

The manual water level monitoring measurements have been plotted on graphs (hydrographs) to provide a visual interpretation of the rise and fall of water levels over time.

In Ireland, there is usually a deficit of moisture in the soil in the summer months and September. The rainwater that soaks into the ground in summer is usually taken up and used by the growing plants, and water does not percolate below the root zone to recharge the groundwater system. There are, of course, exceptions to this generalisation.

Groundwater continually flows from places where the water table is high to places where it is lower; in other words, it flows by gravity. Generally, it flows from the higher land down into the valleys, and emerges in the streams, drains and rivers on the valley floor. These surface water features are the local base level to which groundwater flows. The drainage of the groundwater system continues when there is no rainwater recharge percolating down into the ground. As a result, there is usually a gradual 'recession' of the groundwater levels during the summer in Ireland. The recession stops, or is reversed in autumn when plant uptake of water diminishes, and the first heavy rain exceeds the soil moisture deficit. During the late autumn and winter a large proportion of the rainfall percolates down to the top of the 'water table'. The additional water makes the level of the water table rise.

Therefore, when looking at the water level measurements made in wells and boreholes around the quarry, it would be expected that there is a rise in water levels in autumn and winter, and a recession of water levels in summer. If the pattern of rainfall and vegetation growth does not change from year to year, then the rise and fall of groundwater levels will follow roughly the same pattern from year to year. The weather in Ireland does not stay the same, and the timing and intensity of the rain varies. Therefore, the pattern of the rise and fall of groundwater levels (the hydrograph) will vary. The height of the rise in winter is usually the most variable., but the depth of the recession in summer is usually less variable. If rainfall amounts and timing roughly conforms to the long term average, then the end of the summer groundwater recession usually does not go below a certain level.

Therefore, when looking at the long hydrographs, for the monitoring wells and boreholes, a key characteristic to observe is the depth or the level at the end of the summer recession.

If the level at the end of the recession is progressively higher over the course of several years it could mean that the climate is changing, and the amount of rainfall soaking through the soil is increasing. It could also mean that there has been a change in the land use from grassland to, say, arable crops that are harvested in mid summer. With no crops growing in late summer, the soil moisture deficit may be less, and rain in, say, August may be able to pass through the soil down to the water table.

Conversely, the end of the recession may get deeper year after year. This could be climate change and a reduction in rainfall. Or, it could mean that development in the area is increasingly

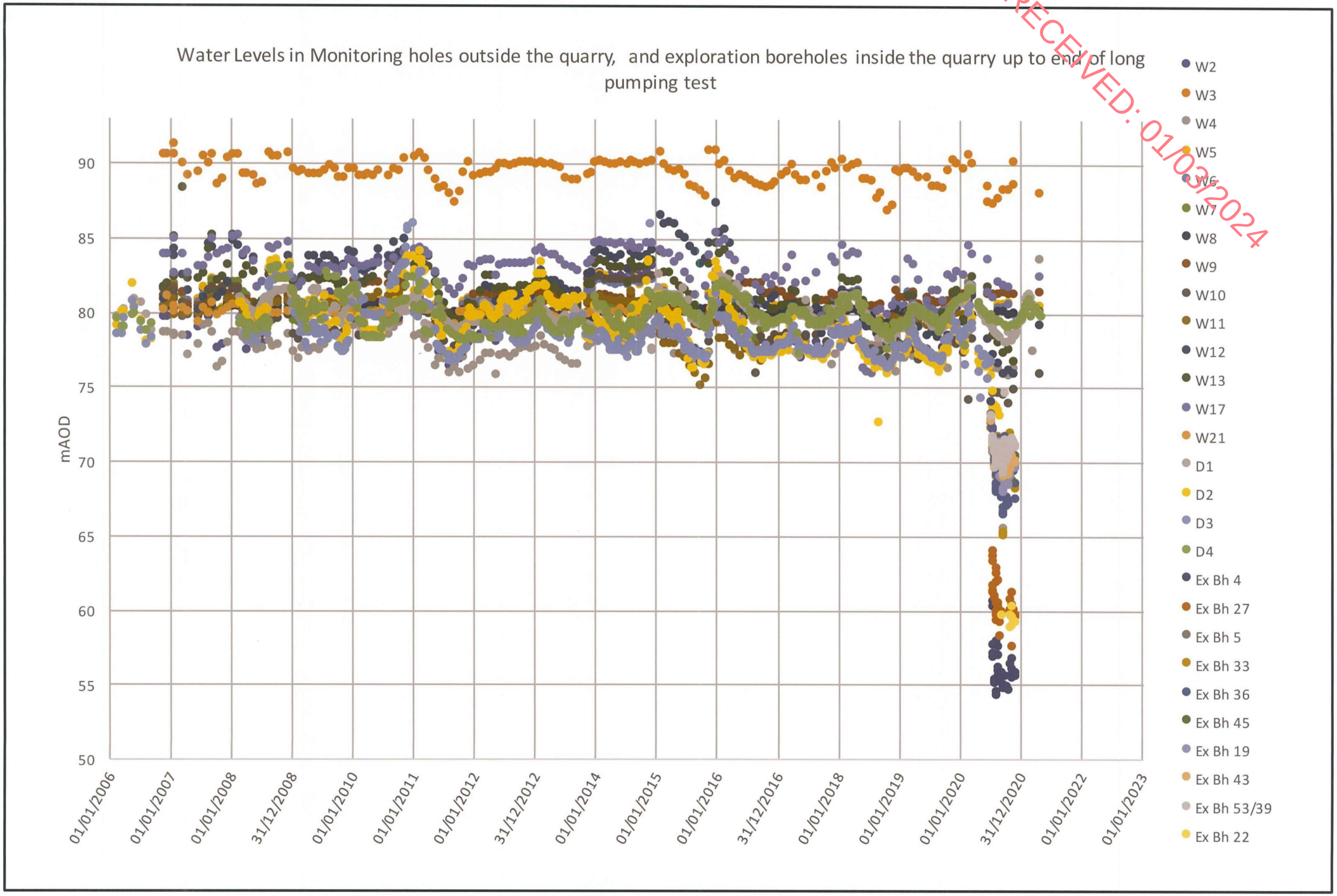


Figure 4.1 Monitoring Wells and Boreholes - Water levels 2006 to end of 2020

withdrawing water from the groundwater resource. This increasing withdrawal of water could be also caused by either the development of a new groundwater public supply scheme, or increased pumping from an existing scheme, to meet the needs of an expanding town or village, or it could be an increase in the development of dispersed rural housing, with each house having its own new water supply borehole. Another obvious reason, in the context of this report, is that the end of the summer recession may be lower year on year, because there is the on-going development of a quarry where the working floor of the quarry is below the water table.

Therefore, when looking at water level hydrographs covering many years, it is instructive to look particularly at the levels at the end of the summer recession, and see if they show any long-term trends.

4.2 Water level monitoring programme – manual measurements

The water level monitoring by Kilsaran around the Rathcore quarry was not carried out just to meet the requirement of planning conditions, but principally to find out whether the development of the quarry was having an influence on water levels around, and obtain any early warning signs of a trend that might create a significant problem for adjacent neighbours or the environment.

The majority of the neighbours have agreed to a member of Kilsaran's staff walking onto their property once a month and measuring the water level in their well or borehole. The person from Kilsaran taking the measurements are often asked by the householders whether the water levels have gone up or down.

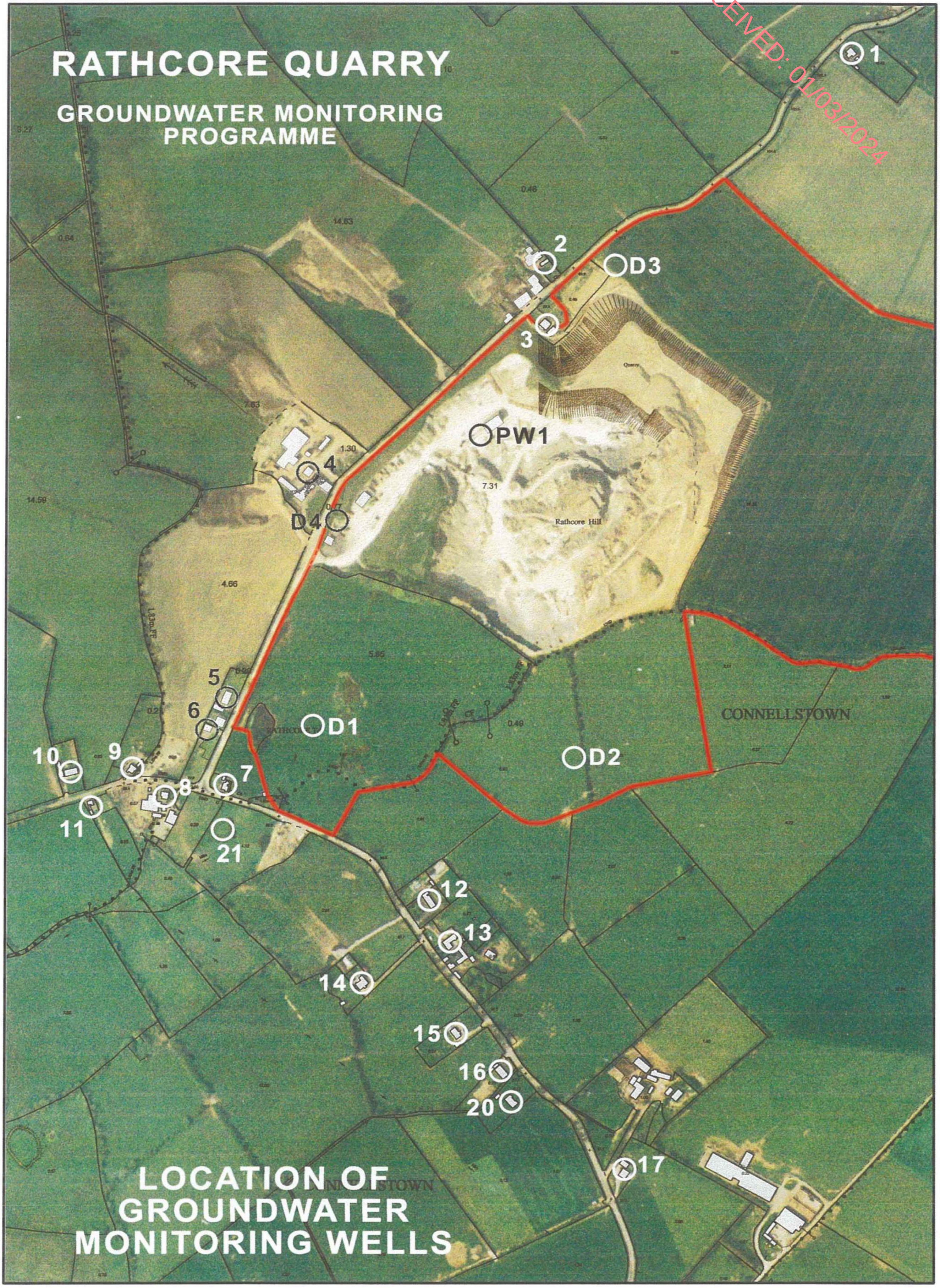
The manual water level monitoring programme was intensified before the start of the long pumping tests. "Diver" water level pressure transducers, made by Eijkelkamp in Holland, were installed in the three pumping boreholes and two exploration boreholes inside the quarry excavation.

A Diver was also installed in a core hole to the northwest of the quarry with a deep water level that appeared to respond to events in the quarry. Another Diver was installed in a shallow well, used for domestic purposes, close to this core hole.

A Diver was installed in borehole SG4 at St Gorman's spring that had been monitored by Sarah Blake for her thesis. She had installed a similar instrument (Solinst) from the Geological Survey in SG4 in 2018. We swapped the Kilsaran instrument for the Survey's instrument in August 2019.

I placed the Kilsaran diver on the same cord, at the same depth, in order to maintain the continuity of the record from the same position.

Figure 4.2 Original Groundwater Monitoring Programme - site locations



The record of water level and temperature at St Gorman's spring is important for Kilsaran. So much so, that I placed a second diver in SG4 at a slightly lower depth as a back up, in case the first instrument stopped for any reason.

Figure 4.1 is a graph showing all the manual measurements of water levels from 2006 to the end of the main pumping test in December 2020. The graph is cluttered with data points. The purpose of the graph is to provide an illustration of the number of sites and data points. In overview, it also shows that the elevation of the water levels, from boreholes and wells, lies within a relatively narrow band between 75 and 85 metres above Ordnance Datum (m.AOD). The one exception is W3, an important shallow dug well just to the northwest of the quarry, where the water levels are around 90 m.AOD.

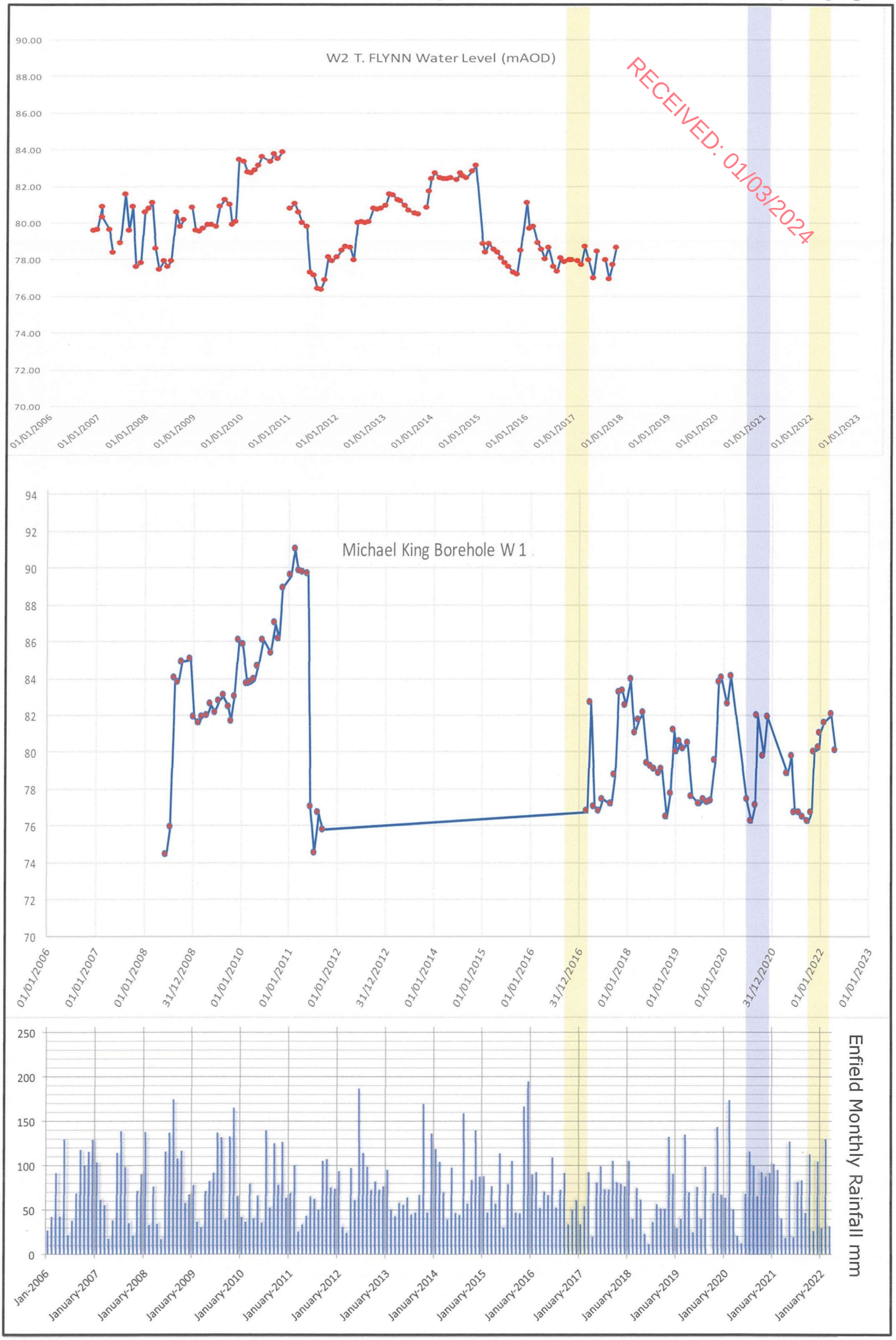
The data points that are significantly lower during the long pumping test in mid to late 2020, are the manual measurements in exploration boreholes close to the pumping boreholes inside the quarry.

The data points on the graph show water levels, in both deep boreholes and shallow dug wells, rising and falling with the seasons. The overall pattern also appears to show a gentle fall in water levels over the 15 years. The fall is about 1-2 metres. The first interpretation of this trend could be that increasing pumping from the quarry is responsible, but that cannot be the reason because the quarry did not start pumping water until October 2013. The reason for this apparent trend is not immediately obvious from all the data plotted on one graph, but looking at the individual hydrographs described below is more informative.

To assist while describing the hydrographs; Figure 4.2 shows the location of the boreholes and wells around the quarry that formed the basis of the manual water level monitoring programme. Some monitoring points have dropped out because of change of the access to the wellhead, change of ownership or change of agreement. The airphoto base for the map is from 2000. The quarry has extended south in the last 20 years. For example, the excavation reached core hole marked 'D2' in 2020, and it became unsafe to continue taking water level measurements thereafter.

The four core holes around the quarry are marked with the letter 'D'. All the other monitoring points are numbered on the figure, but given the prefix 'W' in the records of measurements. 'W' is used for both boreholes and wells. All these are privately owned, and almost all in use for domestic purposes. Therefore, many measurements could have occurred during pumping or just after the pump had stopped pumping, and the water level was still rising in the borehole. Most pumps are connected to a pressure tank to maintain pressure in the domestic water system. The pump in the well or borehole often turns on for just a few minutes at frequent intervals to

Figure 4.3 W1 and W2 Water Level hydrographs



maintain pressure, therefore the amount of water pumped is small and the drawdown in the borehole or well is usually small. However, boreholes that are not very productive usually have a deep drawdown of water levels of several metres, even during short pumping periods.

I have plotted the routine water level monitoring data on individual graphs in the following figures. The data from two sites is on each page. The monthly rainfall totals from Enfield are plotted on the same time-scale at the bottom of each figure.

Figure 4.3 shows the water levels for two boreholes to the north of the quarry.

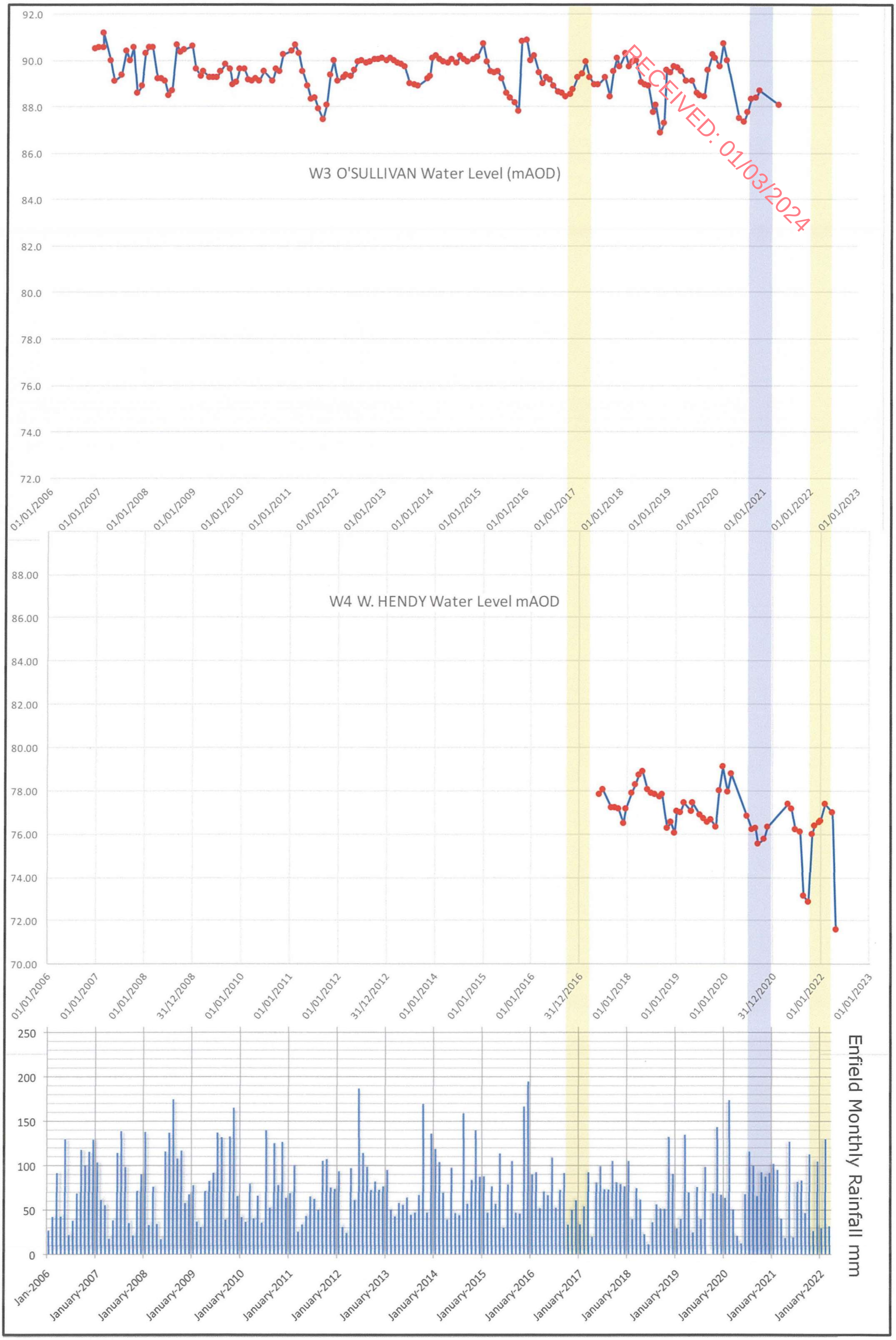
Three faint coloured vertical bands are superimposed on the hydrographs and the rainfall for reference. The pale blue band shows the main long pumping test period in 2020. The left pale yellow band shows the autumn and winter months from September 2016 to March 2017 when there was less than normal rainfall, and St Gorman's Well did not flow that winter. The right hand pale yellow band shows the same months for 2021-2022, when again the Well did not flow. These coloured bands are on all the figures showing the monitoring well hydrographs.

W1 appears from the geology described in Chapter 2, to be sited in, or on the edge of, the southern Rathcore block of Waulsortian limestone. The borehole may be on a northeast to southwest aligned Cenozoic strike slip fault (see Figure 2.47). As will be described below, the water level in deep core hole D3, close to the same fault alignment, rapidly responds to pumping in the quarry. Therefore, it was expected that the water levels in borehole W1 might be similarly affected. Instead the water level is low at the beginning of the long test but appears to rise during the test.

The water level hydrograph for W1 is unusual. It appears that the water level rises 14 metres at the start between, 2008 and 2011, but if the first two measurements are discounted as pumping water levels, then the overall rise is only 6-7 metres. This is similar to the 6 metre rise over the same period in borehole W2, and in deep core hole D3. The large rise in water levels particularly between 2009 and the start of 2011 is found in these three deep holes in the Waulsortian limestone just north of the quarry close to an apparently major Cenozoic fault.

The rise in water levels in the Waulsortian may not be restricted to just this small area north of the quarry. As will be described in Chapter 5, the 12 month Standardised Precipitation Index shows that this period was notably wetter than usual. There are field observations at the same time indicating that St Gorman's Well was flowing for longer than it did in subsequent years. The hydrographs in this period for boreholes W1 and W2 and deep core hole D3 may represent a general period of above average recharge into the Waulsortian groundwater flow system under the whole area.

Figure 4.4 W3 and W4 Water Level hydrographs



The hydrograph for W1 drops suddenly in 2011. There are four water level measurements that are roughly 10 metres lower than seem natural. It is assumed that these water levels are pumping water levels. There is a four year gap in the hydrograph when the top of the borehole was not accessible. When measurements resumed, the water levels appear to fluctuate naturally with the seasons, but did not reach the heights achieved in 2010.

Borehole W2 is assumed to be in the Waulsortian close to the fault. Its hydrograph stopped in 2017 because the site was not accessible. The water levels in the 2016-17 winter were relatively low and there was no significant rise in water levels. This indicates that little rainfall recharge entered the Waulsortian bedrock groundwater system in this area. St Gorman's Well also did not flow in the winter of 2016-17. W2 prior to 2016-17 had shown a 4 to 7 metre annual rise and recession of water levels.

Figure 4.4 shows W3 and W4.

W3 is a 5 metre deep, dug well on the north western flank of the quarry lands. It was dug into sands and gravels, and sandy till. It has formed an important monitoring point for the shallow groundwater levels in the overburden close to the quarry. It provides a good record for assessing recharge throughout the year, and also the duration of the water level recession in summer. It can be seen that the recharge peak was low in the winter of 2016-17, as in deep borehole W2 across the road, and water levels appeared to rise during the summer rains in 2020, during the main long pumping test in the quarry.

There is a slight trend of a fall in water levels since 2006, with prolonged water level recessions in the summers of 2015, 2018 and the spring of 2020.

The hydrograph for W3 in Figure 4.4 consists of the manual measurements, but in March 2019 I installed a Diver pressure transducer, and there is now a continuous record of measurements taken at 10 minute intervals for over 3 years. The Diver records will be discussed and described later in this chapter.

W4 is a borehole to the north west and close to the quarry. It is sited on the Airborne geophysics conductivity boundary between very low conductivity Waulsortian limestone and very high conductivity deeply weathered 'Supra Waulsortian' bedrock as found in BHP 1500=98=3. The borehole is in frequent use for a large farm and business. The recent, unusually low, water levels may be pumping levels relating to the business, and hence not representing natural water levels.

There is a slight downward gradient for the lowest level of the end of summer recession for 2017 and 2018, and this gradient extends to 2020. It is therefore difficult to determine whether the lowest water level in 2020 was caused by an effect of the long pumping test in the quarry.