WATER RECHARGE INTO THE MAGNESIAN LIMESTONE AQUIFER

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Abstract

The study reported in this paper was prompted by the proposed development of a new quarry almost adjacent to an existing Magnesian Limestone quarry in County Durham. Concerns were raised concerning loss of water resource from the Magnesian Limestone aquifer, a potential impact on public water sources down dip and the potential for upwelling of Coal Measures groundwater into the Magnesian Limestone. The quarry operator voluntarily conducted a substantial recharge trial using an instrumented infiltration lagoon and monitoring borehole array.

Water balance studies and borehole water level monitoring demonstrated that recharged water quickly travelled through the unsaturated zone and caused an observable and reasonably uniform increase in groundwater levels beneath and around the recharge site.

Artificial recharging of water into UK aquifers for storage purposes has been carried on since the 1890's but using the practice for impact mitigation in rock aquifers is relatively rare. Examples of successful recharging of such aquifers do exist in many other countries. Some informal rock aquifer recharge is known to have been carried out in the UK but such operations do not appear to be thoroughly instrumented or widely reported.

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Introduction

The practice of artificially recharging water into UK aquifers has been carried on for many decades, usually for purposes of water supply by utilising aquifers as underground storage reservoirs. Experimental work was carried out in the 1890's on Hackney Marshes, and the Enfield – Haringey artificial recharge scheme in the Lea valley has been operating since the late 1970's (O'Shea *et al.*, 1995, Flavin & Joseph, 1983). The Sherwood Sandstone (Environment Agency, 2009), Lincolnshire Limestones and Lower Greensand have also been candidate aquifers for recharge by both borehole and infiltration pit methods (Downing, 1993).

Less well known but nonetheless well researched and successfully implemented is the local recharging of sand and gravel aquifers, usually through open pits, most frequently initiated to mitigate or prevent impact on sensitive wetland features due to the dewatering of sand and gravel quarry workings.

However, the artificial recharging of waters for impact mitigation purposes in rock aquifers is relatively rare in the UK but examples of successful recharging of hard rock aquifers do exist in many other countries. Some informal rock aquifer recharge is known to have been carried out in the UK but such operations do not appear to be thoroughly instrumented or widely reported.

Background

The behaviour particularly of fissured limestone aquifers in response to either local dewatering of quarries or local recharge is not well understood. This uncertainty was explored during an unpublished study co-ordinated by MIRO in 2003. Data provided in confidence by several quarry operators active in major UK limestone aquifers usually demonstrated, in this study, very unpredictable aquifer behaviour when compared with Darcian groundwater flow theory.

The study reported in this paper was prompted by the development of a planning application for a new quarry almost adjacent to Thrislington quarry in County Durham. Concerns were raised by the Environment Agency into matters of loss of resource from the Magnesian Limestone aquifer, a potential impact on public water sources down dip and the potential for allowing upwelling of Coal Measures groundwater from beneath the Magnesian Limestone into that strata sequence. The quarry operator voluntarily conducted a substantial recharge trial using an instrumented infiltration lagoon and monitoring borehole array.

GEOLOGY AND HYDROGEOLOGY

Thrislington Quarry lies to the east of Ferryhill in County Durham. Quarrying has taken place on the site since the early 1950s, and much of the excavated limestone is burnt in on-site kilns for a variety of applications. The burnt products are traded internationally and primarily used for steel fluxes, refractory repair products such as those for blast furnace liners, and high magnesium fertilisers. Other materials produced on site are used for conventional construction materials.

Thrislington Quarry and the proposed new quarry lie on the narrow Magnesian Limestone outcrop ridge that runs from Nottinghamshire and Derbyshire to County Durham. British Geological Survey mapping and Memoirs of the area identify the Permian Lower and Middle Magnesian Limestone, now referred to as the Raisby and Ford Formations respectively (Smith *et al.*, 1986), overlying the Marl Slate and Permian (now Yellow) Sands. Figure 1 illustrates both the solid geology and the location of the study site. Lower and Middle Carboniferous Coal Measures are present at depth and have been subject to underground mining until recently. Some Glacial Till is present at the surface to the east of the A1(M) dual carriageway, including the northern and eastern parts of the Eastern Extension.

Table 1 shows the generalised geological succession for the area based on the BGS mapping supplemented by previous site investigations.

Age	Formation	Description	Approximate Thickness (metres)
Recent	Alluvium, undifferentiated	Clays and silts	0-2.5
Pleistocene	Glacial Sands & Gravels	Sands and gravels	0-10
	Boulder Clay and Glacial Drift, undifferentiated	Silty clay with sand and gravel	0-30
		UNCONFORMITY	
Upper Permian	Ford (formerly Middle Magnesian Limestone) Formation	White to buff soft, oolitic limestone	0-50
	Raisby (formerly Lower Magnesian Limestone) Formation	Buff to yellow, fine-grained dolomitic limestones	10-50
	Marl Slate Formation	Grey, organic-rich, laminated siltstones and dolomites	1-5
	Yellow (formerly Permian) Sands Formation	Weakly cemented, coarse, yellow siliceous sandstone	0-30
		UNCONFORMITY	
Carboniferous (Silesian)	Middle and Lower Coal Measures	Mudstone, siltstone, sandstone, seatearth and coals	450

***Table 1.** Stratigraphy of the general area around Thrislington Quarry.*

The existing quarry extends approximately 2km by 1km and works the Raisby Formation down to its contact with the Marl Slate. In the base of the quarry the Marl Slate is breached in places to assist quarry drainage and to permit local excavation of the underlying Yellow Sands. The sand excavation (the so-called 'Sand Hole') is partially filled with water, and acts as a sump into which runoff and groundwater inflow is drained prior to being pumped off-site to the west.

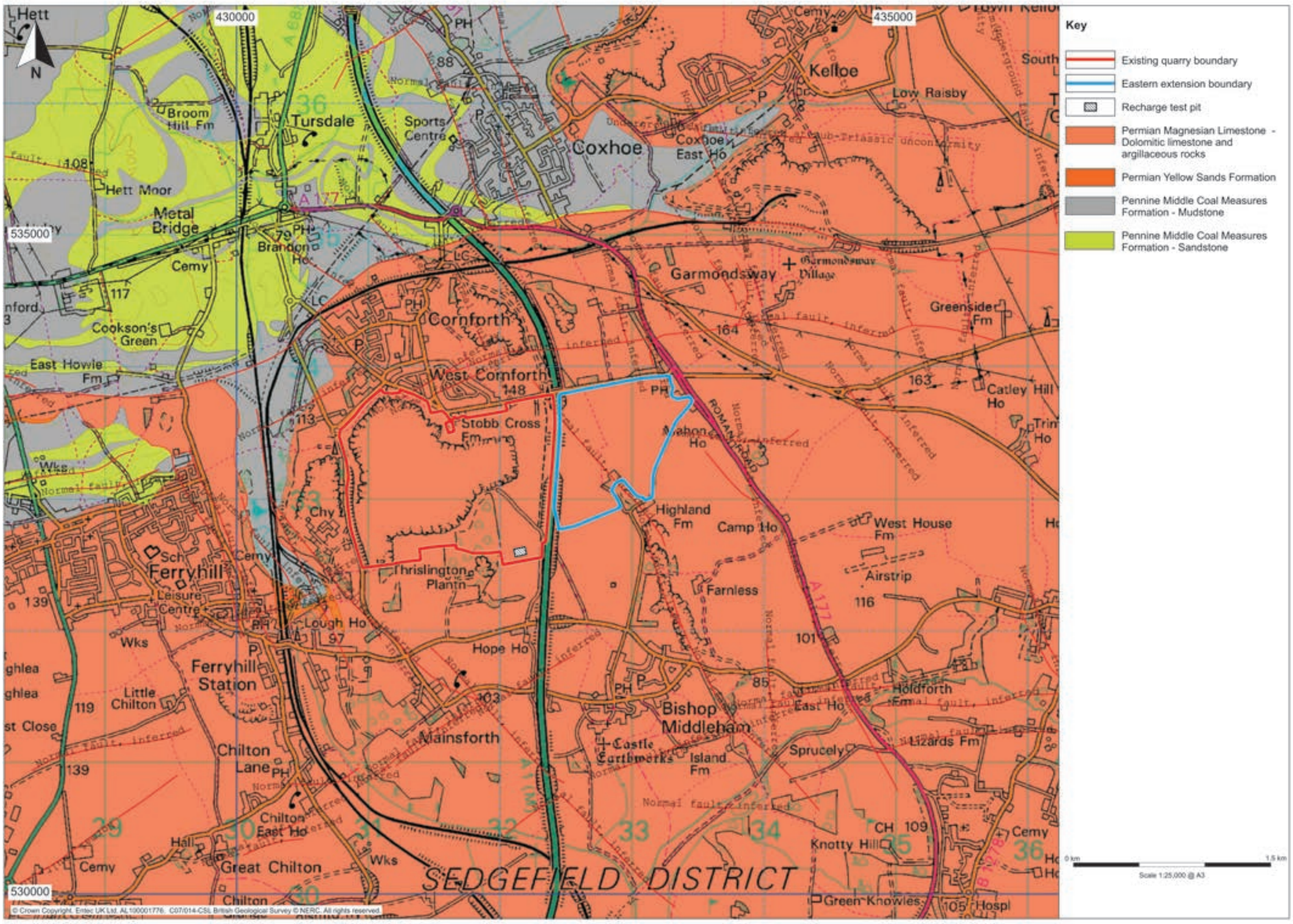


***Figure 1.** Solid geology around Thrislington Quarry.*

A reasonably extensive groundwater level and discharge monitoring network is in place at the quarry (Figure 2), with monitoring results at certain locations extending back to 1994, and in recent years the detailed site hydrogeology has been thoroughly studied for Lafarge by its consultants, Entec UK Ltd. Groundwater levels have been recorded for the Magnesian Limestone, Yellow Sands and Coal Measures, from which the hydrographs of Figure 3 demonstrate from limited data the potential for downward groundwater flow from the Magnesian Limestone into the Yellow Sands and then into the Coal Measures.

Water monitoring demonstrates that in the vicinity of Thrislington Quarry the Magnesian Limestone water levels are typically seven metres above those in the Yellow Sands and two metres above in the vicinity of the Sand Hole, indicating the potential for downward vertical

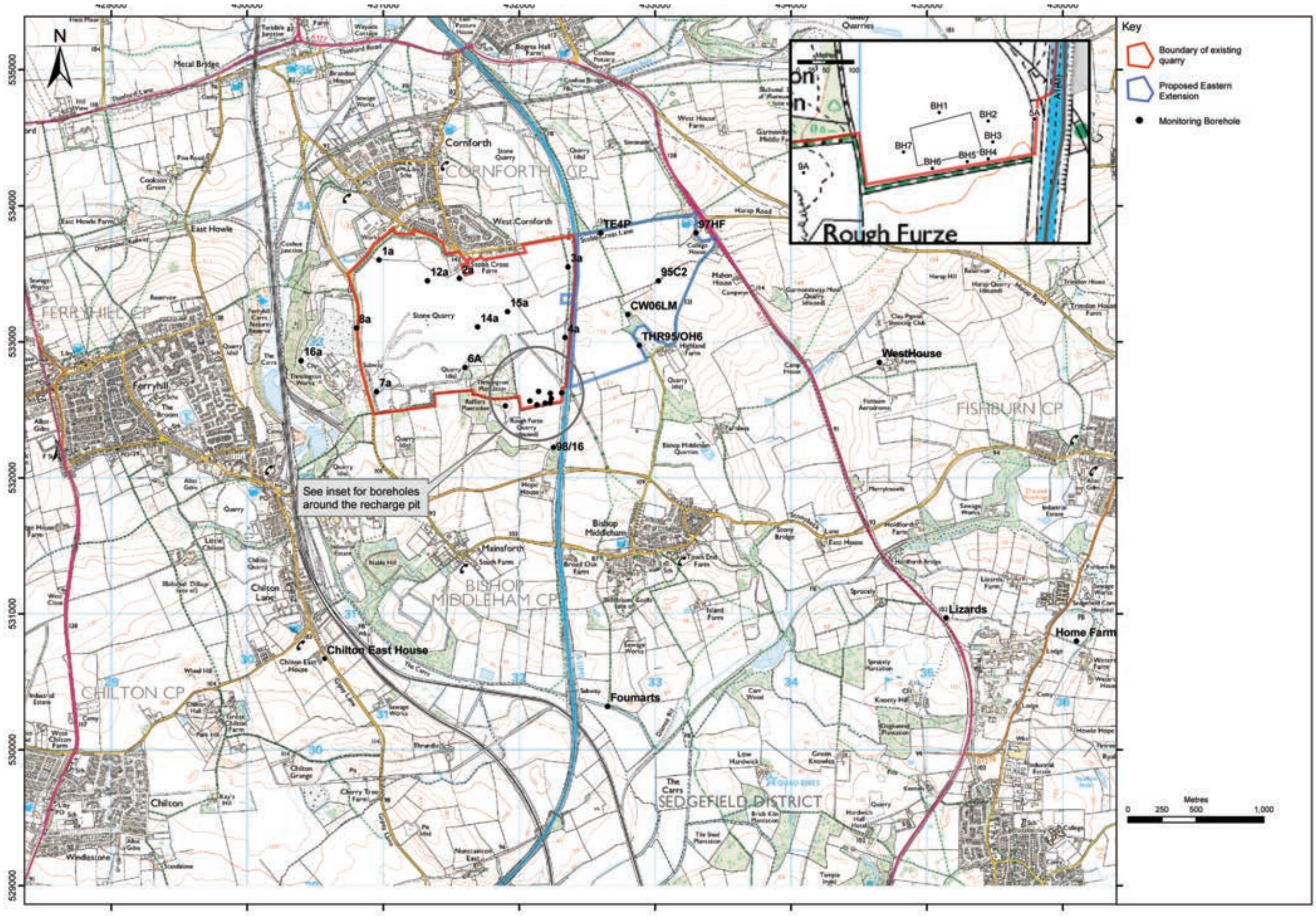


Figure 2. Location of monitoring boreholes and recharge pit.

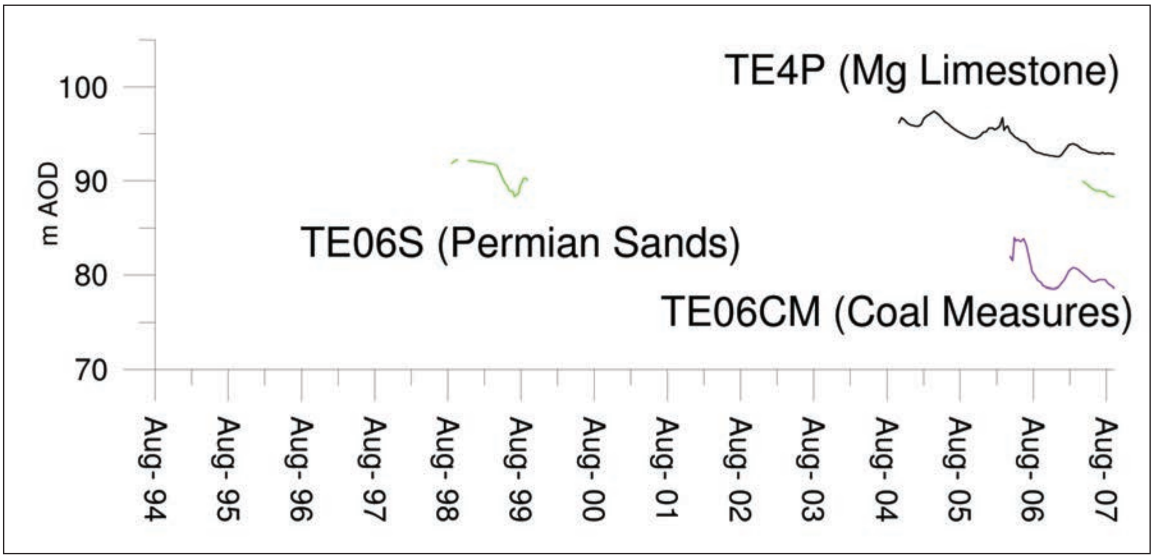


Figure 3. Pre-trial groundwater levels in boreholes.

flow between the two strata through the intervening Marl Slate. This contrasts with aquifer conditions further south, where upward vertical flow of high sulphate waters from the Coal Measures into the Magnesian Limestone has been reported (Neymeyer, 2007), possibly attributable to the cessation of abstractions from the Coal Measures at Mainsforth Colliery in the early 1970s (Cairney & Frost, 1975, Younger 1993). The cessation of abstraction from the Coal Measures is also identified in these studies as the main reason for the long term rise in water levels identified in the confined limestone to the south and east of the quarry.

Groundwater level contours for both the Magnesian Limestone and the Yellow Sands were produced using April 2004 data. Figure 4 shows the Magnesian Limestone plot and confirms that limestone groundwater flow is broadly west to east beneath the existing quarry, but turning more north-west to south-east beneath the Eastern Extension.

The contouring shows high groundwater levels beneath the Eastern Extension between 94mAOD in the north-west, falling to 91mAOD in the south-east, some 1 to 12 metres above the base of the limestone. In the main quarry the water table is generally in the range 104mAOD in the west, falling to 92mAOD in the east, where the base of the limestone is approximately 90 to 95mAOD and the land surface is generally 130 to 140mAOD.

The flow in the Yellow Sands is more north-west to south-east, under a more gentle hydraulic gradient.

EASTERN EXTENSION PROPOSALS

The extension on land east of the A1(M) dual carriageway is planned to be a supplementary quarry measuring approximately 1km on it's North to South axis by 0.75km West to East. This excavation would be connected to the existing quarry by a tunnel under the motorway, thereby enabling mineral to be transported to the processing plant.

10km to the south east of the eastern extension lie several groundwater public water sources serving Hartlepool. The long thin groundwater protection zones for these boreholes extend to just beneath the eastern extension. Although this overlap only covers a very small percentage of the catchments, it was important to demonstrate that the catchments will not be derogated or, should potential derogation be identified, that appropriate mitigation can be implemented.

The Environment Agency also required assurance that the dewatering, needed to enable dry working of the quarry would not lead to the local vertical hydraulic gradient being reversed, with an upward gradient driving poor quality Coal Measures water up into the limestone aquifer and towards the public water sources.

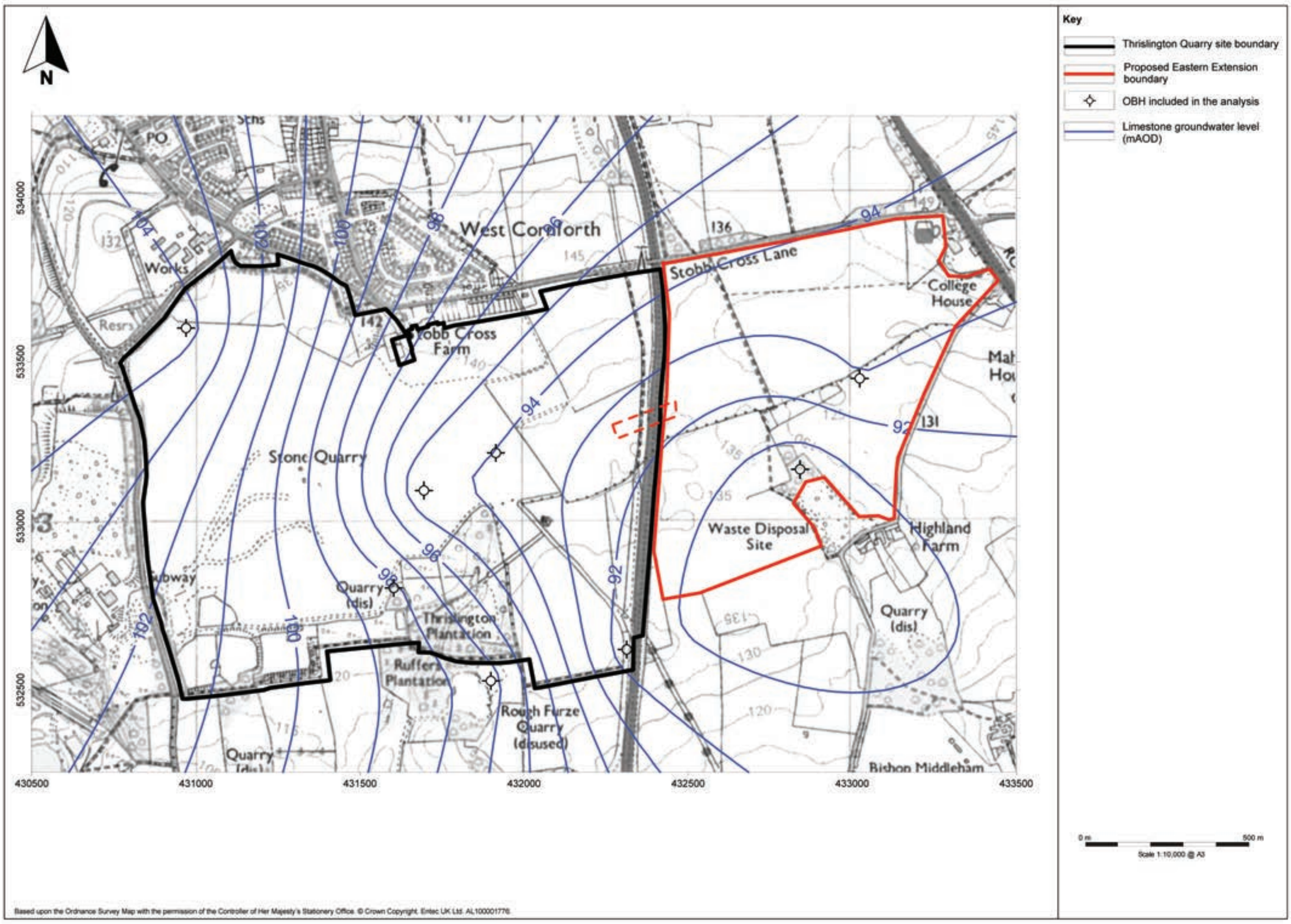


Figure 4. *Average (April 2004) Lower Magnesian Limestone groundwater level contours.*

EASTERN EXTENSION MITIGATION STRATEGY

In recognition of these concerns, Lafarge proposed mitigation measures comprising several infiltration pits down gradient (south and east) of the eastern extension, such that when dewatering is required from the excavation the water can be recharged back to the limestone aquifer. The implementation of structured monitoring and mitigation schemes is long established at various other locations in the country (Wardrop *et al.*, 2001).

Lafarge is aware of at least two rock quarry complexes in the UK where recharge had been practiced for many years, but these older operations had little monitoring infrastructure and a sparse data record with which to support the proposal. The Environment Agency, local water company, and the County Planning Authority required a high level of confidence that the proposed mitigation scheme would be effective. The principle of a heavily instrumented field trial was therefore developed as the most conclusive method of demonstrating an effective mitigation strategy, with the major additional benefit of providing data with which to design the infiltration pits and monitoring network of the future artificial recharge scheme.

The main aim of the field trial was to demonstrate that realistically large volumes, akin to those expected to be encountered as a result of dewatering in the Eastern Extension (about 1100-1500 m^3/d), could be successfully recharged to the Magnesian Limestone aquifer. This dewatering volume estimate was arrived at from the average daily discharge from the main quarry of some 1,800 m^3/day, and reflects that the main quarry is more than twice the footprint of the eastern extension and receives imported water by way of aggregate processing water pumped from an off site mineshaft.

The trial also aimed to show that vertical head gradients would not be adversely affected by the proposed recharge scheme.

The trial and the monitoring protocols were agreed in advance with the Environment Agency, and the exercise embraced a range of recharge rates and varying groundwater conditions.

THE RECHARGE TRIAL

The essence of the trial was to construct an infiltration pit within the permitted area of the existing quarry west of the A1 dual carriageway, create a network of monitoring boreholes in appropriate locations around the pit (inset on Figure 2), and then pump water into the feature at various rates over a suitable period of time whilst monitoring the behaviour of the pit and the aquifer.

After satisfying planning conditions in respect of archaeology and soil stripping, a rectangular excavation measuring 100m long by 50m wide by 10m deep was constructed some 100m to the south of the upper southern face of the existing quarry, immediately to the east of Thrislington Plantation (NZ 3215 3258). This test site will soon be lost as the quarry face is advanced southwards.

The feature was formed by conventional drill and blast techniques, with walls left as close to vertical as was safe, and in a condition that would be fully representative of the mitigation features proposed for the eventual eastern extension.

The floor of the excavation, just as in a normal quarry, had been trafficked by wheeled dump trucks and thus was likely to demonstrate substantially reduced infiltration capability due to the formation of a layer of comminuted compacted limestone over the naturally fractured rock. For this reason, the floor of the recharge feature was ripped by a bulldozer once there was no further requirement for dump truck traffic. Crucially though, it must be recognised that the floor of a recharge feature need not be the only, or indeed the main, infiltration surface available for recharge. The near-vertical sidewalls of the excavations are inherently less clogged and less prone to future blinding by siltation, and presented a potential infiltration area almost as great as the excavation floor itself.

Seven observation boreholes comprising 50mm geowrapped standpipes in 100mm diameter drilled holes surrounded the feature, shown on Figure 2. The boreholes were positioned 10m to 25m from the pit edge, representing radii of 41m to 115m from the point of discharge, and measured water levels only in the Magnesian Limestone. The boreholes were positioned so as to enable groundwater level contours to be constructed beneath the entire extent of the trial site, though with an emphasis towards the down-gradient direction where the recharged water was anticipated to travel. The authors wished to demonstrate that groundwater levels in the limestone responded to the infiltration in the vicinity of the site and confirm that the infiltration was reaching the water table. An indication of water level 'mounding' and the preferential direction of flow would give some confidence that monitored water levels could be used to trigger progressive mitigation measures in future.

Twelve of the pre-existing boreholes in the quarry and around the perimeter of the proposed eastern extension (Figure 2) were selected to monitor the trial, including a number of Yellow Sands boreholes. The majority of the borehole water levels were monitored by data-loggers, with weekly manual check dips, the latter consistently tracking the electronic data.

Background monitoring records exist from 1999 for the quarry network while Environment Agency records pre-date 1994. A very reliable dataset exists against which to judge the efficacy of the recharge activity.

An off site Environment Agency "Reference Borehole" was identified that could confidently be expected, not to influenced by the trial pumping, such that meteorological and aquifer behaviour away from the site could be identified.

Supporting data comprised:

1) Daily rainfall for Lafarge's Thrislington rain gauge;
2) Meteorological Office potential evaporation for open water;
3) Pumped volume into the infiltration pit; and
4) Water level within the pit.

A sump was excavated in the floor of the operating quarry to the north of Thrislington Plantation (figure 4) in order to provide water for the trial. The location was believed to be substantially unaffected by both the routine quarry dewatering carried out in the 'Sand Hole', located in the south west corner of the quarry, and from risk of recharge from the infiltration feature. The sump used a diesel pump feeding 770m of pipeline rising 41m to a metered discharge point at the infiltration pit. A 50mm PVC tube was installed on one corner of the infiltration pit for manual water level monitoring purposes.

PRE – TRIAL

A 'trial test' undertaken in November and December 2007, involving volumes of recharge water up to 1,000m^3/d. The purposes of this preliminary test were to confirm the feasibility of the recharge approach; to establish the logistics and monitoring requirements of the main test; and check the pump, pipework and monitoring infrastructure in order to establish a sustainable pumping rate in balance with the supply capability of the sump.

The informal test started on 20th November 2007, and discharges into the infiltration pit continued for most working days until 11th December, with an additional isolated discharge on 17th December. A maximum discharge of 990m^3/d was achieved on 3rd December, whilst over the days of operation the average discharge was 485m^3/d.

During this period all the water was seen to infiltrate very rapidly into the floor of the recharge feature. At the time, after a substantial period of dry weather, the water table in the Magnesian Limestone was generally 30 to 35m below the floor of the feature and was clearly identified in all of the monitoring boreholes.

All 7 monitoring boreholes successfully identified a rise in water table attributable to recharge pumping with a lag time of only an hour or two between start of recharge and a rise in water table being identified. The typical rise was in the order of 5 to 7m. A major component of the recharge was identified in the down dip monitoring boreholes which is intuitively unsurprising but nevertheless satisfactory outcome in the circumstances.

On cessation of pumping the induced rise in the groundwater table decayed over a period of 3 to 4 days with most of the recovery occurring within 24 hours.

THE MAIN TRIAL

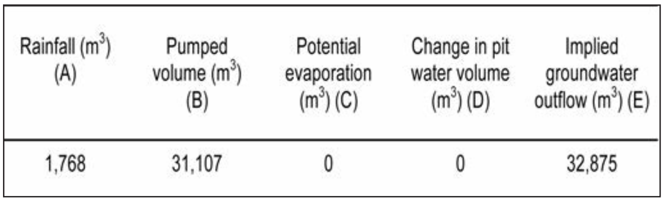
The main trial commenced on 14th January 2008, with discharges occurring on the majority of working days until 29th February 2008. Dry weather constrained the available water at times, with daily rates varying from 0 to 2120m^3/d. During the days of operation the average discharge was 900m^3/d. The maximum weekly discharge rates were around 1000m^3/d initially, with increases each week to a maximum of 2120m^3/d in early February 2008. Thereafter, maximum weekly rates were around 1500m^3/d.

Effectively a stepped recharge test has been carried out along the lines of the conventional stepped discharge test for borehole testing and the results were considered amenable to similar analysis.

RESULTS

i. Water Balance

Groundwater outflow from the infiltration pit (E) was calculated as the sum of rainfall (A) and the pumped volume into the pit (B), minus the sum of potential evaporation (C) and change in the pit water volume (D). The water balance for the entire informal and formal test is presented in Table 2 below representing discharge for *c.*50 days of activity.



Rainfall (m^3) (A)	Pumped volume (m^3) (B)	Potential evaporation (m^3) (C)	Change in pit water volume (m^3) (D)	Implied groundwater outflow (m^3) (E)
1,768	31,107	0	0	32,875

Table 2. *Water Balance Results*

The overwhelmingly dominant inflow to the infiltration pit was from the pumped volumes, with rainfall only accounting for approximately 5% of the total inflow.

The change in the pit water level is shown as zero because the infiltration pit did not fill with water at any point during the test. The discharge pipe outlet rested on the excavated ramp used by dump trucks to exit the recharge excavation, and the water was seen to run over the surface of the ramp for approximately 25m before a significant proportion of it drained into a noticeable fissure part way down the ramp. Much of this water reappeared from the pit side of the ramp and it is thought that the fissure could be largely an artefact of the ramp creation. No standing water was created in the floor of the infiltration feature, other than a few square metres where water was visible in the bases of the ripping lines created by the bulldozer, and no water level was recorded in the infiltration pond monitoring point provided.

Volumes for potential evaporation are also zero for similar reasons, the absence of any standing water preventing any significant evaporation losses. Accordingly, the total groundwater outflow from the pit is simply a sum of the rainfall and the pumped volume into the pit.

The performance of the pit is encouraging, suggesting that the anticipated Eastern Extension recharge rate of 1,100 to 1,500m^3/d is confidently achievable.

ii. Groundwater Response

Water balance is the critical factor in assessing the feasibility of artificial recharge but the groundwater level response is of interest and proved very useful in understanding the groundwater flow mechanisms in the Magnesian Limestone.

Pre-trial Groundwater Levels

Water levels within the Magnesian Limestone demonstrate a general north-west to south-east hydraulic gradient, ranging from about 98mAOD in the west (BH 6A) to 74mAOD in the east (Lizards Farm) shown on Figure 2. The water levels are some 30m beneath the pit at about 95 to 100mAOD. In the western limestone outcrop areas, the water level response to natural recharge is quite marked, with water level changes of 5m not uncommon. In contrast, water levels recorded in boreholes further to the east are generally much flatter and less responsive, as they monitor levels where the Magnesian Limestone is covered by drift. Seasonal fluctuations within these boreholes are typically up to one metre.

Groundwater levels within the Yellow Sands are monitored within the existing site and the Eastern Extension. They are generally 5-10m below those in the Magnesian Limestone, implying the potential for downward vertical flow, and they respond more slowly to recharge events. That they respond to recharge at all suggests that the Marl Slate Formation, which lies between the Yellow Sands and the Magnesian Limestone, behaves more like an aquitard than an aquiclude.

Groundwater levels within the Coal Measures are monitored at fewer locations. In general, levels within the Coal Measures appear to be below those in the Yellow Sands and Magnesian Limestone, again implying downward vertical groundwater flow.

Trial Groundwater Levels

Responses to the varying discharges into the infiltration pit were clearly visible in all the hydrographs for the boreholes surrounding the pit, with a typical net rise of around 7m. The nature of the response reflected the nature of the discharge regime. For example, including periods when shortage of sump water meant discharges into the pit were intermittent, the limestone groundwater levels were very variable and displayed rapidly responding peaks. That the effect on water levels was so obvious, repeated and widespread is encouraging in terms of the predicted success of a future artificial recharge regime.

One borehole, for instance, at the commencement of the main trial demonstrated 90% of its water level rise within the first 12 hours with full rise at 20 hours. At cessation both boreholes 4 and 5 demonstrated 90% of the recovery to natural water levels at 24 hours with full recovery at about 3 days. The shape of the recovery curve is very similar, in reverse, to that of a borehole pump test recovery curve in a Darcian aquifer.

Monitoring boreholes to the north and north east of the infiltration site display a slightly less spiky and slightly subdued response that is entirely consistent with the flow direction analysis presented later.

Observed water level responses are sufficiently similar to theoretical behaviour to suggest Darcian flow and the effect of fissures, that in karstic aquifers elsewhere have resulted in water completely bypassing monitoring networks, must be only local. The authors interpretation is that the aquifer benefits from a sufficiently well connected fracture network as to approximate Darcian behaviour at the study scale.

INTERPRETATION

The shape of the induced mound resulting from the artificial recharge needs to be borne in mind when locating future infiltration pits. For example, if an infiltration pit is positioned too close to existing workings, the rapid rise in water levels could result in significant recycling of water between the pit and the workings. This does not mean that the operation fails to meet its objectives with respect to water resource retention, but it does introduce inefficiencies and increased pumping costs. This potential difficulty can be avoided by locating the infiltration pit further away from the workings, and/or by employing more than one pit.

The time lag between recharge and full water level rise was only a day or so, despite the underlying limestone unsaturated zone being 30-35m thick. This rapid travel time implies the dominance of small scale fissure flow in the unsaturated zone. All the test boreholes responded to the discharge at approximately the same rate and time, despite the discharge originating from a point source. This suggests that the infiltrating water moved rapidly laterally as well as vertically, most probably along bedding planes and other discontinuities within the unsaturated zone.

Superimposed on the daily limestone water level fluctuations was a longer-term variation. Average groundwater levels increased until the end of January 2008, and then showed a gradual decline. The boreholes distant from the pit are not thought to have been impacted by the trial and show a similar long-term variation, strongly suggesting that the variation reflected the natural seasonal groundwater level trend.

Boreholes within the Yellow Sands were responding to the recharge test but in a relatively muted fashion, with a rise of no more than one metre. The differing response between the Magnesian Limestone and the Yellow Sands resulted in downward vertical gradients between the aquifers increasing during the periods of active recharge. This implies less potential for upward flow of contaminated waters from the Coal Measures, and is a very important benefit of the recharge scheme.

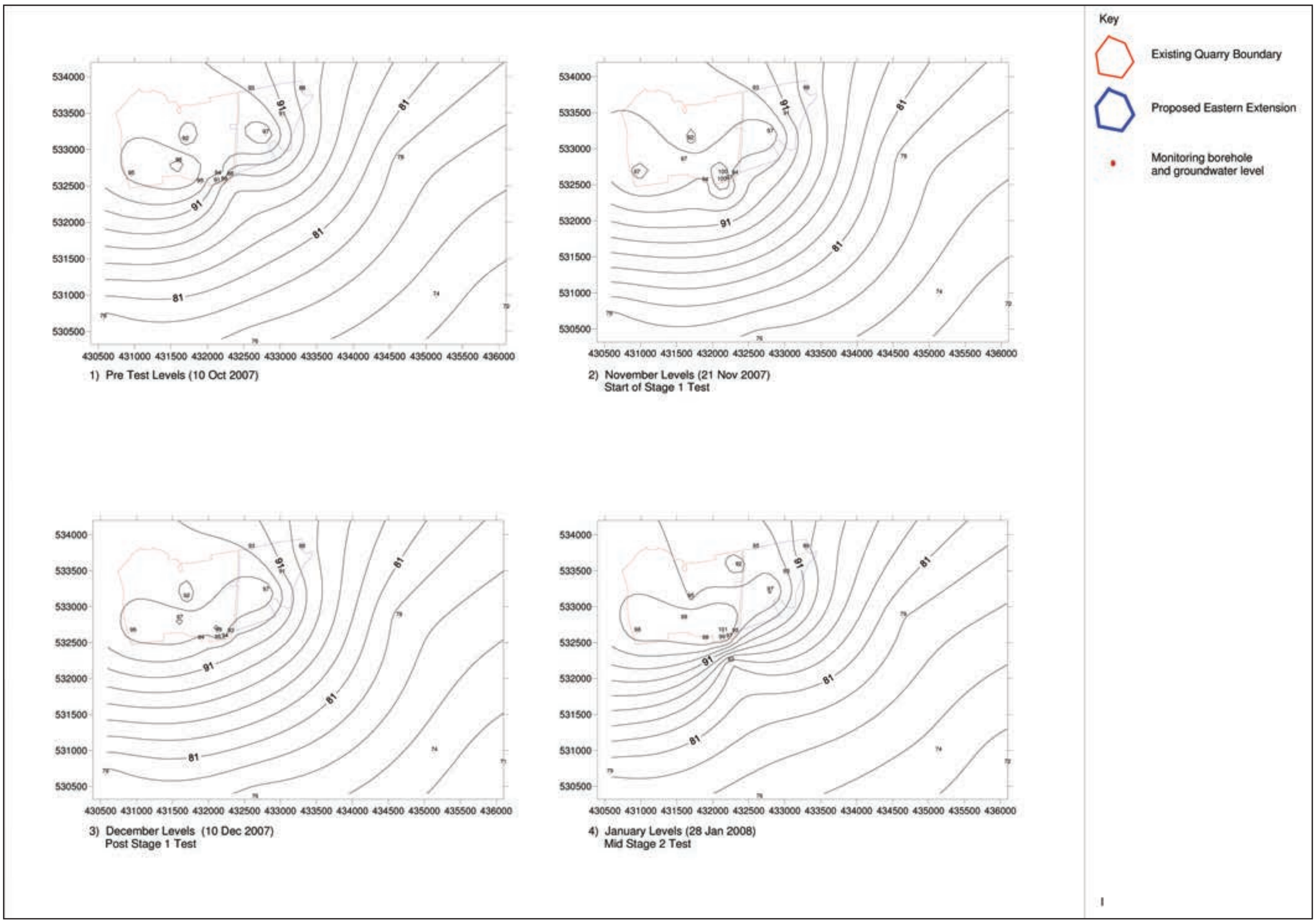
Post-trial Groundwater Levels

The recharge test finished at the end of February 2008, but monitoring continued, to observe groundwater level recovery. In general, groundwater levels within the Magnesian Limestone in the following weeks fell to levels slightly higher than those seen in the pre-trial period, due to continued natural recharge.

Groundwater Level Contours

Several limestone groundwater level contour plots were produced as a means of evaluating the impact of the recharge test and four of these plots are presented in Figure 5.

All four plots show that the regional groundwater gradient in the Magnesian Limestone is to the south east, but in other respects there are some noticeable differences. Before the trial started, groundwater levels across the recharge site were relatively uniform at about 92mAOD. Just after the commencement of the



1) Pre Test Levels (10 Oct 2007)

2) November Levels (21 Nov 2007)
Start of Stage 1 Test

3) December Levels (10 Dec 2007)
Post Stage 1 Test

4) January Levels (28 Jan 2008)
Mid Stage 2 Test

Figure 5. *Magnesian Limestone groundwater level contours before, during and after the recharge trial.*

preliminary test, a localised recharge mound with maximum levels of over 98mAOD had formed, with some flow directed towards the north. The mound was seen to quickly dissipate on cessation of the preliminary test, only to quickly reform during the main trial, though its shape is altered somewhat because of the continued natural regional recharge during the intervening period.

The northerly component of flow from the infiltration pit towards the existing quarry represents a local reversal of the regional hydraulic gradient, as could be envisaged with a recharge mound being superimposed on a gently sloping water table. Groundwater levels were too low to intercept anything other than the lowest point of the quarry, and the southern quarry face remained dry. From the local configuration of the contours, their direction and gradient, around the preliminary test recharge mound, it is estimated that some 25% of the width of the recharge front as approximated by the 97mAOD contour is directed to the north. Using a Darcy-type calculation this would imply that some 15% of the flow is to the north, laterally towards the sump pump and/or sub-vertically downwards into the deeper limestone and the Yellow Sands.

No attempt was made to construct groundwater level contours for the Yellow Sands or the Coal Measures, since there is insufficient data and this was not a main purpose of the trial.

CONCLUSIONS

Although relatively rare in the UK water recharge into rock aquifers has been documented in many other countries. For instance, Barruco (2002) describes an artificial recharge scheme to help prevent saline intrusion into coastal aquifers in Sardinia, where sufficient information was collected to evaluate the scheme and to validate a model describing the flow and transport processes in the aquifer. The Central Groundwater Board of the Indian Ministry of Water Resources (2000) describes widespread use of infiltration features in various geological settings mostly intended to capture surplus monsoon rainfall and make it available for later abstraction from groundwater.

The International Association of Hydrogeologists list several examples of practical artificial recharge, mostly for the purposes of protecting or enhancing groundwater supplies in arid regions. A long running series of biennial symposia are reported through the American Society of Civil Engineers Publications.

This trial has demonstrated that using an infiltration pit to recharge water back into the Magnesian Limestone aquifer is a viable means of minimising loss of groundwater resource associated with the dewatering of the eastern extension. The trial water balance clearly illustrates that all water discharged into the infiltration pit becomes recharge to groundwater, with no surface ponding of water and no net losses. Artificial recharge increased downward vertical hydraulic gradients in the aquifer, minimising the risk of induced upward flows of contaminated groundwater from the Coal Measures. The predominant lateral groundwater flow direction of the recharged water was to the south east, and this is expected to be even more evident in the eastern extension, thus providing effective resource protection to the catchment zones of the Hartlepool Public Water Supply boreholes.

The trial has also indicated that simple boreholes of appropriate design in this setting are an effective method of monitoring water level response to artificial recharge in this fissured aquifer. A marked response to the recharge was observed at all nearby monitoring boreholes, suggesting that monitored water levels could be used to control a future recharge operation within a monitoring and mitigation scheme.

Apart from confirming that the recharge scheme proposals are essentially sound, the trial helped address some of the practicalities of the larger recharge operation. For example, the hydraulic conductivity of the limestone surface was higher than anticipated, and sediment binding was not a particular problem, so any future infiltration pits can be much smaller than the pit used during the trial. The local reversal of the hydraulic gradient was shown to occur in the vicinity of the infiltration pit, with some flow heading back towards the quarry, and to avoid unnecessary recirculation of water the future infiltration pit(s) will need to be located further from the quarry void.

The test has also revealed information about the dominant groundwater flow mechanisms in the aquifer, including rapid transmission times through the unsaturated zone, the behaviour of the Marl Slate as an aquitard rather than aquiclude, and definite hydraulic continuity between the Magnesian Limestone and the Yellow Sands.

The conclusions therefore are that the recharge experiment was highly successful. As a result, the Environment Agency felt able to withdraw its hydrogeological concerns regarding the development, leading to the proposed quarry extension receiving a resolution to grant planning permission. It must be emphasised that the results of this trial and any conclusions here presented are specific to this part of the Magnesian Limestone aquifer. Any implications drawn for other areas and particularly other hard rock aquifers must be treated with caution, and reliance should instead be placed on the results of field trials.

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